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Weather and Crops

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The key atmospheric variables that impact crops are solar radiation, air temperature, humidity, and precipitation. The day-to-day variability of these across the landscape can be described as *weather.* Weather extremes at critical periods of a crop's development can have dramatic influences on productivity and yields. The long-term average temperature and humidity and the total solar radiation and precipitation over a crop's growing season can be described as the climate. It is the climate that, in the absence of any weather extremes, determines the realized yields for a given region.

This chapter addresses how plants respond to these atmospheric variables, how they vary over the season and across Illinois, and to what extent they can be predicted, from several weeks to several seasons into the future.

Crop Response to Weather Variables

The response of crops to the different weather variables is quite complex and difficult to describe. If one of the variables is limiting (for example, temperatures that are too hot or too cold), then the effects of solar radiation or precipitation do not greatly affect the crop. When none of the variables is limiting, the crop will respond to the variable that is farthest from the optimum for that variable. Describing the physiological response of crops at the field level introduces additional uncertainty in predicting crop yield. Predicting the exact response of crops to the weather is, as a result, an inexact science, and one that contains great uncertainty.

The information presented in this chapter is based on "normal" weather conditions. Normal is defined by the World Meteorological Organization as a 30-year period updated every decade. The current period is 1971 to 2000. New 30-year climate normals will be computed in 2011 using the 1981 to 2010 period. A "normal" year seldom occurs, if ever, because there is always variability of the weather from normal across years and within the year, with some periods being wetter/drier, hotter/cooler, sunnier/cloudier than normal.

Temperature

Other than planting, temperature is the main variable that determines when a crop will grow. It also determines, along with precipitation and solar radiation, how well a crop will grow and how fast it will develop. There are four temperature thresholds, called the cardinal temperatures, that define the growth of a crop: the absolute minimum, the optimum minimum, the optimum maximum, and the absolute maximum. The absolute minimum and maximum temperatures define the coldest and hottest temperatures at which a crop will grow. Temperatures between the optimum minimum and maximum define the range of temperature where the crop performs the best. Corn (*Zea mays* L.), for example, has an absolute minimum temperature of 50 °F (10 °C), an optimum minimum of 64 °F (18 °C), an optimum maximum of 91 °F (33 °C), and an absolute maximum of 117 °F (47 °C). Corn is an example of a C4 crop, which originates from a tropical

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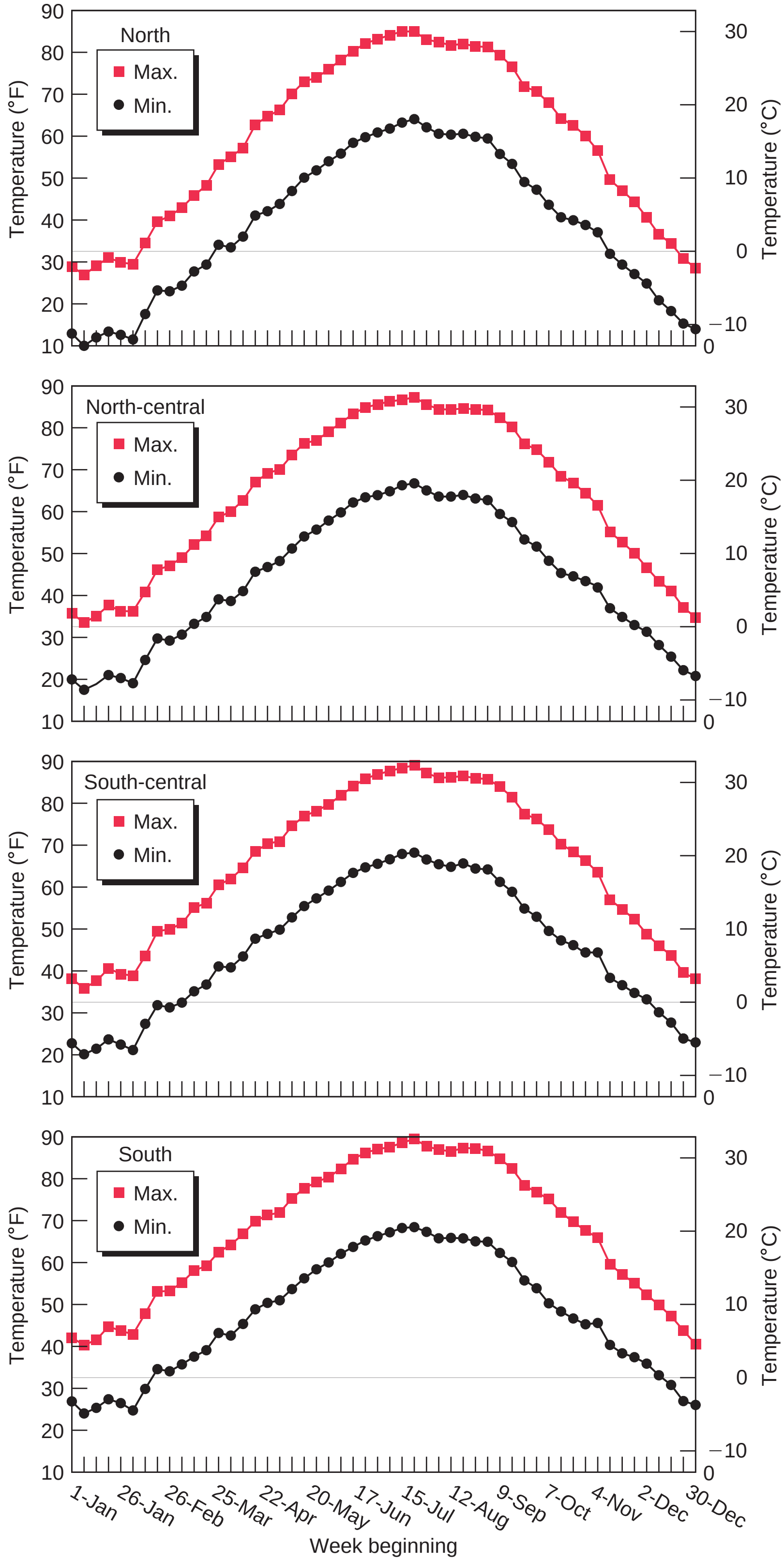

Figure 1.1. Average weekly minimum and maximum temperatures for four regions of Illinois, 1971 to 2000. The north region is represented by crop reporting districts (CRDs) 1 and 2; the north-central by CRDs 3, 4, and 5; the south-central by CRDs 6 and 7; and the south by CRDs 8 and 9.

environment. C4 crops, which also include Miscanthus (*Miscanthus* x *giganteus*) and sorghum (*Sorghum bicolor*), have absolute minimum temperatures ranging from 45 to 50 °F (7 to 10 °C), optimum minimums from 59 to 81 °F (15 to 27 °C), optimum maximums from 91 to 104 °F (33 to 40 °C), and absolute maximums from 104 to 117 °F (40 to 47 °C). C3 crops, including wheat (*Triticum aestivum*), soybean (*Glycine max*, Merrill), and alfalfa (*Medicago sativa*), have absolute minimum temperatures ranging from 36 to 41 °F (2 to 5 °C), optimum minimums from 59 to 68 °F (15 to 20 °C), optimum maximums from 73 to 91 °F (23 to 33 °C), and absolute maximums from 81 to 100 °F (27 to 38 °C).

These temperature thresholds can be used with **Figure 1.1** to identify the weeks when the weekly mean maximum and minimum temperatures are within the absolute and optimum temperature ranges. Using corn as an example, the weekly mean minimum temperature is at or above the minimum optimum temperature from April 1 through September 16 in the northern two crop reporting districts (CRDs 1 and 2) and from March 5 through September 23 in the southern two crop reporting districts (CRDs 8 and 9). The north-central region, represented by crop reporting districts 3, 4, and 5, experiences weekly mean minimum temperatures within the optimum temperature range approximately one week earlier in the spring and one week later in the fall than the north region and one week later in the spring and one week earlier in the fall than the south-central region, represented by crop reporting districts 6 and 7. During these periods, the temperature conditions are generally considered to be optimum for corn growth and development.

Growing degree units. Research has shown that crop development—the time from planting to flowering and/or maturity—is more closely correlated with temperature than with the number of days after planting. Growing degree units (GDU), also known as growing degree days (GDD), are used to relate temperature to crop development. GDUs are accumulated when the mean daily temperature exceeds a threshold identified for a crop. For example, wheat has a threshold temperature of 45 °F. If the mean daily temperature for a day is 46 °F (8 °C), one GDU will accumulate in that day. If the next day's mean temperature is equal to 50 °F (10 °C), then 5 GDUs will accumulate for the day and 6 GDUs will have accumulated for the two-day period. The basic equation for computing accumulated GDUs is

$$GDU = \sum_{Day=1}^{n} \frac{T_{mx} - T_{mn}}{2} - T_b$$

where T_{mx} is the maximum daily temperature, T_{mn} is the minimum daily temperature, and T_b is the threshold temperature. If the daily average temperature, computed as the sum of the maximum and minimum temperatures divided by 2 minus the base temperature, is less than zero, the GDU accumulation for that day is zero.

For cool-season crops, such as cereal crops, and most C3 crops, the base temperature is 45 °F (7 °C). For warm-season and most C4 crops, a modified GDU method is used. The basic equation is the same as the one at the left, but if the minimum temperature is lower than the base temperature, then the day's minimum temperature is set equal to the base temperature, usually 50 °F (10 °C). The maximum daily temperature is also modified if the daily maximum temperature exceeds 86 °F (30 °C), in which case the maximum temperature is set equal to 86 °F.

The annual accumulated GDUs are greatest in the southern region of Illinois **(Figure 1.2).** The annual accumulation of GDUs is 1,260 F (700 C) more in the south than in the north for a base 45 °F (7 °C). For the modified 50 °F (10 °C) accumulation, the north accumulates 1,080 F (600 C). This greater accumulation in the south compared to the more northerly regions of Illinois is the result of an earlier start to accumulation in the spring, a later end in the fall, and a pace slightly faster during the summer, when the south accumulates approximately 35 F (21 C) more GDUs per week. The greater accumulation in the

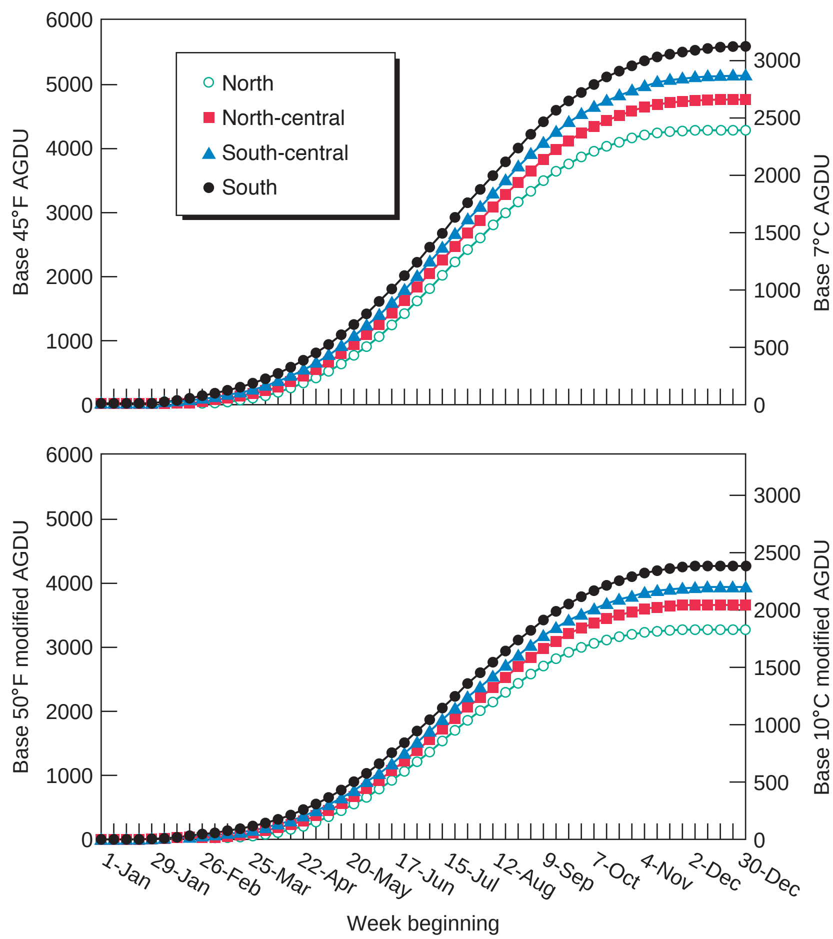

Figure 1.2. Average accumulated growing degree temperatures for four regions of Illinois, 1971 to 2000. The north region is represented by crop reporting districts (CRDs) 1 and 2; the north-central by CRDs 3, 4, and 5; the south-central by CRDs 6 and 7; and the south by CRDs 8 and 9.

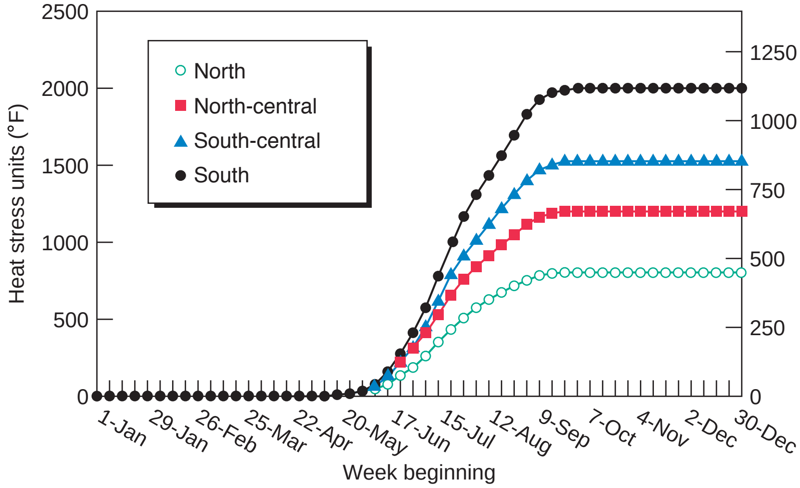

Figure 1.3. Average heat stress unit accumulations for a temperature stress base of 90 °F (32 °C) for four regions in Illinois, 1971 to 2000. The north region is represented by crop reporting districts (CRDs) 1 and 2; the north-central by CRDs 3, 4, and 5; the south-central by CRDs 6 and 7; and the south by CRDs 8 and 9.

south provides the potential for growing crops that require a longer growing season to mature than in the north.

Temperature stress. Crops experience stress from both heat and cold. Heat stress mostly occurs in the summer, while cold stress occurs in the spring and fall, usually when crops are being established or maturing. Cold stress is not a serious problem for most agronomic crops in Illinois; heat stress is more likely, especially in summers when temperatures approach or exceed 90 °F (32 °C).

When temperature exceeds a crop's optimum maximum, the crop experiences heat stress. A heat stress unit (HSU) is defined as the number of degrees the maximum daily air temperature is above the heat stress threshold times the number of days. For example, if the heat stress threshold is 90 °F (32 °C), and the maximum temperature is 94 °F (34 °C), then the number of heat stress units equals 4 F (2 C) HSU. Each day the maximum temperature reaches 94 °F (34 °C), an additional 4 F (2 C) HSUs are accumulated.

Heat stress affects plants because as temperature increases, respiratory reaction rates speed up, using more of the photosynthetic compounds manufactured in a day. Also, with elevated maximum temperature, especially temperatures that exceed 100 °F (38 °C), plants require more water to maintain optimum water content in their tissues. If the soil cannot meet the additional water requirement, heat stress is compounded by an added water stress.

On average, the southern part of Illinois accumulates approximately 2,000 F HSUs (1,111 C HSUs) with a stress threshold of 90 °F (32 °C), compared to 805 F HSUs (447 C HSUs) in the northern regions. Heat stress units generally begin accumulating around the first of June and continue to accumulate until mid- to late September **(Figure 1.3).** HSUs accumulated using a stress threshold of 86 °F (30 °C) are approximately double the HSUs accumulated using a stress threshold of 90 °F (32 °C). Using a stress threshold of 95 °F (35 °C), the accumulation is approximately 20% of HSUs accumulated using a 90 °F (32 °C) stress threshold. Most crops in Illinois can withstand temperatures below 95 °F (35 °C) unless they are accompanied with drought stress, so heat stress usually results in only minor yield losses.

Soil temperature. Soil temperatures in the autumn determine when ammonium nitrogen fertilizer may be applied without excessive nitrification occurring during the autumn and winter. With soil temperatures at a depth of 4 inches (10 cm) below 50 °F (10 °C), the rate of nitrification is reduced, but the process becomes negligible only when soil temperatures are below 32 °F (0 °C). The maps in **Figure 1.4** show the last day in the fall that 4-inch (10-cm) soil temperatures are above 50 °F (10 °C) and 60 °F (16 °C). Normally, soil temperatures throughout the state are consistently below 50 °F (10 °C) by the end of November. Maps showing the dates when soil temperatures fall below 60 °F (16 °C) are included as a guide for estimating when anhydrous ammonia application with a nitrification inhibitor may begin. Soil temperature can be estimated by computing the average of the mean air temperature for the preceding 7 days. These estimates tend to overestimate soil temperatures by 1 to 2 °F (0.5 to 1.0 °C) in the autumn. The error creates a conservative estimate of the soil temperature—so, for example, when the 7-day mean temperature is 50 °F (10 °C), the soil temperature may be 48 to 49 °F (9 °C).

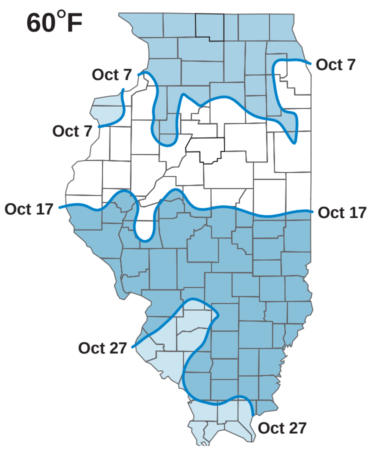

Figure 1.4. The average last dates in autumn when Illinois 4-inch soil temperatures were above 60 °F (15.6 °C) and 50 °F (10 °C), 1971 to 2000.

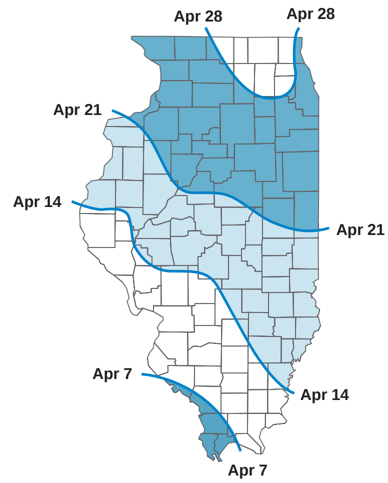

Figure 1.5. Average last occurrence in spring of 32 °F (0 °C) in Illinois, 1971 to 2000.

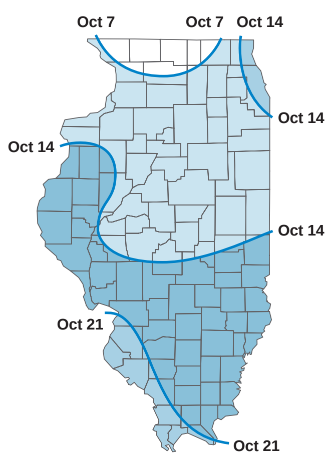

Figure 1.6. Average first occurrence in spring of 32 °F (0 °C) in Illinois, 1971 to 2000.

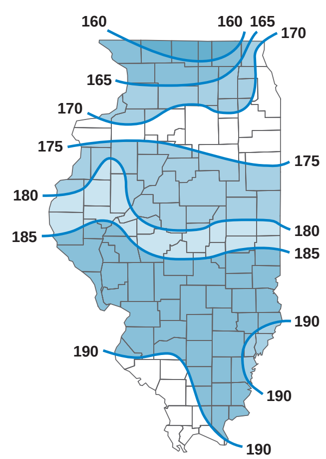

Figure 1.7. Average frost-free growing season length (days) in Illinois, 1971 to 2000.

Growing season length. The growing season is defined as the period between the last spring frost and the first fall frost. A frost will generally occur when the minimum temperature is less than or equal to 32 °F (0 °C). Most annual crops are planted after the major risk of frost or freeze has passed. However, late frosts—particularly very late frosts—can damage both annual and perennial crops during the spring. Frosts or freezes with temperatures less than 30 °F (–1 °C) result in major damage to crops in the spring. Mean dates of last spring frosts are as early as April 7 in southern Illinois and as late as April 28 in northern Illinois **(Figure 1.5)**. In 1 out of every 10 years, the last spring frost can occur as early as March 27 in southern Illinois and as early as April 21 in northern Illinois. In nine years out of 10 the last spring frost occurs as late as April 24 in southern Illinois, and as late as May 14 in northern Illinois.

The average dates of first fall frosts range from October 7 in northern Illinois to October 21 in southern Illinois **(Figure 1.6).** In 1 out of 10 years, the first fall frost occurs by September 26 in northern Illinois and October 6 in southern Illinois. In 9 out of 10 years, the first frost occurs before or on October 21 in northern Illinois and November 5 in southern Illinois.

These dates mean that the normal growing season is generally less than 170 days in northern Illinois and more than 185 days in southern Illinois **(Figure 1.7).** In north-central Illinois, which includes crop reporting districts 3, 4 and 5, the growing season is approximately 180 days.

Precipitation

The type, timing, and amount of precipitation received during the year play critical roles in crop productivity. Precipitation types include unfrozen (rain) and frozen (snow, sleet, and hail). Snow and sleet occur in the winter and hail in the warmer seasons. In the winter, frozen precipitation is less efficient than unfrozen in recharging the soil profile due to its accumulating on the soil surface, which is quite often frozen. As the snow melts on a frozen soil surface, the water tends to run off rather than move down into the soil. Also, snow on the surface will sublimate (i.e., be transformed directly from snow to water vapor) and be carried away from the soil surface. Sublimation occurs even with air temperatures below freezing. Snow may also blow off fields and into ditches and fence rows, further limiting its contribution to soil moisture in the field.

Rain is generally more efficient in recharging the soil profile and thus is more available for crops. The efficiency of rain in recharging the soil depends on the rate or intensity with which the rain falls. Rain showers or storms that fall at rates greater than 0.5 inches an hour (12.7 cm/hr) are less efficient than lighter showers because the water forms ponds on the surface and runs off the fields into ditches and rivers, carrying along precious topsoil.

The timing of precipitation is critical to crop growth. In the period from harvest to planting, referred to as the fallow season, recharge of the soil profile occurs. In Illinois, there is usually enough precipitation to recharge the soil profile by January of the year following the harvest. In those years when the soil profile is not recharged by January, rainfall during February, March, and April is usually adequate to recharge the soil profile. If the soil profile is not sufficiently recharged during the fallow season, the possibility of drought during the upcoming growing season increases because of a greater likelihood of a soil water deficit during critical crop growth stages.

Timing of precipitation. The timing of rainfall while crops are growing is critical. During seed germination and stand establishment, either too much or too little rain can influence yields. Too much rain, especially with cool temperatures, can result in seed diseases, causing poor stands, or can saturate the soil, causing poor soil aeration and poor germination and stands. Dry soils during germination and stand establishment can result in either poor seed germination or weak and small plants that may not withstand dry weather during the early growth of the crop, causing smaller plant leaf area. For corn, the critical time during the early growth lasts for approximately 30 days, from planting to tassel initiation, when the corn leaves are being initiated and beginning to grow.

During the rapid vegetative growth stage, too much rain can result in a smaller shoot-to-root ratio and the establishment of shallow roots. When this happens, the crop is more susceptible to dry spells during the hot months of July and August when the crop is flowering and establishing harvestable grain on ears of corn or pods on soybean plants. A dry period after the crop stand has been established will result in a greater shoot-to-root ratio, with roots growing deeper into the soil profile and allowing the plant to use more of the water stored in the soil. After a dry spell, if adequate rain to recharge the soil is received in the 2 weeks before corn tasseling and pollination, the effect of the dry spell will be minimized. Rainfall during the week or two before the start of flowering in the soybean crop will also reduce the effect of a dry spell during the pure vegetative growth stage.

Rainfall of 1 to 2 inches in the 2 weeks following corn pollination will generally result in the highest yields, especially if the period of pollination had adequate soil moisture. The period from corn pollination to maturity is about 60 days. If soil moisture is near normal or wetter than normal, a dry spell from day 14 to day 60 after pollination will have a small influence on final corn yield. However, if no rain were to occur during those 46 days, final yield and quality of the corn crop would be reduced.

Because the soybean crop continues to flower and fill pods from the start of flowering to almost the beginning of maturity, soybean requires adequate rainfall throughout the months of July and August for best yields. Failure to receive adequate rainfall during flowering and pod fill will result in fewer flowers and pods on the plants.

Generally, annual rainfall exceeds the water requirement of Illinois crops. Mean annual rainfall is greatest in southern Illinois **(Figure 1.8),** about 45 inches (115 cm). In the rest of the state, annual precipitation is about 37 inches. (95 cm). However, there is a south–north gradient: seasonally, there is more precipitation in the south-central region during spring and fall than in the north-central and northern regions. Conversely, summer precipitation is greater in the north (12 in./30 cm) and north-central regions than in the south. Winter is the driest season, with about 5 inches (13 cm) of precipitation in the north and 10 inches (25 cm) in the south. Spring is the wettest season in the south, with more than 13 inches (33 cm) of rain, whereas summer is the wettest season in the north, with 12 inches (30 cm) of rain.

While wetter-than-normal years usually benefit crop yields, years that are drier than normal can greatly reduce yield. The severity of the reduction is a function of the size and timing of the rainfall deficit. **Figure 1.9** shows the annual distributions of rainfall for the central CRD (CRD 4) in the dry years of 1971 to 2000. The driest year, 1988, began with below-average precipitation in January and February. Late March through early April received about 3 inches (8 cm) of rain. Following that rainy period, rainfall was evenly distributed but below normal throughout the growing season. The second-driest year was 1976. From May through July, there were 2- to 3-week periods with little or no rainfall followed by a week or two when 3 inches (8 cm) of rain fell. August through December was the driest period. In 1971, the third-driest year of the period, rainfall was below average until mid-June, when about 5 inches (12.70 cm) of rain was received from mid-

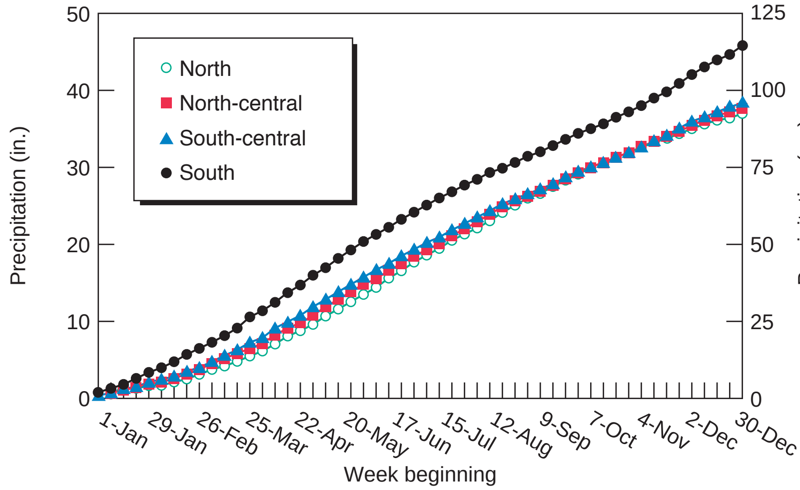

Figure 1.8. Normal accumulated rainfall from January through December for four regions of Illinois, 1971 to 2000. The north region is represented by crop reporting districts (CRDs) 1 and 2; the north-central by CRDs 3, 4, and 5; the south-central by CRDs 6 and 7; and the south by CRDs 8 and 9.

June through mid-July. The earlier pattern then returned, with about 4 inches (10 cm) of rain received through late November. In 1992, the first 6 months of the year were drier than normal. July was much wetter than normal. August through December received near-normal rainfall. The start of 1996 was also drier than normal, followed by above-normal rainfall in April and May. The rest of the year was drier than normal, with the exception of a wet week in July (7–14).

The corn and soybean yields for these years in Illinois' central crop reporting district demonstrate the importance of rainfall timing. To fully understand the impact, corn yields must be adjusted to remove the effect of genetic improvement on yields. Studies have shown that corn yields have increased about 1.1 bu/A/yr (69 kg/ha/yr) due to genetic improvement (A.F. Troyer, 2004, "Background of U.S. hybrid corn II: Breeding, climate and food." *Crop Science*, Vol. 44, pp. 370–380). Corn yield from one year can be adjusted to a different year by adding 1.1 bu/A/yr (69 kg/ha/yr) times the number of years separating the two years. For example, the corn yield in 1988 was 68 bu/A, giving a 1996 genetically adjusted yield of 77 bu/A (4.2 metric tons per hectare—tons/ha). Soybean yields do not increase as rapidly as corn yields, so a genetic adjustment for soybeans is not available.

Corn and soybean yields were the lowest in 1988, the year with a prolonged drought throughout the growing season. Corn yield (adjusted to approximate 1996 genetics) was 77 bu/A (4.8 tons/ha), and soybean yield was 27.5 bu/A (1.8 tons/ha). In the second-driest year, 1976, genetically adjusted corn yield was 147 bu/A (9.2 tons/ha), and soybean yield was 37.5 bu/A (2.5 tons/ha). This was the year with the wettest spring but little or no rain during 2- to 3-week stretches **(Figure 1.9).** Although 2 to 3 inches (5.08 to 7.62 cm) of rain fell during or shortly after pollination, it was not enough to offset the dry conditions during rapid vegetative growth followed by very little rain during grain fill. In 1971, when a dry spring with little rainfall until late June and early July was followed by rainfall of less than an inch each week during grain fill, the final average corn yield adjusted to 1996 genetics was only 133 bu/A (8.4 tons/ha), and the final average soybean yield was 38 bu/A (2.6 tons/ha). Rainfall in 1992 can be compared to the 1971 rainfall in that the spring and early-growth periods of corn were equally dry. However, from late June through late July, about 12 inches (30 cm) of rain was received. The average 1992 corn yield adjusted to 1996 genetics was 156 bu/A (9.8 tons/ha), and the average soybean yield was 46 bu/A (2.1 tons/ha). In 1992, the July rains were adequate to offset some of the effects of a dry early growing season and a dry grain-fill period. Even though 1992 was wetter than 1996, the average genetically adjusted 1996 corn yield was only 1 bu/A (63 kg/ha) less than in 1992, and soybean yields were 0.5 bu/A (34 kg/ha) less. The 1996 year began dry, followed by a wet planting season, a dry period of rapid vegetative growth, a wet period 1 to 2 weeks before pollination, and a relatively dry grain-fill period. The timely rains during 1992 and 1996 show the importance of adequate rainfall in the growing season.

Potential Evapotranspiration

Evapotranspiration is the removal of water from soil by a combination of evaporation from the soil surface and transpiration (loss of water vapor) from plant leaves. Surface evaporation is limited to the top 2 to 4 inches of soil, while

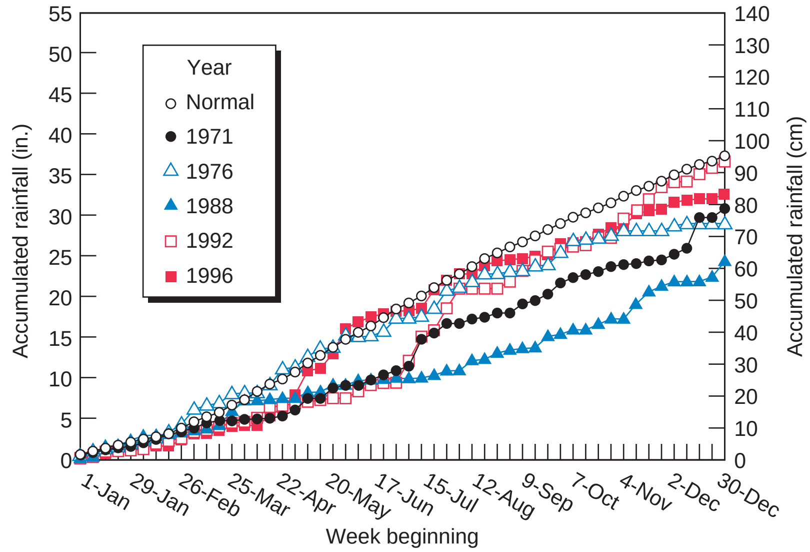

Figure 1.9. Rainfall distribution in the Illinois central crop reporting district (CRD 4) during the dry years of 1971, 1976, 1988, 1992, and 1996.

transpiration results in removal of water from the soil to a depth equal to the deepest roots.

Potential evapotranspiration is the amount of water that would evaporate from the soil surface and from plants when the soil is at field capacity. Field capacity defines the amount of water the soil holds after it has been saturated and then drained, until drainage virtually ceases. Soil that is drier than field capacity will experience actual evapotranspiration less than potential evapotranspiration. Actual evapotranspiration will also be less than potential evapotranspiration when plant canopies do not totally cover the soil.

Potential evapotranspiration is greatest in dry years with low humidity and predominantly clear skies and least in wet years with high humidity and cloudier-than-normal skies. Total potential evapotranspiration, from April though September, ranges from about 33 inches (84 cm) in dry years to about 27 inches (69 cm) in wet years. During wet years, actual evapotranspiration will approximately equal potential evapotranspiration. In dry years, actual evapotranspiration will be less than potential evapotranspiration. During the growing season, the normal total monthly evapotranspiration is least in September, approximately 3.8 inches (9.7 cm), and greatest in June and July, approximately 5.8 inches (14.7 cm). Potential evapotranspiration is highest in June and July because the sun is highest in the sky during those months, and more solar radiation is received during each day because of more daylight hours. Drought conditions occur when the potential evapotranspiration exceeds rainfall by more than the normal difference for several months in a row.

Soil Moisture

The amount of water held in the soil is determined by soil texture, soil drainage, precipitation, and evapotranspiration. During the summer months, evapotranspiration generally exceeds the rainwater absorbed by the soil, and the soil profile dries out. From October through April, evapotranspiration is usually less than precipitation, and the soil profile is recharged.

Wet soils in spring play an important role in determining how many days are suitable for field work. When soil moisture is normal or wetter than normal, even small rains will result in field work delays on all but the sandiest soils in Illinois. Rains greater than 0.10 inch (0.25 cm) often delay field work, especially in the spring and early summer, when soils are the wettest. On average, there are 7 days each month with rainfall greater than 0.10 inch (0.25 cm) during April and May, 6 days each in June and July, and 5 days each in August, September, and October.

During the spring planting season, the amount of water in the top 6 inches (15 cm) of soil controls field work activities. When the top 6 inches of soil is wet, planting is delayed, and nitrogen can be lost to either denitrification or leaching. Traffic on or tillage of fields when soil is near field capacity (80% of saturation) causes maximum compaction. During an average spring, soil moisture in April is great enough that rains of more than 0.3 inch (0.8 cm) will bring the soil water to field capacity. In the wettest years, rains greater than 0.3 inch result in significant periods of near-saturated soils in the upper 6 inches. The rainfall amounts shown in **Table 1.1** are the minimum amounts of rain needed to trigger denitrification and provide optimum compaction conditions. When the subsurface soil levels are dry, more rain than the amounts shown is needed to have this effect. Only in the driest years will soils seldom reach field capacity.

Excessive soil moisture in late spring and early summer may result in loss of nitrogen through denitrification and leaching and may lead to the development of seed, root, and crown diseases. Conversely, dry soil during planting may result in poor stand establishment and may cause plant stress when dryness occurs during the periods of flowering and seed set.

The typical arable soil in Illinois is a silt loam or silty clay loam that will, on average, hold approximately 7.5 inches (19 cm) of plant-available water in the top 40 inches (101 cm) of soil. Plant-available water is defined as the amount of water in the soil between field capacity and wilting point. The wilting point is defined as the amount of water still in the soil when plants are unable to recover at night from wilting during the day. Illinois soils hold about 6.5 inches (17 cm) of water in the upper 40 inches of soil at the wilting point. Water in the top 40 inches of soil at saturation is approximately 14 inches (36 cm). Individual soils vary significantly from the average. Coarse-textured soils, such as sands, hold less plant-available water and less water at the wilting point and field capacity than do fine-textured soils or soils with high clay content.

Whenever plant-available water in the top 40 inches (101 cm) of soil is less than 3.8 inches (10 cm) in June, July, or August, plants will show significant moisture stress during the day. Soil moisture is generally below this limit only during the driest months of July and August. Even in these months, soils should experience some periods above this stress threshold, especially following rains. In the wettest years, plant-available water exceeds plant needs, and periods of saturation may occur during the summer months.

Solar Radiation

Plants use the solar energy from the sun to fix carbon dioxide from the atmosphere, in combination with water from the soil, into carbohydrates that cause plants to grow, reproduce, and provide the grain and vegetation used as food by humans and animals. The solar energy available to plants is a function of sunshine intensity and duration. In southern Illinois, the intensity of sunshine is greater than in the northern regions. This greater intensity of sunshine in the south does not translate into significantly more total solar energy available in a single day compared to the north because the longer days during the summer in the north offset the lower intensity sunshine with more hours of sunshine.

Total daily solar energy received at the earth's surface has units of megajoules per square meter per day (MJ/m^2/day). The average solar energy received by a crop on relatively clear days around the summer solstice is approximately 31 MJ/m^2/day **(Figure 1.10).** At the spring equinox, clear-day total solar energy is approximately 23 MJ/m^2/day, and at the autumn equinox approximately 21 MJ/m^2/day.

A question often asked is how cloudiness and low solar radiation affect yields. New technology allows continuous measurement of the exchange of CO_2 between the atmosphere and the earth's surface. When plants are fixing CO_2 through the process of photosynthesis, the flux of CO_2 is toward the surface. By summing the quantity of CO_2 that is being fixed by the plant over the daylight hours and simultaneously measuring the solar energy available to the crop, the efficiency of solar energy use by the crop can be estimated. The carbon fixation rates given below were obtained from data gathered over 4 years of corn and 4 years of soybean CO_2 flux monitoring in central Illinois.

A heavily overcast day in this discussion means no shadows would be seen at any time. An average day is one when light shadows would be seen, such as on a very hazy day when the sky has a blue-gray appearance or when the skies are partly cloudy and there are periods of both full sun and full shade (when no shadows are visible). A clear sunny day is characterized by deep blue skies with no clouds visible.

Table 1.1. Water content in the top 6-inch soil layer of a typical Illinois silt loam or silty clay loam during April, May, and June, and the minimum rain needed to bring soil moisture to field capacity.

	Dry		Average		Wet	
Month	Water content (in.)	Rain needed (in.)	Water content (in.)	Rain needed (in.)	Water content (in.)	Rain needed (in.)
April	1.5	0.7	1.9	0.3	2.4	0.0
May	1.2	1.1	1.6	0.7	2.2	0.1
June	0.9	1.4	1.5	0.8	2.0	0.3

Dry conditions apply when the months of April, May, and June have less than 2 in. of rainfall each month; average conditions, between 2 and 4 in. each month; wet conditions, more than 4 in. per month.

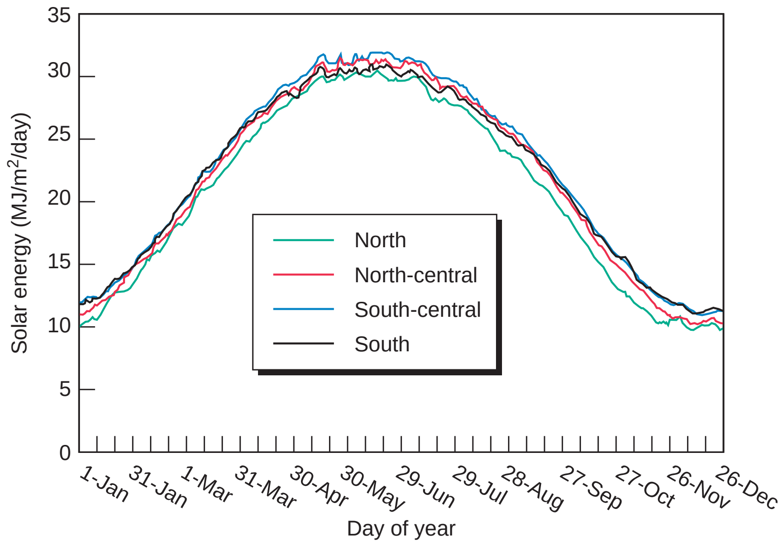

Figure 1.10. Daily solar energy received on clear days throughout the year for four regions in Illinois. The north region is represented by crop reporting districts (CRDs) 1 and 2; the north-central by CRDs 3, 4, and 5; the south-central by CRDs 6 and 7; and the south by CRDs 8 and 9.

When the crop has a full canopy, leaf area index greater than 2.7 the rate of carbon fixation by corn results in an accumulation of approximately 0.14 bushels of grain per acre per megajoule—bu/A/MJ (8.8 kg/ha/MJ). An average heavily overcast day between May and August receives about 8.2 MJ of solar energy. Thus, if all the carbon fixed by photosynthesis were to go into the grain, the yield gain on a heavily overcast day would be 1.2 bu/A/day (75.5 kg/ha/day). The average daily solar energy received during the same period is about 21.7 MJ, which translates into about 3.1 bu/A (194.9 kg/ha/day). On an average clear sunny day, the daily solar energy available to the crop is approximately 29.7 MJ, producing about 4.3 bu/A (270.4 kg/ha/day) of grain during the day. So on a heavily overcast day, approximately 1 bu/A would be lost compared to an average day, and an additional 1.2 bu/A would be gained on a clear day compared to an average day.

The average rate of carbon fixation by soybean results in an accumulation of about 0.07 bu/A/MJ (4.7 kg/ha). Thus, on a heavily overcast day, about 0.6 bu/A (40.4 kg/ha/day) would accumulate, while on an average day, 1.5 bu/A (101.1 kg/ha/day) would accumulate, and on a clear sunny day, 2.0 bu/A (134.7 kg/ha/day) would accumulate. Compared to an average summer day, the yield loss on a heavily overcast day would be approximately 0.9 bu/A (60.6 kg/ha/day), and the yield gain on a clear day would be 0.5 bu/A (33.7 kg/ha/day).

These estimates are just rules of thumb and cannot precisely specify yield loss due to cloudiness. Further, the rate of carbon fixation depends on the supply of water and minerals and the presence or absence of disease and insects. If there is an adequate supply of water and minerals without the presence of disease or insects, the rate of carbon fixation may be greater than the rates given here. Conversely, if the supply of water or minerals is not adequate, or there is disease or insect pressure on the crop, the rate of carbon fixation will be lower than the rate given here, and yields will be lower. With higher carbon fixation rates under optimum growing conditions, the effect of cloudiness will be greater. Under suboptimal growing conditions, the effect of cloudiness will be less.

Weather and Climate Forecasts and Accuracies

Forecasting the weather variables at different time scales is important to both short-term and long-term planning in agricultural production. Short-term predictions, from hours out to 2 weeks, called weather forecasts, are important for day-to-day management decisions. Long-term predictions, for seasons out to a year or two in advance, called climate forecasts, are important for successful crop selection and crop rotation planning.

Day-by-day weather forecasts up to 2 weeks out are widely used in agriculture and are readily available from the National Weather Service and private forecasters; the forecast accuracy does decrease, however, the farther the forecast is from present day. Climate predictions beyond 2 weeks cannot specify the exact weather conditions on any specific day. Rather, they identify the general conditions that will occur, whether the period will be generally warmer or cooler or wetter or drier than normal. A number of techniques have been developed for climate forecasts that can be put into two broad categories: statistical and physical.

Statistical techniques rely on historical climate data to establish relationships between different time periods. For example, an analysis of Illinois temperature data for 1895 to 2001 identified the 35 warmest winters. Following those winters, the summer temperatures were above normal in 18 summers, near normal in 10, and below normal in 7. A very simple statistical climate prediction can thus be developed for summer temperatures based on winter temperatures: if winter temperatures are above normal, the odds for a warm summer increase.

Statistical techniques have several limitations, however. They do not incorporate any knowledge of the causes of variations. In many cases, there is no consistent relationship on which to base a prediction. For example, following the 35 warmest autumns, 11 winters were drier than normal, 12 were wetter than normal, and 12 were near normal. Thus, warm autumn temperatures provide no predictive information about precipitation the following winter.

By contrast, physical prediction techniques rely on known causes of climate variations. A prominent example is the El Niño, a periodic disruption of the ocean and wind currents in the equatorial Pacific Ocean. Weather is affected not only in this region but in other parts of the world, including the United States. An El Niño event occurs about every 4 to 7 years and lasts for about a year.

Since 1995 the National Weather Service has produced climate predictions of temperature and precipitation out to a year in advance. They use both statistical and physically based techniques to develop their predictions. Their techniques include running global climate models, examining similar conditions in the historical record, and considering recent trends in temperature and precipitation.

Influence of El Niño and La Niña on Illinois Climate

The equatorial Pacific Ocean can be considered to be in one of three phases: normal, El Niño (warm), or La Niña (cold). The surface winds at the equator blow from east to west in the normal phase, which causes warm waters to collect at the western end of the basin. As the warm water is pushed westward, it is replaced by colder water upwelling from below, along the eastern edge of the basin. Heavier precipitation in the basin follows the warmer waters and is therefore found in the western half of the basin. During an El Niño event, easterly winds die down and sometime reverse. This allows warm water to return to the eastern half of the basin and effectively caps the upwelling of cold water. Heavy precipitation also shifts eastward, bringing wetter-than-normal conditions to the eastern basin and drier-than-normal conditions to the western basin.

Easterly winds found in the normal phase intensify during a La Niña. This causes even more warm water to collect in the western basin and the upwelling in the eastern basin to be stronger. As a result, waters in the eastern basin are much colder than average, and precipitation is pushed further west.

The three phases have atmospheric impacts that extend beyond the Pacific Ocean basin. El Niño and La Niña events have strong impacts on North American weather because North America is “downwind” of the Pacific Ocean. Because most North American weather patterns move from west to east, the weather systems tend to originate or pass over and are in some way influenced by the Pacific Ocean. Normal life cycles of El Niño and La Niña begin in late spring or summer, develop fully by the following fall or winter, and then weaken by the next spring. As a result, most impacts of these events occur in the colder months in Illinois.

Typical Illinois weather impacts of El Niño include these: during strong events, warmer conditions prevail from December to March with less snow, followed by wet conditions during March through May; in weaker events, the impact on temperature is minimal and drier conditions may prevail from January to March.

Typical Illinois weather impacts of La Niña include these: generally drier conditions during July and August, when La Niña events begin, and in November to January and April to June, as La Niña progresses. In weaker events, warmer conditions may occur during October to December and February to May.

General weather characteristics of both El Niño and La Niña can be identified, but each event has a unique personality based on timing of the event, intensity of sea-surface temperature changes, and area of the ocean over which these changes occur. For example, a strong storm track developed over the Midwest during the winter of the 2007–08 La Niña event. This resulted in heavy precipitation that continued into the spring and early summer—very atypical of La Niña.

The National Weather Service Climate Prediction Center monitors conditions in the Pacific Ocean and issues forecasts on any upcoming El Niño and La Niña events. This information also is used in their seasonal forecasts of temperature and precipitation. Scientific research over the past

20 years has led to breakthroughs in understanding this phenomenon. As a result, it is now possible to anticipate by several months the beginning and evolution of these events. Research also has increased knowledge about how these events affect the climate of Illinois.

Considerable research is identifying other causes of climate variations. It is likely that in the future, physically based climate predictions will gradually become more skillful for anticipating conditions a few months to a few years ahead. A primary focus of this research is the relationship of atmospheric circulation patterns to the condition of the land and ocean surface. The distribution of sea-surface temperatures affects atmospheric circulation patterns, the most prominent example being El Niño. However, anomalies of sea-surface temperatures in other parts of the oceans also have effects on the atmosphere, but they have not yet led to the dramatic improvements in predictive skill as obtained with El Niño events. Some future improvements likely will result, however. The condition of the land surface, particularly the extent of snow cover and the amount of soil moisture, also affects climate. For example, there is evidence that deficient soil moisture in the southern Plains and Midwest during early summer often leads to dry, hot conditions later in summer because of decreased evaporation.

Generally, weather and climate forecasts focus on predicting temperature and precipitation, and the amount of cloudiness and sunshine are inferred from these forecasts.

2

Corn

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Corn was an important crop for people who lived in the area that became Illinois before the Europeans first set foot here; it was the staple food crop of the people who lived in the Cahokia area some 1,000 years ago. It was a crop of choice when Europeans settled and started to farm in Illinois, and acreage in the state first reached 10 million acres in 1895. Acreage over the past 100 years has ranged from about 7 to 13 million acres and is now about 50% of the row-cropped acres in the state.

The major reason that so much corn is grown in Illinois is that the soils and weather are very well suited to the crop, and as a result yields are high. **Figure 2.1** shows yield trends for corn and other major Illinois field crops over the period 1990 through 2008. Corn yields have increased by 2.6 bushels per year over that period, or a total of more than 45 bushels, or some 30%. There are few places in the world, and none without extensive irrigation, that can point to such high productivity for any crop. In 2007, the average U.S. yield was nearly twice the world average yield, and the average Illinois yield was about 15% higher than the U.S. average yield. Illinois produces about 17% to 18% of the U.S. corn crop, and more than 7% of the corn produced in the world.

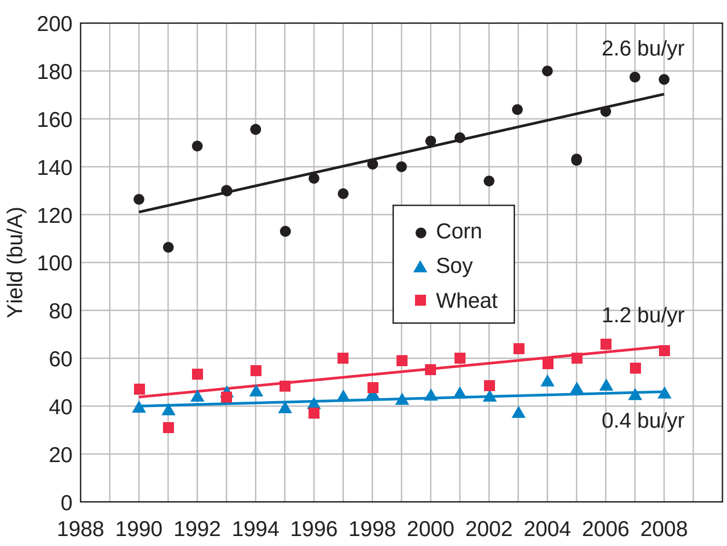

Figure 2.1. Yield trends of corn, soybean, and wheat in Illinois from 1990 through 2008. The "trend line" yields for each crop are shown, with average per-year yield change.

Though corn is by far the highest-yielding grain crop in Illinois, differences in soils and weather mean that yields are not consistently high in all locations and all years. Some find it useful to develop yield goals for individual fields, though the fact that yields are often higher than expected when the weather and management are ideal means that most producers have had yields higher than their realistic expectations (goals) at least once in recent years. That means that management should be done in ways that don't greatly restrict yield potential, even in above-average yields. As an average, though, it can be a useful exercise to look up yield potential for individual soil types, as listed in University of Illinois publications *Soils of Illinois* (B778), *Average Crop, Pasture and Forestry Productivity Ratings for Illinois Soils* (B810), and *Optimum Crop Productivity Ratings for Illinois Soils* (B811).

Corn Plant Development

Understanding the development of the corn plant, including when during its life cycle it is most vulnerable to stress, is a great help in managing this crop. **Figure 2.2** outlines plant development. Another very useful reference is *How a Corn Plant Develops* (Special Publication No. 48), from Iowa State University. The basics of this system are as follows:

- Ve refers to "vegetative" emergence.
- Vn, where n is the number of leaves with collar visible **(Figure 2.3).** Plants typically develop about 20 leaves, but the lowermost leaves are damaged by expansion of the stalk and often disintegrate. So by the time of pollination there may be only 14 to 16 intact leaves.

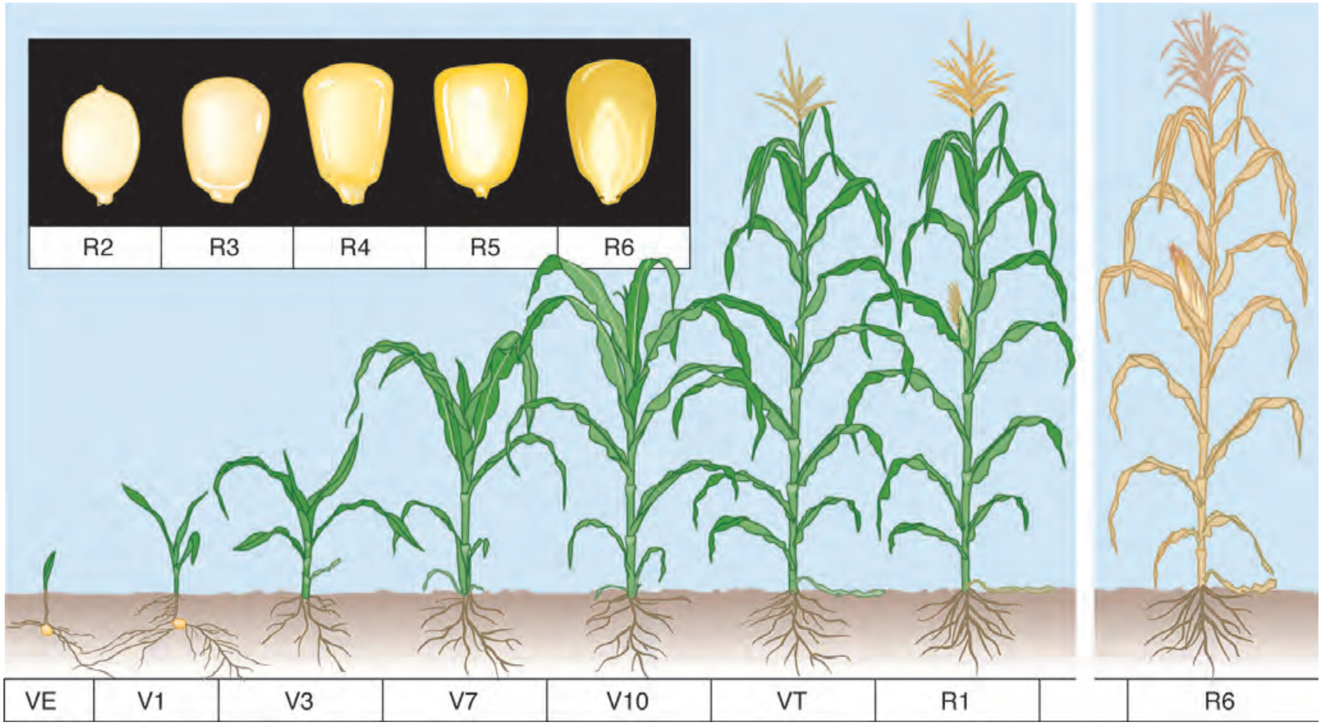

Figure 2.2. Corn plant development.

● Rn, or "reproductive" stage n, where n goes from 1 (silking, which coincides with pollen shed) to R6, which is physiological maturity.

This staging system is almost universally used, though other methods in use count leaves when they have most of their area exposed, which occurs several days before the collar appears.

Many years ago scientists observed that corn plant development follows very closely the accumulation of average daily temperatures during the plant's life. This accumulation is calculated as "growing degree days" (GDD). The GDD concept has been very useful in knowing how the crop will respond to temperatures and in helping fit hybrids into situations where expected GDD accumulations are known from weather records.

The GDD accumulation for a day is the average of the low and high temperature, minus 50 °F. The subtraction of 50 degrees is done because corn plants don't grow much at or below 50 °F. If the low temperature for the day is below 50 °F, then use 50 instead of the actual low temperature; otherwise, the GDD could be negative. Another modification made in the case of corn is a high temperature cutoff, done because growth rates don't continue to increase as temperature increases above a certain point. This cutoff point for corn is 86 °F; if the high temperature for the day is above 86, then use 86 instead of the actual high temperature.

If the low temperature for a day is 50 or higher and the high is 86 or lower, then average the high and low temperatures and subtract 50. So a day with low and high temperatures of 60 and 80 would produce (60 + 80) ÷ 2 – 50 = 70 – 50 = 20 GDD. For a day with temperatures of 44 and 66, substitute 50 for the actual low: (50 + 66) ÷ 2 – 50 = 58 – 50 = 8 GDD. And for a warm day with temperatures of 74 and 93, substitute 86 for the actual high: (74 + 86) ÷ 2 – 50 = 80 – 50 = 30 GDD. Note that the maximum GDD possible for a day is 86 – 50 = 36, but this would require a low temperature of 86 or higher, which is very unusual in Illinois. If the daytime high temperature is 50 or less, the GDD for that day is 0.

Figure 2.3. A V4 corn plant. Notice that the collar of the 4th leaf from the base is visible, but the 5th leaf collar has not yet emerged from the whorl of leaves.

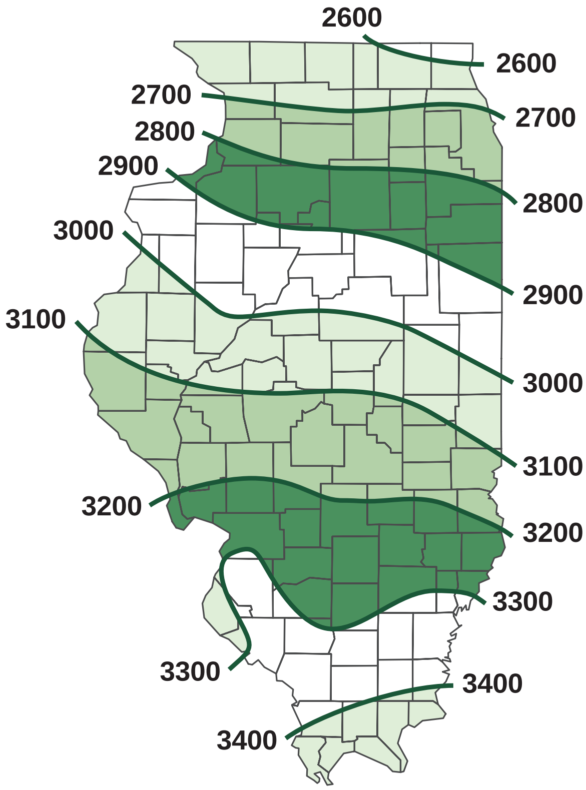

Figure 2.4. Average number of growing degree-days in Illinois, May 1 to September 30, based on 1971–2000 data. Map provided by the Illinois State Climatologist Office, Illinois State Water Survey.

Corn hybrids grown in Illinois have planting-to-harvest GDD requirements ranging from 2,200 to 2,400 for early hybrids grown in the northern part of the state to 2,800 to 2,900 for late hybrids grown in the southernmost part of the state. A full-season hybrid for a particular area generally matures in several hundred fewer GDD than the number given in **Figure 2.4.** Thus, a full-season hybrid for northern Illinois would be one that matures in about 2,600 GDD, while for southern Illinois a hybrid that matures in 2,900 GDD or more would be considered full-season. Medium-maturity hybrids require 100 to 200 fewer GDD than full-season hybrids. This GDD "cushion" reduces the risk of frost damage and also allows some flexibility in planting time; it is usually not necessary to replace a medium-maturity hybrid with one maturing in fewer GDD unless planting is delayed into June.

Research has shown that the number of GDD required for the corn crop to reach particular stages of development tends to be fairly consistent. **Table 2.1** shows the predicted GDD required to reach each vegetative (V) and reproductive (R) stage for a hybrid that requires a total of 2,700 GDD from planting to physiological maturity. These numbers are approximate, especially for R stages, which are not particularly exact. But they should work reasonably well to help predict when, under average temperatures, a crop will reach certain stages.

Table 2.1. Approximate GDD needed to reach different growth stages of a corn crop (planted at the normal time, using a hybrid that requires 2,700 GDD to reach maturity).

Stage	GDD from planting	Stage	GDD from planting
VE	115	V13	995
V1	155	V14	1,045
V2	235	V15	1,095
V3	315	V16	1,140
V4	395	V17	1,180
V5	475	V18	1,220
V6	555	VT (tassel)	1,350
V7	635	R1 (silk)	1,400
V8	715	R2 (blister)	1,660
V9	795	R3 (milk)	1,925
V10	845	R4 (dough)	2,190
V11	895	R5 (dent)	2,450
V12	945	R6 (mature)	2,700

In some recent work in Indiana and Ohio, researchers found that the GDD requirement for corn hybrids decreased when planting was later than May 1. For each day that planting was delayed after May 1, the reduction in GDD requirement was about 6.5 GDD; thus, a 2,700 GDD corn hybrid planted on May 20 would require only 2,700 – (20 x 6.5) = 2,570 GDD. While the actual decrease in GDD varied somewhat among years, the fact that there is an expected decrease indicates that changing to a shorter-season hybrid when planting is delayed should rarely be done. This decrease in GDD requirement, however, usually comes at the cost of decreased yield; planting on time is still an important goal.

Hybrid Selection

When tested under uniform conditions, the range in yields among available hybrids is often 50 or more bushels per acre. Thus it pays to spend some time choosing the best hybrids. Maturity, yield for that maturity, standability, and disease resistance are the most important factors to consider when making this choice.

Yield

Corn yields have risen steadily and dramatically over the past two decades (**Figure 2.1**), due partly to improved management, but mostly to genetic improvements in hybrids. While several genetically modified (GM) "traits" now exist in commercial hybrids, these traits by themselves have not likely contributed much of the improvement in yield potential of hybrids. Traits available to date help protect against insects or provide resistance to herbicides; both of these trait types help improve protection against yield loss from pests, but they may not directly increase genetic yield potential. Still, most of today's better hybrids are sold in versions that include GM traits, and many hybrids contain multiple GM traits, combinations of which are called "stacks."

Concern exists with what many consider to be a lack of genetic diversity among commercially available hybrids. Although it is true that a limited number of genetic pools, or populations, were used to produce today's hybrids, these pools contain a large amount of genetic diversity, and there is no evidence that this diversity is "running out." In fact, a number of studies have shown that breeding progress for most traits is not slowed even after a large number of cycles of selection. Many of today's hybrids are substantially better than those only a few years old, and there is no evidence that the rate of improvement is decreasing.

Despite considerable genetic diversity, it is still possible to buy the same hybrid or very similar hybrids from several different companies. This happens when different companies buy the same inbreds from a foundation seed company that breeds or markets inbreds, or when hybrid seed is purchased on the wholesale market, then resold under a company label. In either case, hybrids are being sold on a nonexclusive basis, and more than one company can end up selling the same hybrid.

Many producers would like to avoid planting all or most of their acres to the same or very similar hybrids. One way to do this is to buy from only one company, though this may not be the best strategy because it discourages looking at the whole range of available hybrids. Another way of ensuring genetic diversity is to use hybrids with several different maturities. Finally, many dealers have at least some idea of what hybrids are very similar or identical and can provide such information if asked. Even when the genetics are similar, the way by which hybrid seed is produced—the care in detasseling, harvesting, drying, grading, testing, and handling—can and does have a substantial effect on its performance.

Maturity

Maturity is one of the important characteristics used in choosing a hybrid. Hybrids that use most of the growing season to mature generally should produce higher yields than those that mature much earlier. The latest-maturing hybrid should reach maturity at least 2 weeks before the average date of the first killing freeze (32 °F), which occurs about October 8 in northern Illinois, October 15 in central Illinois, and October 25 in southern Illinois. Physiological maturity is reached when kernel moisture is 30% to 35%. It is easily identified by the appearance of a black layer on the base of the kernel where it attaches to the cob. The approach to maturity also can be monitored by checking the "milk line," which moves from the crown to the base of the kernel as starch is deposited. The kernel is mature soon after the milk line reaches the base of the kernel.

Full-season hybrids are often considered to have higher yield potential due to the fact that they use more of the growing season. There is evidence, though, that this relationship may not consistently hold true with modern hybrids. **Figure 2.5** shows the data from the regional hybrid trial in northern Illinois in 2007, where there was almost no relationship between harvest moisture (as a measure of maturity) and yield. This pattern has been very common in recent years; it is rare to find trials in which later hybrids yield more. One reason is that late-season weather is not always favorable for filling the grain of later-maturing hybrids. It may also be that corn breeding efforts have concentrated on early and mid-maturity hybrids. Earlier hybrids can be harvested earlier, and they have drier grain at harvest and so require less drying cost. As a result of the good performance of earlier hybrids, the range in maturity between "early" and "full-season" hybrids is smaller than it was a few decades ago.

Most seed companies describe the maturity of a particular hybrid in terms of "days." This designation does not predict how many days the hybrid will actually take to produce a crop. Rather it refers to a "relative maturity" (RM)

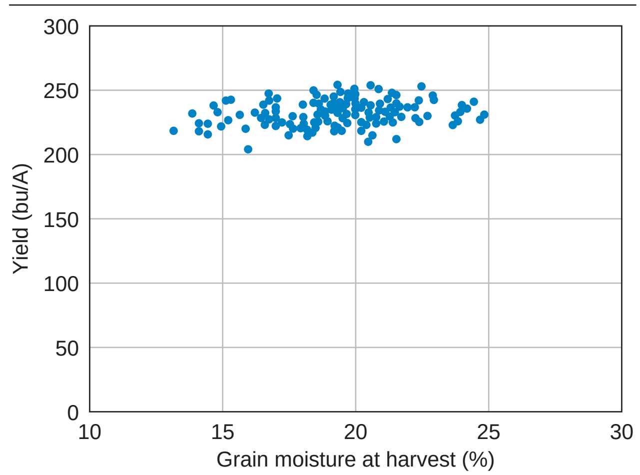

Figure 2.5. Relationship of grain moisture at harvest and grain yield among hybrids in the northern Illinois regional hybrid trial, 2007. Data are averaged over three locations, and each point represents a different hybrid. Relative maturity (RM) ratings ranged from 100 days (very early) to 115 days (late), and grain moisture was well correlated with RM. Source: University of Illinois Crop Sciences Variety Testing Program.

rating based on comparison with hybrids of known maturity. This rating is useful as a comparative measurement—comparing relative maturity ratings tells us whether one hybrid will mature earlier or later than another hybrid. RM ratings tend to change slightly as hybrids are moved north or south, reflecting comparative differences with other hybrids adapted to different regions. The number of growing degree days required to reach maturity is also available from some companies. It is more consistent from place to place than is RM, but RM is more commonly used. As a guideline, 100-day RM hybrids require about 2,400 GDD from planting to maturity, and each additional RM day later adds about 25 GDD to the total GDD requirement. So a 110-day RM hybrid may require about 2,650 GDD and a 115-day hybrid about 2,800 GDD.

After yield and maturity, resistance to lodging is usually the next most important factor in choosing a hybrid. Because large ears tend to draw nutrients from the stalk, some of the highest-yielding hybrids also have a tendency to lodge. Such hybrids may be profitable due to their high yields, but they should be watched closely as they reach maturity. If lodging begins or if stalks become soft and weak (as determined by pinching or pushing on stalks), then harvesting these fields should begin early. Stalk disease organisms are always present in the soil, but if stalks are able to retain some sugars up to maturity they usually can fend off invasion by these organisms. It also helps to have good growing conditions early in the season so that stalks get larger and "woody" enough to stand well at the end of the season. But maintaining stalk quality means that the stalk has to compete with the ear for sugars, and if there is not enough sugar to meet the demand, especially if stress reduces photosynthesis (sugar production) during grain fill, then the stalk often loses out.

Resistance to diseases and resistance to insects are important characteristics in a corn hybrid. Leaf diseases are easiest to spot, but stalks and ears also should be checked for disease. Resistance to insects such as the European corn borer and corn rootworm are incorporated into most modern hybrids using Bt genes. Another useful trait is the ability of the hybrid to emerge under cool soil conditions, which is especially important in reduced-till or no-till planting.

More than 10 years ago, seed companies began to release hybrids containing "genetically engineered" or "genetically modified" (GM) traits. These were initially single-gene traits, genetically transferred into the corn plant from another organism; for example, the Bt gene came from a bacterium. This technology holds great potential since it means that genes found in almost any living organism or even genes produced in the laboratory can be put into a crop or animal. Most of the genes released in this way so far have been for resistance to insects or herbicides, and they have been incorporated into commercial hybrids using backcrossing. Backcrossing takes time, and except for the inserted gene, the resulting hybrid is usually little or no better than the parent into which the gene was crossed. Complex traits such as yield are usually controlled by many genes that interact with one another. Such groups of interacting genes are very difficult to isolate and transfer, so progress for traits such as yield will probably continue to depend largely on traditional methods of breeding. Genetic techniques developed in recent years that can help show what genes are present in high- versus low-yielding lines are, however, proving useful as a way to increase the rate of genetic improvement.

With the many hybrids being sold, choosing the best one can be challenging. The fact that individual hybrids often are sold for only two or three years adds to this challenge; by the time we know what to expect from having grown a hybrid, it is often no longer sold. An important source of information on hybrid performance is the annual report *Performance of Commercial Corn Hybrids in Illinois*, published soon after harvest on the Web at vt.cropsci.illinois.edu. The report summarizes hybrid tests run each year at 12 Illinois locations and includes yield information from the previous 2 years. The report gives data on yields, grain moisture, and standability of hybrids. Other sources of information include your own tests and tests conducted by seed companies, neighboring producers, and extension staff. Producers should see the results of as many tests as possible before choosing a hybrid.

Planting Date

Long-term studies show that the best time to plant corn in much of Illinois is in mid- to late April, with little or no yield loss when planting is within a week on either side of this period. Weather and soil conditions permitting, planting should begin sometime before the optimal date to allow for delays related to weather. Corn that is planted 10 days or 2 weeks before may not yield quite as much as that planted on or near the optimal period, but it will often yield more than that planted 2 weeks or more after.

Figure 2.6 shows yield changes over planting dates from a recent study in different regions of Illinois. The planting time that produced the highest yield was about April 6 in southern Illinois, and April 16 and 17 in central and northern Illinois. Yields declined by only about 1/2 bushel per day as planting was delayed to early May. Yield loss then accelerated with later planting, with average losses of about 1 bushel (0.5%) per day for the first third of May, 1.5 bushels for the second third, and 2 bushels for the last

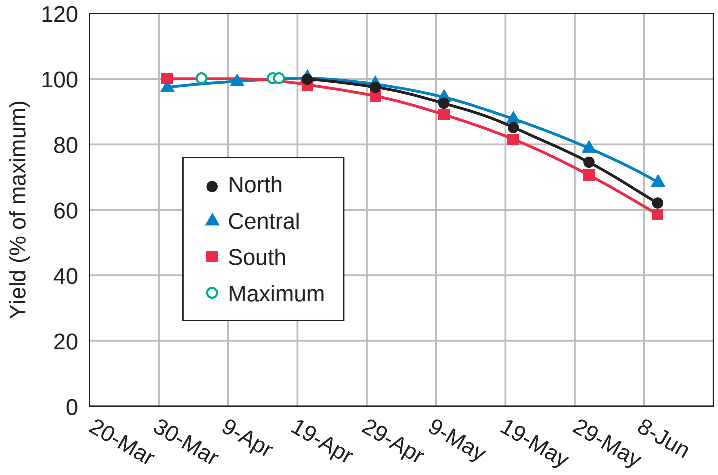

Figure 2.6. Changes in corn yield by planting date in three Illinois regions, two locations per region. Data are averaged over three years (2005 to 2007). The green circles indicate the dates when maximum yield occurred.

third. Yield losses continue to accelerate as planting is delayed into June, and expected yields reach 50% of early-planted yields by about June 20 to 25.

Early planting results in drier corn in the fall, allows for more control over the planting date, and allows for a greater choice of maturity in hybrids. In addition, if the first crop is damaged, the decision to replant often can be made early enough to allow use of the first-choice hybrid. Disadvantages of early planting include cold, wet soil that may produce a poor stand, more difficult weed and insect control, and increased likelihood of frost damage after emergence. Improved seed vigor, seed treatments, and GM traits that greatly improve insect and weed management options have substantially reduced the first two hazards, and the fact that the growing point of the corn plant remains below the soil surface for 2 to 3 weeks after emergence minimizes the danger of frost damage. In general, the advantages of early planting outweigh the disadvantages.

The lowest temperature at which corn germinates is about 50 °F, and some people like to measure soil temperature at the planting depth before starting to plant. Soil temperature, however, is not the major consideration in deciding when to start planting. A more important consideration is the condition of the soil: It generally is a mistake to till and plant early when soils are still wet, and the advantages of early planting may well be lost to soil compaction and other problems associated with "mudding in" corn, whether using conventional tillage or no-till techniques. If the weather conditions have been warm and dry enough to result in workable soils by early April, then planting can begin in early April in southern and central Illinois and in or before mid-April in northern Illinois, with little danger of loss. The weather may change after planting, however, and a return to average temperatures means slow growth for corn planted this early. Rainfall after planting can also lead to emergence problems. It may be desirable to increase seeding rates by a few thousand seeds per acre for April planting, mainly to allow for greater losses and to take advantage of the more favorable growing conditions that the crop is likely to encounter.

When planting begins in April, it is generally best to plant fuller-season hybrids first, but planting midseason and then early hybrids in sequence tends to "stack" the times of pollination and harvest of the different maturities. It is probably better to alternate between early and midseason hybrids after the fuller-season hybrids are planted. This practice helps to spread both pollination risks and the time of harvest.

Planting Depth

Ideal planting depth varies with soil and weather conditions. Emergence is more rapid from relatively shallow-planted corn, so early planting should not normally be as deep as later planting. For most conditions, corn should be planted 1-1/2 to 1-3/4 inches deep. Early-planted corn should be in the shallower end of this range, keeping in mind that variation in depth means that some seeds will end up shallower than average and may not establish plants as easily. Later in the season, when soil temperatures are higher and evaporation is greater, planting as much as 2-1/2 inches deep to reach moist soil may be advantageous, especially if the forecast is for continued dry weather.

Planting depth studies show not only that fewer plants emerge when seeds are planted deep but also that those emerging may take longer to reach the pollination stage and may have higher moisture in the fall. Deeper planting also brings more danger of reduced stand due to crusting or wet soils and an increased chance of uneven emergence, which can cause yield loss.

Plant Population

The goal at planting time is to establish the highest population per acre that can be supported with normal rainfall without excessive lodging, barren plants, or pollination problems. Plant populations used by corn producers in Illinois have been rising steadily, with most fields now having

28,000 to 32,000 plants at harvest. The data in **Figure 2.7** illustrate why populations are increasing. The results from northern Illinois are mostly from high-yielding fields under good weather conditions, while those from southern Illinois are from less-productive soils, with weather conditions ranging from stressed (dry weather) to very good. Yields respond to populations as high as 35,000 to 40,000 under good conditions in northern Illinois, while under less-ideal conditions in southern Illinois, yields leveled off between 25,000 and 30,000 plants per acre. The fact that yields leveled off but did not drop off as population increased above that needed for maximum yield is an important feature of how modern hybrids respond to population. Today, the loss from having populations too high for the conditions is typically only the cost of the extra seed that was not needed—there is no large increase in barrenness and drop in yield, as was often the case with older hybrids. This finding shifts the best risk management approach from making sure population is not too high to making sure population is high enough to take advantage of conditions when they are good.

Our research shows little change in plant population response when planting time changes from April to mid-May **(Figure 2.7).** In all of these studies, plant population is the population established by thinning to exact stands, so it is very close to the population at harvest time. Most people plant 5% to 10% more seeds than the target population at harvest. Under good conditions, it is not uncommon for more than 95% of seeds to establish plants.

While **Figure 2.7** shows that plant population producing the highest yield did not change much with the planting date, other factors are important in setting plant population:

- **Hybrid**. Though hybrids differ in their ability to tolerate the stress of high populations, such differences can be difficult to predict, and they have been decreasing over time. In recent years, most hybrid types with problems of barrenness or standability at high populations have been replaced by hybrids selected under higher populations. Most modern hybrids can tolerate populations of 25,000 to 28,000 per acre even when weather conditions are stressful. Under good soil conditions, most need populations above 30,000 per acre to produce the best yields. One characteristic commonly defined by seed companies is ear "flex," which refers to the ability of the hybrid to change its size in response to population or conditions. Thus "flex-ear" hybrids might be planted at lower populations on less-productive soils and increase their ear size if conditions are better than normal. The opposite is "fixed-ear" hybrids, which tend to maintain ear size better as populations increase but to increase ear size less if populations are low for any reason. In practice, most producers have had high yields when plant populations have been relatively high, and most modern hybrids are of the fixed-ear type. On productive soils, populations should be kept high, and how a hybrid might flex its ear size under low population is of little interest.

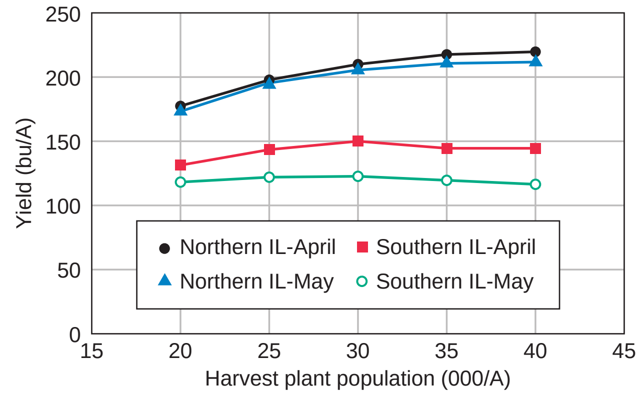

Figure 2.7. Plant population responses for corn planted early (April) and moderately delayed (mid-May) in northern and southern Illinois. Data are averaged over three years.

- **Planting date.** Early planting enables the plant to produce more of its vegetative growth before and during the long days of summer and to finish pollinating before the hot, dry weather that is normal for late July and early August. Early planting usually produces larger root systems as well. So to the extent that early planting produces conditions for higher yields, early-planted corn might respond slightly more to increases in population, even though results averaged over years (**Figure 2.7**) do not show this clearly.
- **Row spacing.** While many people believe that corn grown in narrower rows should be grown at higher plant population, our research results do not support this; for a given hybrid and field, the same population should be established regardless of row spacing.
- **Yield level: variable-rate planting?** Many newer planters can vary seed-drop rates across the field, and to many this seems a very logical approach. A number of studies have shown that, at least across trials, high yields usually require higher plant populations. **Figure 2.8** has some recent data from Illinois trials. Notice that there are some points well off the line, but according to the line on the graph, each 5-bushel increase in yield required about 1,000 more plants per acre. Compared to using the same population at all sites, having the optimum population at each site returned about $15 more per acre. These trials were conducted at sites ranging from northern to southern Illinois, and they included some stress environments in southern Illinois, where the optimum population was 20,000 plants per acre, the lowest population used in the studies. While these data suggest that higher-yielding parts of fields do need more plants, it

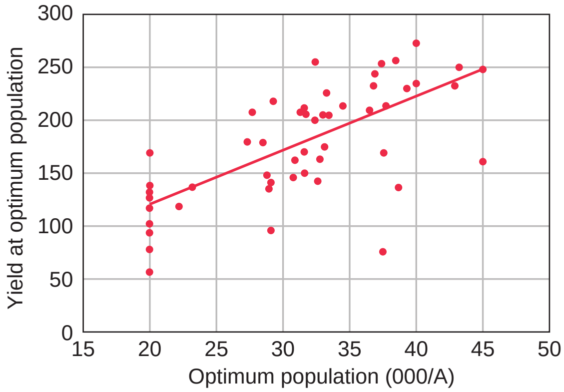

Figure 2.8. Relationship between optimum plant population and corn yield at that population over 53 recent trials in Illinois.

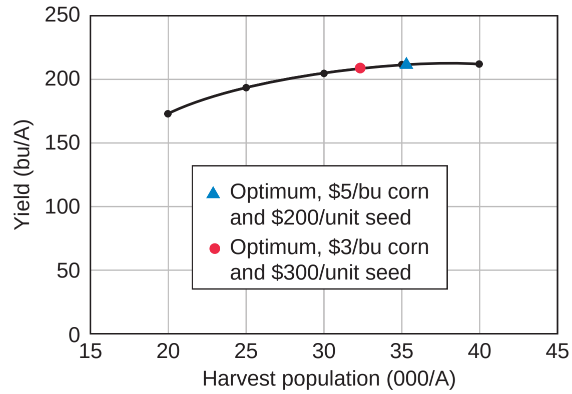

Figure 2.9. A plant population response averaged over nine Illinois trials. Optimum plant populations for two seed cost–corn price situations are shown.

is not easy to know in advance what the higher-yielding parts of a field will be. Previous yield maps might help, but if the weather is especially good during the season, dropping the population in the "low-yielding" areas might be counterproductive. In general, having population too low for conditions is more costly than having population too high. So vary seeding rates according to productivity, but make sure that populations are high enough to take advantage of above-average conditions in all parts of the field. Except in areas with very light, drought-prone soils, dropping less than 28,000 is probably not warranted. In fields without such soils, varying seed drop rates by 2,000 to 3,000 around an average of 32,000 to 35,000 might result in some economic benefit in some years. It might be instructive to vary planting rate by strip, using the normal rate and one higher and one lower rate on either side, then use a yield monitor to see how much benefit is provided. Remember that one year's results, while useful, are unlikely to repeat a second year.

- **Seed and corn prices?** Corn seed prices and corn prices have risen in recent years, and because plant populations should be close to the point where the last plants added yield just enough to pay for the seed to establish them, it may make sense to take seed costs and corn prices into account when setting seed drop rates. **Figure 2.9** uses some population response data to illustrate how this works. When the ratio of the seed cost to the corn price increases—that is, seed cost goes up more than corn price—then the optimal population decreases. In the example shown in the figure, increasing this ratio by 2.5 times decreased the optimum plant population by about 2,800 plants per acre and decreased the yield by 2.5 bushels. Most changes would not be this large, and the fact remains that decreasing the population can, if the year turns out to be very good, cause some lost yield and income opportunity.

It can be helpful to set seed drop rates according to conditions at the time of planting, in addition to such factors as soil productivity and hybrid characteristics. See the corn seed drop calculator at iah.ipm.illinois.edu/corn_seed_drop to determine seeding rates and to help calibrate planters.

Row Spacing

Recent survey data from the National Agricultural Statistics Service show that about 80% of the corn acres in Illinois are planted in rows from 20.6 to 30.5 inches apart, which would be mostly 30-inch rows, with perhaps some 22- or 24-inch rows. Some 10% of acres are listed as having row widths between 30.6 and 34.5 inches apart, which would be mostly 32-inch rows, but may include some 30-inch rows where there is some variability in spacing on the planter or between passes. Another 5% are in 36-inch rows, and the rest are in rows less than 20 inches or more than 36 inches apart. There has been some recent interest in rows narrower than 30 inches apart, and in twin-row configurations, which are usually paired rows spaced 6 to 8 inches apart, with 30 inches between pairs of rows. But 30-inch rows remain the norm, and indications are that this is changing slowly, if at all.

Interest in narrowing rows to less than 30 inches has grown for a number of reasons: Reports of narrow-row performance in the northern part of the Corn Belt (Minnesota and Michigan) have been positive; newer hybrids can, unlike those used in 20-inch-row experiments in the 1960s, stand and yield well at the higher populations that normally accompany narrow rows; and the required equipment is more widely available. Drawbacks to row spacing of 20 inches or less include the requirement for a new cornhead, which tends to be heavy for its width. Fitting equipment tires between narrow rows is difficult or impossible, which may rule out side-dress applications of nitrogen or require driving over plants in order to apply herbicides. Narrow rows are also difficult to walk through to scout, and reports are that harvest of narrow rows is tiring.

Although some of our work in Illinois in the 1980s had shown yield increases of 5% to 8% when row spacing was reduced from 30 to 20 inches, more recent results have not shown as much increase. **Figure 2.10** shows the response to narrowing rows from 30 to 15 inches, with plant population thinned carefully to 30,000 plants per acre, at 15 sites in Illinois. Only one site (No. 9) showed a significant yield difference (in favor of 15-inch rows); averaged over all sites, yields from the two row spacings were virtually identical. There was also no trend for higher- or lower-yielding sites to show more response to narrowing the row spacing. Earlier work had shown that narrow rows produced higher yields at low plant populations but not at high ones. These results indicate that most hybrids can form a complete canopy, and produce high yields, in 30-inch rows if plant populations are maintained high enough.

Despite some questions about the yield response expected from narrowing the rows to less than 30 inches, some producers are investing in the equipment needed to make this change. Other benefits to narrower rows may include slightly more yield stability over a range of weather conditions, better suppression of early-emerging weeds, and the fact that moving to narrower rows usually means a move to somewhat higher plant populations. For those who need to be convinced that narrow rows will produce enough extra yield to pay the cost of conversion, it might be prudent to first increase population at existing row spacing, to see if that's a constraint on yield. If we believe that complete canopy formation is the goal, then getting a complete canopy by using higher populations instead is usually more cost-effective than doing so through narrow rows. It is certainly not necessary to convert to narrower rows in order to get "permission" to raise plant populations.

It is common for those who do change to narrower rows to wonder if a change in hybrid might be necessary to better take advantage of the narrower rows and the (often) higher populations. It is likely that shorter, earlier-maturing hybrids with fewer leaves or narrower leaves will tend to respond more to both narrow rows and higher plant populations than will later, taller hybrids with more leaf area. However, such hybrids should be chosen for narrower rows only if they are in fact superior in their ability to produce yield and stay standing. In most cases, the best hybrids for 30-inch rows are likely to also be the best ones for 15- or 20-inch rows if they are managed well. Until breeders start to select hybrids in narrower rows, we expect most hybrids to do very well in 30-inch rows and to show limited response to narrower rows.

There has recently been an increase in the marketing of twin-row planters. Twin rows have the advantage of not requiring a new cornhead; rather, the two paired rows are gathered into the same row unit at harvest. Twin-row configurations also allow the use of conventional equipment for spraying, without having to drive down corn.

The main advantage suggested for twin rows is that the plants are spaced farther apart; plants that are 6 inches apart in 30-inch rows (34,848 plants per acre) are, if planted in a "diamond pattern," 9.6 inches away from their nearest neighbor across a 7.5-inch twin row. Some who advocate twin rows emphasize the importance of maintaining such a diamond pattern for maximum benefit. In practice, it can be difficult to maintain such a pattern with most commercial planters, especially if dropped population changes. We do not yet have enough research results to estimate how much yield advantage there might be when switching to twin rows. Limited data and some anecdotal evidence indicate that yield increases will be small, especially for those who manage 30-inch rows well.

Results we have seen so far indicate that, while some modest responses may result from narrowing rows from 30 inches, these differences may not be very large or very consistent. There are few serious problems with narrower rows, however, and some producers may find moving to narrower rows beneficial. Producers who are doing a very good job in 30-inch rows might calculate

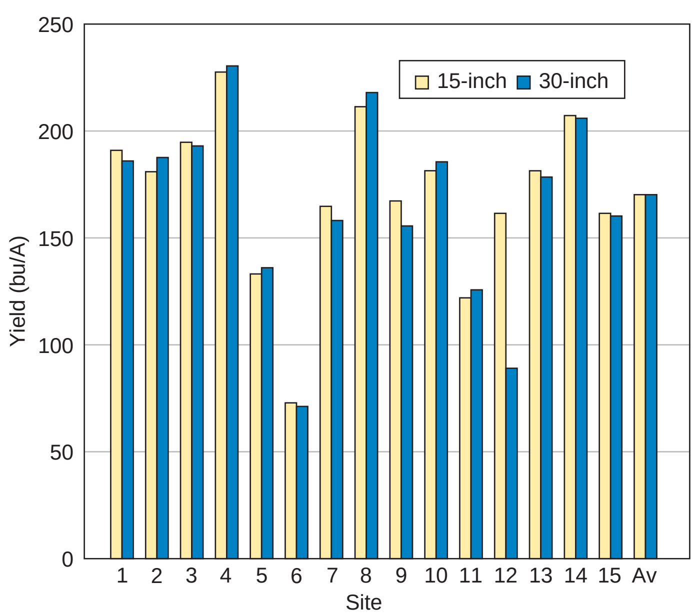

Figure 2.10. A comparison of yields from 15-inch and 30-inch rows at 15 Illinois sites. Plots were larger than normal, and all were thinned to 30,000 plants per acre.

the potential return to moving to narrower rows by assuming a yield increase over fields and years of no more than 2% to 3%, and perhaps less if plant populations and yields have been high in 30-inch rows. If possible, try to observe narrow rows in the field and speak with producers who have experience with narrow rows before making the change. Some might want to borrow narrow-row equipment and put side-by-side strips in a few fields to see what response they could expect. If you do this, be sure the narrow rows that are harvested are bordered by narrow rows; otherwise, there might be an edge effect that makes the narrow rows appear to do better than they actually do.

Uniformity of In-Row Plant Spacing and Plant Size

In recent years a number of researchers have reported that uneven distribution of corn plants down the row can decrease yield. The evenness of distribution of plants in the row can be measured using a statistic called the standard deviation, which is calculated from measurements of individual plant-to-plant distances and which ranges from zero with perfect spacing to 6 inches or more in cases where plants are very unevenly distributed. Standard deviation tends to increase with lower plant populations because missing plants (skips) leave large gaps in the row. Doubles—two plants in the space usually occupied by one plant—also increase standard deviation. Because skips and doubles usually have very different effects on yield, it is clear that standard deviation is not a perfect measure.

Table 2.2 gives the results of a series of planter speed studies that were conducted by farmers in east-central Illinois. These results showed that, even though planting faster tended to increase the standard deviation of plant spacing, it had little effect on plant population or yield. In only 1 of the 11 trials that were averaged to produce the data in the table did faster planting decrease yield, and in that trial faster planting also decreased the plant population. If a planter can drop the intended number of seeds when run at a faster speed, there appears to be little reason to slow it down unless faster planting causes a lot of variation in the depth of planting. Our general conclusion on the effect of plant distribution in the row may be summed up as follows: Within reason, plant spacing uniformity within the row has little effect on yield if plant population is adequate for high yields.

Table 2.2. Effect of planter speed on corn plant spacing variability (standard deviation), plant population, and yield.

Planting speed (mph)	Std deviation (in.)	Plants/A	Yield (bu/A)
3	2.87	27,231	152.5
5	2.99	27,373	152.2
7	3.22	26,996	153.1
LSD 0.05	0.33	NS	NS

While plant spacing uniformity generally has little effect on yield, the same cannot be said about plant size uniformity. Results of a number of studies show that uniformity of emergence is important, especially at high populations where plants must compete with neighboring plants for light, water, and nutrients. When a plant emerges more than a few days later than its neighbors, or is injured while its neighbors are not, chances are that it will never regain its competitiveness with its neighbors, and as a result it will usually yield less than other plants. We have also found that the plants next to a late-emerging or injured plant, while they often yield more as a result of gaining competitively against their weak neighbor, do not make enough extra yield to make up for the loss of yield by the plant that falls behind. The net result is that any unevenness that develops early in the season often results in some yield loss. In extreme cases, where we have injured plants between healthy neighbors early in the season, injured plants produce no yield at all, even though they might complete their growth cycle. Normally, such plants are not "weeds"—they don't hurt the yield compared to their being absent altogether—because they are so small.

Crop Canopy

All of a crop's growth and yield results from the ability of its green leaves to absorb sunlight and to turn sunlight energy into usable energy in the form of sugar, which the plant uses to make all other plant material, including grain. How soon in the season the leaf area appears, how fast it develops, and how long it stays healthy, well nourished, and green are thus critical to production success. The crop canopy refers to the leaf cover that a crop maintains; it includes both the leaf area of the plants and how the leaves are arranged to intercept sunlight. The total leaf area in an acre of corn is usually 3 to 4 times the ground area; we refer to this proportion as the leaf area index (LAI). An LAI of 3.5 to 4.0 is very efficient, in that it's close to the minimum amount it takes to absorb nearly all of the sunlight.

Figure 2.11 illustrates the importance of canopy cover during grain fill. These data were taken from a plant population trial at Urbana. They help explain some of the responses to such things as row spacing, plant population, and nitrogen supply. Though there may be exceptions, such as when pollination fails or pests are severe, it is clear that forming and maintaining a canopy that intercepts at least 95% to 98% of the sunlight after pollination is essential for high corn yields. In a real sense, managing row spacing and plant population for a particular corn hybrid should be seen as managing to produce and maintain this canopy.

The success of an attempt to “manage for canopy” can best be measured by looking down the rows at about noon on a clear day in early August. **Figure 2.12** shows how an ideal canopy intercepts nearly all of the sunlight. Although you probably can’t tell whether light interception is 95% or 98% or slightly less than that, streaks or patches of sunlight on the soil beneath the canopy indicate that you probably have not optimized the management of that particular hybrid for the soil and conditions in that field.

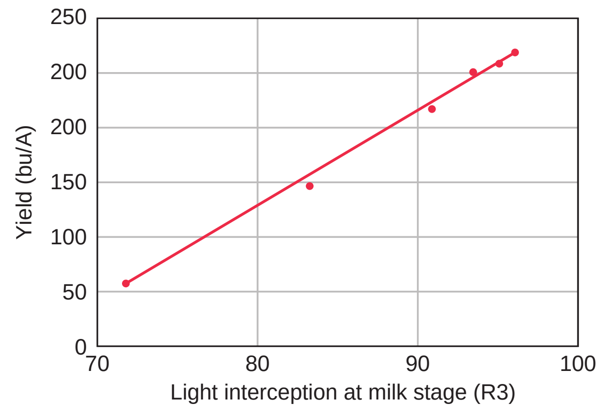

Figure 2.11. Relationship between light interception during grain fill and corn yield. Plant populations ranged from 10,000 to 35,000 per acre, corresponding to interception levels ranging from low to high.

Dealing with Crop Difficulties

Stand Counting

The most common method of taking plant populations is to count the number of plants in 1/1,000 of an acre, which is 17.424 feet, or 17 feet 5 inches, for 30-inch rows. For other row spacings, divide the number 522.72 (17.424 x 30) by actual row spacing to give the number of feet of row in 1/1000 of an acre. This length of row is small enough that it’s easy to bias the count by consciously or unconsciously selecting better-than-average places to count.

Taking plant counts in longer sections of row usually provides less opportunity for bias and can give more accurate counts. That means that fewer counts per field might be needed, if stands are relatively uniform. Using a measuring wheel instead of a tape can make such counting more efficient. Simply push the measuring wheel down a row while counting plants; it’s much faster to count plants in groups of three. When you reach 150 plants, record how many feet the measuring wheel has traveled for the count. For 30-inch rows, divide this distance into the number 2,613.6 to give plant population in thousands. For other row spacings, divide the number 78,408 by the actual row spacing to give the number into which the distance traveled should be divided.

Figure 2.12. Low amounts of light reaching the soil beneath a good corn canopy indicate very high percentages of light interception.

Replanting

Although it is normal that 5% to 10% of planted seeds fail to establish healthy plants, additional stand losses due to insects, frost, hail, flooding, or poor seedbed conditions may call for a decision on whether to replant a field. The first rule in such a case is not to make a decision in haste. Corn plants often outgrow leaf damage, especially when the growing point, or tip of the stem, is protected beneath the soil surface, or up to about the six-leaf stage. If new leaf growth appears within a few days after the injury, the plant is likely to survive and produce near-normal yields, providing its neighbors are affected the same way.

When deciding whether to replant a field, assemble the following information: original planting date; likely replanting date and expected number of plants per acre in the replanted stand; and costs of seed, planting operation including tillage if needed, and pest control for replanting.

When the necessary information on stands and planting and replanting dates has been assembled, use **Table 2.3** to determine both the loss in yield to be expected from the stand reduction and the yield expected if the field is replanted. To do this, locate the expected yield of the reduced plant stand by reading across from the original planting date to the plant stand after injury. If the damaged plant stand or planting date is between two of the lines or columns listed, estimate the percentage between the two numbers on either side. Then locate the expected replant yield by reading across from the expected replanting date to the stand expected after replanting. Subtract the expected yield from the damaged stand from that expected from the replanted stand. The difference between these

Table 2.3. Percent of maximum corn yield expected from different planting dates and plant populations in northern Illinois.

Planting date	% of maximum yield for final plant population (000/acre)						
	10	15	20	25	30	35	40
April 1	54	68	78	88	95	99	99
April 10	57	70	81	91	97	100	100
April 20	58	71	81	91	97	100	99
April 30	58	70	80	89	95	97	96
May 9	55	68	77	86	91	93	91
May 19	50	63	72	80	85	86	84
May 29	44	56	65	73	77	78	75
June 8	35	47	56	63	67	67	64

numbers is the percentage of yield increase (or decrease) to be expected from replanting.

For example, corn planted at 35,000 per acre on April 25 with its plant stand reduced to 15,000 by cutworm injury would be expected to yield 71% of a normal stand. If such a field were replanted on May 19 to establish 35,000 plants per acre, the expected yield would be 86% of normal. Whether it would pay to replant such a field depends on whether the yield increase of 15 percentage points would repay the costs to replant. In this example, if replanting is delayed until early June, the yield increase to be gained from replanting disappears. For a calculator to help make replanting decisions, see iah.ipm.illinois.edu/corn_replant.

Weather-Related Problems

Corn frequently encounters weather-related problems during the growing season. The effects of such problems differ with the severity and duration of the stress and the stage of crop development at the time of the stress. Descriptions of some stress conditions and their effects on corn growth and yield follow:

- **Flooding.** The major stress caused by flooding is lack of oxygen needed for the root system to function properly. If water covers the leaves, photosynthesis also stops, and mud deposited on the leaves and in the whorl can cause ongoing problems. Plants at V2 or smaller are generally killed after about 3 or 4 days of being submerged. Death occurs more quickly in warm, sunny weather because high temperatures speed up the processes that use oxygen, warm water has less dissolved oxygen, and bright sunshine can damage submerged leaves. In contrast, plants may live for more than a week under flooded conditions if the weather is cool and cloudy. When plants reach the six- to eight-leaf stage, they can tolerate a week or more of standing water, though total submergence may increase disease incidence. Plants that have been submerged usually suffer from reduced root growth and function for some time after the water recedes, and in some cases roots never fully recover. Tolerance to flooding generally increases with age, but reduced root function from lack of oxygen is often more detrimental to yield before and during pollination than during rapid vegetative growth or grain fill.
- **Hail.** The most common damage from hail is loss of leaf area, though stalk breakage and bruising of the stalk and ear can be severe. Loss charts based on leaf removal studies generally confirm that defoliation at the time of tasseling causes the greatest yield loss (often 100%), while loss of leaf area during the first 3 to 4 weeks after planting or when the crop is near maturity generally causes little yield loss. Loss of leaf area in small plants usually delays their development, and plants that experience severe hail damage may not always grow normally afterward, even if they stay alive and grow back.
- **Cold injury.** Corn is of tropical origin and is not especially tolerant of cold weather. Although the death of leaves from frost is the most obvious type of cold injury, leaves are often damaged by temperatures in the low 40s or upper 30s, and photosynthesis can be reduced even if the only symptom is a slight loss of leaf color. The loss of leaves from frost is generally not serious when it happens to small plants, though such loss delays plant development and can delay pollination to a less favorable (or, less frequently, a more favorable) time. There have been cases, however, where temperatures are low enough to cool the soil to near the depth of the growing point and to either kill or seriously damage small plants. Frost injury symptoms may appear on leaves even when nighttime temperatures do not fall below the mid-30s; radiative heat loss can lower leaf temperatures to several degrees below air temperatures on a clear, calm night. If frost kills leaves before physiological maturity (black layer) in the fall, sugars usually can continue to move from the stalk into the ear for some time, although yields generally are lowered and harvest moisture may be high due to high grain moisture at the time of frost and to the slow drying rates that usually follow premature death.
- **Drought.** Through the late vegetative stage (the end of June in normal years), corn is fairly tolerant of dry soils, and mild drought during June can be beneficial because roots generally grow downward more strongly as surface soils dry. The crop also benefits from the greater amount of sunlight that accompanies dry weather. In the 2 weeks before, during, and in the 2 weeks following pollination, corn is very sensitive to drought, and lack of adequate water can cause serious yield losses. Most of these losses

are due to failure of pollination, and the most common cause of this is the failure of silks to emerge on time. When this happens, the silks do not receive pollen, so kernels are not fertilized and do not develop. Developing kernels can also abort for several weeks after pollination. Drought later in grain fill has a less serious effect on yield, though root function may decrease and kernels may not fill completely. But any time soils are dry enough to reduce the amount of water available for transpiration (water loss through the leaves), photosynthesis decreases and the chance of yield loss increases.

- **Heat.** Because drought and heat usually occur together, many people assume that high temperatures are a serious problem for corn. In fact, corn is a crop of warm regions, and temperatures up to 100 °F usually do not cause injury if soil moisture is adequate. Extended periods of hot, dry winds can cause some tassel "blasting" and loss of pollen, but pollen shed usually takes place in the cooler hours of the morning, and conditions severe enough to cause this problem are unusual in Illinois. Corn hybrids vary in their sensitivity to both heat and drought, and there is currently some effort to develop GM corn with drought tolerance. Because drought is not the normal condition in Illinois, hybrids should be chosen based on their ability to yield well over a range of conditions, including drought stress, but not solely on their tolerance to drought.

Estimating Yields

Making plans to harvest, store, and market the crop often calls for estimating yields before corn is harvested. Such estimates are easier to make for corn than for most other crops because the number of ears per acre and number of kernels per ear can be counted fairly easily and accurately. These numbers are used to estimate the number of kernels per acre, which is then divided by the expected number of kernels per bushel to estimate yield in bushels per acre.

Corn yields can be estimated after the kernel number is fixed, or about 2 to 3 weeks after the end of pollination. Walk to a predetermined spot in the field (to avoid bias), and count the number of ears with more than 50 kernels in 1/1,000 of an acre (17.424 feet or 15 feet, 5 inches in 30-inch rows; divide the number 522.72 by the actual row spacing to get this distance for other row spacings). Take three ears from the row section that was counted. To avoid using only good ears, take the third, sixth, and 10th ears in the length of row. Do not take ears with so few kernels that they were not included in the ear count. Count the number of rows of kernels and the number of kernels per row on each ear. Multiply these two numbers together for each ear, then average this kernel count for the three ears. Take this average kernel number times the number of plants to give the estimated number of kernels in the 1/1000 of an acre.

Divide the number of kernels in 1/1000 of an acre by the number (in thousands) of kernels that you expect a bushel to have. This number was 90 (thousand) in older hybrids, but kernel weights have increased in recent years, and it's usually more accurate to use a number between 75 and 85, especially in more productive fields, where good yields are likely. Hybrids differ some in kernel weight, and this can be factored in if it's known. But the final weight of kernels is always a best guess, although this guess usually improves as grain filling progresses. A helpful calculator to assist in estimating yield is located at iah.ipm.illinois.edu/corn_yield_estimate.

Special-Use Corn

There remains considerable interest in producing corn with characteristics that give the grain higher value. Most such types are more or less normal corn in terms of how the plant grows and develops, and most do not require special management, though there are some exceptions. Care during harvesting, drying, and storage usually is critical to maintaining quality and preventing mixtures with other types of corn. Some types also require isolation from other types of corn to prevent or minimize cross-pollination, which can compromise grain quality. This is usually done by maintaining a certain distance from other corn, but in some cases it may be done in time as well, by requiring the specialty corn to be planted later so pollen from normal corn is not present when the specialty corn pollinates.

Many specialty types are grown under contract. The contract buyers often specify what hybrids may or may not be used, and they may specify other production practices to be used or avoided. Some contracts also may include pricing information and quality specifications. Risks associated with growing specialty types of corn vary considerably. Milling companies may buy corn with "food-grade endosperm," requiring only that the grower choose hybrids from a relatively long list of popularly grown hybrids; the risk in this case is small. By contrast, some types of specialty corn may not yield or stand well and so may entail considerable risk. Production contracts in such cases may shift some of the risk to the buyer. In any case, every grower of specialty types of corn should be aware of risks associated with each type.

Food-grade corn, either white or yellow, is one of the most common specialty types grown in Illinois. Many normal hybrids produce good quality for use as food, and so the largest difference in growing food-grade corn is the care needed in drying the crop in the field or with low temperatures and the storage, handling, and delivery needed to keep kernels intact. **Waxy** corn contains 100% amylopectin starch, compared to 75% in normal corn. Amylopectin starch has certain characteristics that are useful in food and industrial products. In contrast, **high-amylose** corn has lower amylopectin and more than 50% amylose, which has different properties than amylopectin and so has use in a different group of food and industrial products. Waxy corn yields much like normal corn, so it carries little risk even if there's not much premium for it. High-amylose corn usually yields much less than normal corn and is normally grown only under contract.

Nutritionally enhanced corn, with higher-than-normal oil or protein, may have more value as livestock feed than normal corn, and some hybrids are available with these characteristics. Many who choose to grow these hybrids feed the grain themselves; the market for nutritionally enhanced hybrids like these remains small, in part because there are alternative sources of extra protein and oil to add to livestock feed.

Popcorn is a specialty type with very hard endosperm that expands rapidly when water in the endosperm is turned to steam by rapid heating. Most popcorn is produced under contract to a processor. Popping volume is an important characteristic of popcorn hybrids, and premiums may be paid for hybrids that have high popping volume, especially if they produce less yield. There are yellow- and white-hulled popcorn hybrids, as well as types with purple or black seedcoat colors. Most popcorn hybrids are less vigorous than normal corn hybrids and so are less tolerant of adverse weather. Increasingly popcorn is grown under irrigation.

A recent opportunity has developed to produce **non-GMO** corn. There are no known health or nutritional issues with GM corn, but many consumers remain uncomfortable with what they consider "unnatural" corn that contains genes from other organisms, and they are willing to pay extra for grain without any such traits. There are usually strict limits on the amount of GM corn that can be present. Special tests exist for most commercialized GM traits, and loads may be rejected if the amount of GM grain found exceeds the maximum allowed.

With a substantial percentage of corn now being used to produce **ethanol**, there has been some work to develop hybrids that will produce more ethanol per bushel than normal corn. This trait refers to the amount of "highly fermentable starch," or HFS, in the grain. While genetic research has shown that there is some range among hybrids in HFS, most processing plants are able to pay little if any premium for high-HFS grain, in part because of the cost to isolate it from normal grain and because getting more ethanol from such grain might require adjustments in processing that may remove the profitability.

Though commercial development has been slow due mostly to concerns about pollen escape and outcrossing, pharma corn—genetically modified to produce proteins or other products with medicinal properties—has the potential to dramatically lower costs of some very expensive vaccines and other pharmaceuticals. **Nutriceuticals**, which are products with special nutritional value, including higher levels of things like vitamins, might also be produced in GM corn in the future. Production of nutriceutical and pharma corn will require the strictest of isolation, including in some cases isolation by miles of deserts or oceans, to prevent pollen spread to other corn.

Organic corn acreage has been increasing in recent years as the market demand increases. The main difference between normal corn and organic corn is the complex set of rules under which organic corn must be produced. These rules prohibit the use of chemical fertilizer, GM hybrids, or "artificial" pesticides. Major challenges typically include weed control, which is generally restricted to mechanical means, and getting enough nutrients, especially nitrogen, in fields where using manure is not practical. Controlling insects such as corn rootworm without chemicals or the use of GM traits is also difficult. Rules may specify crop rotations and other practices that may make production more expensive. Organic corn generally commands a much higher price than normal corn, so it can be profitable, even if yields are somewhat lower.

3

Soybean

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Illinois is first or second among states in soybean production in the United States, with between 8 and 10 million acres a year over the past decade. Average yields for Illinois during this period are shown in Figure 2.1, on page 13. While yields are high in Illinois compared to many parts of the world, they have not, at least in recent years, been trending upward steadily; instead they show relative stability, with variability related mostly to weather conditions. This chapter will address soybean management, including ways to bring yields up, if not in all of Illinois, then at least on your farm. This is a challenging task.

Soybean Plant Development

A good understanding of how the soybean plant grows and functions can help producers refine their management practices to achieve better yields. An overview of soybean's growth, development, and management requirements for good yields is found in *Soybean Growth and Development* (PM 1945, Iowa State University Extension; parts of this publication can be seen at extension.agron.iastate.edu/soybean/production_growthstages.html).

The growth of soybean plants is tracked by a system that assigns a V number (for example, V1) to vegetative stages of growth depending on the number of the plant's expanded trifoliolate leaves (having three leaflets). **Figure 3.1** shows a V3 plant with three expanded trifoliolate leaves. A leaf is considered "expanded" when the younger leaf above it starts to unroll, so that the edges of the leaflets are no longer touching. Soybeans planted in early May usually reach the V7 or V8 stage by early July, and soon thereafter the first flowers appear on plants. This stage is designated as the first reproductive stage, or R1. Unlike in corn, vegetative stages continue to develop after reproductive stages begin; such development is called indeterminate, because the final size of the plant is not set by the time the plant flowers, and vegetative and reproductive stages overlap.

Unlike corn plants, which begin to flower once a certain accumulated temperature (measured by growing degree days) is reached, soybean plants are influenced to flower by the length of the day; this is called photoperiod sensitivity. Temperature is also important in the rate of soybean development, including when flowering begins. Photoperiod works like this: Soybean plants have a mechanism whereby a certain substance is converted from the inactive form to the active form in the dark. Light makes it revert back to the inactive form. Once nights are long enough to allow enough of the active form to accumulate, the plant starts the flowering process. Warm nights speed up this process, while lights at night, such as street lamps, will inhibit it **(Figure 3.2)** and can greatly delay flowering. For soybean varieties adapted to central Illinois, the nights are long enough by about July 10 or so to allow flowering to start, though warm nights will move this date up. Early-maturing varieties do not need nights to be as long as later varieties, so flowering starts earlier. Moving a variety farther north means that nights are shorter (days are longer in midsummer), so flowering will start later.

Figure 3.1. A V3 soybean plant. The cotyledons are attached, and above them are the cotyledonary leaves, which are single, not trifoliolate. Notice that the fourth trifoliolate leaf is not yet fully expanded. A branch is starting to form in the axil of the first trifoliolate leaf.

Figure 3.2. Interruption of flowering led to late maturity of soybean plants that receive the light from street lamps. These plants were frosted before the photo, but pods are still green.

Once flowering starts, we track the development of flowers and then pods and seeds, with stages R3, R5, and R7 marking the beginning of pod setting, pod filling, and maturity, and stages R2, R4, R6, and R8 marking stages of full flowering, pod setting, seed filling, and maturity. One advantage that soybean has over corn is that the flowering and seed-filling stages take several weeks to complete, and if there are stresses such as dry soils during this time, relief of such stresses during these critical stages can often allow the plant to recover. Early-maturing varieties develop more quickly, so they have a shorter time over which such recovery is possible. Pod filling normally starts in early August and can be nearly finished by early September.

Besides differing from corn in the timing and duration of yield-making events such as flowering and seed filling, soybean plants also tend to produce considerably more leaf area than corn plants, at least collectively in the field. The LAI (acres of leaves per acre of crop) is often as high as 6 or 7 in soybean compared to 3.5 or 4 in a good corn crop. This is part of the reason that soybeans are less sensitive to lower plant populations compared to corn. But producing so much leaf area also takes a great deal of energy, and to the extent that some of the leaf area is not normally needed to produce maximum yields, production of a lot of leaf area can lower plant efficiency. In years with a lot of rainfall in June and July, in fact, leaves are often larger and stems longer, which can result in shading and less seed filling of pods lower in the crop canopy. Seeds in a pod are usually filled using sugars from the leaf attached to the same node as that pod, so if leaves cannot reach into the light, the pods at the same node may not fill completely.

Variety Selection

Soybean varieties are divided into groups according to their relative times of maturity. These maturity groups (MGs) are usually designated using Roman numerals, from 0 (or several zeroes, for very short-season varieties) to MG IX or higher for types developed for very warm climates with shorter days during the growing season. It is also common practice to add a decimal to the MG number, and to refer, for example, to a variety as MG 2.4 or 3.6, to denote gradations within a maturity group. MG numbers are assigned by breeders, and many naming systems for commercial varieties include the MG number (and often a decimal) as part of the name.

Varieties of MG I can be grown in northernmost Illinois, but they are too early for good growth and yield farther south. Varieties of MG IV are best adapted in southern Illinois, and a few MG V varieties are grown in the southernmost areas. Growing soybeans that effectively use the full growing season is generally beneficial to yield, though we have seen limited benefits from using very late-maturing varieties, even if they are able to complete seed fill before frost. As is the case with corn, there has been more breeding attention paid to improving varieties in MG I through MG III than in later-maturing groups. One reason for this is that the mid-South (Arkansas, Tennessee) now produce earlier-maturing soybeans—often MG III and IV—in order to escape hot, dry conditions in late summer. This has diminished the demand for varieties in MG V and later.

Nearly all soybeans grown in the Midwest have an indeterminate growth habit, meaning that vegetative growth continues beyond the time when flowering begins, up to about the time that seed filling begins (R5). Several decades ago, some short-statured determinate or semideterminate (cross of determinate and indeterminate) varieties with maturities appropriate to Illinois were released. The short stature helps these varieties resist lodging in high-yield environments. But they also need above-average growing conditions before flowering to consistently offer a yield advantage, and stress early in the season can result in very short plants and low yields. As a result, few determinate varieties are grown today.

Hundreds of soybean varieties—nearly all privately developed—are named and sold by seed companies. Most soybean acres in Illinois are planted from MG II, III, or IV, with a few MG I and V varieties grown in the northern and southern ends of the state, respectively. For specific performance data on both public and private varieties, consult the latest issue of *Performance of Commercial Soybeans in Illinois*, or visit the website at vt.cropsci.illinois.edu/soybean.html.

Since their first release in the mid-1990s, Roundup Ready soybean varieties have come to occupy more than 90% of the soybean acreage in Illinois. Most people agree that some of the early-released varieties of Roundup Ready soybeans were agronomically inferior, mostly because only limited germplasm was available for release. These varieties have been replaced by newer releases, and today most available data indicate that if there is a yield difference between these two groups of varieties, it is probably in favor of the Roundup Ready varieties. Because these varieties make up such a high percentage of the seed market, private breeding companies have directed most of their efforts to improvement of these and other GM varieties.

While the several different glyphosate-resistant genes are the only GM trait now widely available in commercial varieties, the next few years will see commercial release of GM varieties with traits to give resistance to other herbicides (glufosinate, or Liberty; and dicamba, or Banvel and other trade names) and possibly some with disease resistance and even "yield" genes, though it's not clear that the latter will require gene transfer (or be called GM), since they will likely come from soybean. Other GM traits of interest in soybean might include Bt for insect resistance and some quality traits. There continues to be some consumer resistance to GM soybeans regardless of what trait is involved. This may continue to slow the release of some novel GM traits in soybean, especially those varieties developed for use in foods.

When choosing a variety, first consider a suitable maturity coupled with a good yield record. Further refine your selection by considering the variety's genetic resistance to prevalent pest problems. Another trait to keep in mind is standability, though this is not as big an issue as with corn or as it was with older soybean varieties. Commercial varieties have also been selected against the tendency to have seed shatter from pods before harvest, though unusual weather can still cause some of this. If you are producing for niche-market contracts, your choices will be relatively limited and may not include the best-yielding or most pest-resistant varieties.

So far, there have been few releases of varieties bred especially to have more protein, oil, or other constituents than do normal varieties. Such quality traits are important, however, and breeders avoid releasing varieties that are lower than normal in protein and oil. The use of soybean oil as biodiesel has increased demand for the oil, and the increased availability of corn protein extracted during ethanol production has meant increased competition with soybean protein for use in animal feed. Improvements in the nutritional and feed quality of protein and oil are certainly possible. But it remains difficult to breed for large changes in content, if not quality, of these key components.

Planting Date

Because of the flowering mechanism described, later planting often does not delay flowering as much in soybean as it might in corn; the rule of thumb is that soybean need about 6 weeks of warm weather to develop enough size for best yields by the time flowering occurs. If it's warm and soybean plants begin to flower during the first or second week of July, planting later than late May will not usually allow enough growth for best yields, unless conditions are ideal later in the season. For this reason, soybeans generally yield best when planted in May, with full-season varieties tending to yield best when planted in early May. Earlier varieties tend to be less sensitive to planting date, as long as they are planted by late May. When planting of full-season varieties is delayed until late May, the loss in yield is comparatively less than the penalty for planting corn late. Planting soybeans after corn has been planted is thus the best strategy.

Figure 3.3 shows planting date responses from several studies, one conducted by University of Illinois agronomists in northern Illinois in the early 1990s, the second by Pioneer Hi-Bred International agronomists over a range of Corn Belt locations in 2001, and the third by Dr. Palle Pedersen of Iowa State University at several sites in 2004, a year of very high yields. These results show the variability over years and environments in the response of soybean to planting date. But planting in the first half of May normally produces the best yields. Planting in April, especially early April, can reduce yields, even when stands are good. Planting delays to the end of May often carry relatively mild penalties, though this varies a great deal among years. The reason we see such variability is that

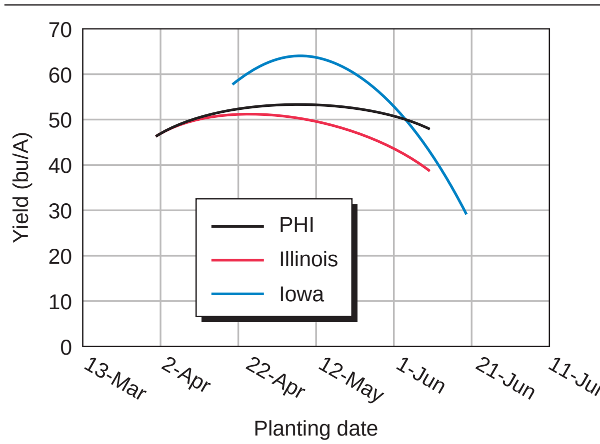

Figure 3.3. Soybean planting date response in three different trials. The PHI results were generated by agronomists with Pioneer Hi-Bred International using several different varieties, the Illinois results are from trials run in northern Illinois, and the Iowa results are from Dr. Palle Pedersen of Iowa State University, from work done in 2004.

conditions later in the season can add to or greatly diminish potential problems from late planting. For example, the 2008 season was relatively cool and wet, and widespread delays in planting were followed by very slow development and late maturity. Even so, yields ranged from good to very good, even in fields planted in mid-June or later.

If temperatures are close to normal, planting date affects the length of time required for soybeans to mature, with delays resulting in fewer days needed for the plant to complete its life cycle. The period from planting to the beginning of flowering is typically 45 to 60 days for full-season varieties planted at the normal time. This interval is shortened as planting is delayed; it may be only about 25 days when such varieties are planted in late June or early July, but this also means that plants may be small and canopy may be less than adequate when flowering starts. A rule of thumb is that for each 2- to 3-day delay in planting, plants reach maturity one day later. The lengths of the flowering and pod-filling periods also are shortened, but the effect of late planting on these phases of development is minor.

Planting dates that extend into June often decrease yield substantially. Such late planting tends to result in a shorter soybean plant with considerably fewer leaves, reducing the yield potential per plant. It is possible to offset somewhat the changes in plant morphology by planting late-seeded soybeans in narrow rows and at a seeding rate higher than is used for early planting. Double-crop soybeans, which are planted after wheat harvest and so are always planted late, often benefit from having narrow rows and high seeding rates. Dry soils can significantly delay soybean emergence and can thus turn it into a “late-planted” crop even if it was planted on time. It is clear why late-planted soybeans are risky and why planting on time is important.

Planting Rate and Seed Issues

Research in Illinois and elsewhere has shown that soybean yields tend to reach a maximum at populations of about 100,000 plants per acre when the crop is planted at the normal time. In some cases, only 50,000 plants have produced yields as high as plant populations 2 to 4 times that high. This illustrates the capacity of an individual soybean plant to increase its size in response to having more room in which to grow. Most data also show a very wide “plateau” over which yields respond little if at all to increasing or decreasing population. In rare cases, plant population can be high enough to reduce yield, but this seldom occurs unless conditions are dry and having more plants causes faster loss of water.

Low soybean plant populations yield less mostly because of their inability to form a complete crop canopy and to intercept all of the sunlight they need to produce higher yields. An insufficient plant population will thus limit yield to about the extent that plants fail to form a complete canopy of leaves. It is important to soybean yield that the canopy be more or less complete—that is, that nearly all of the sunlight is being intercepted—by the time pods begin to form, typically by sometime in the second half of July. A full canopy of healthy leaves on a well-watered crop enables photosynthetic rates to be near their maximum, which helps flowers to stay on the plant and to develop into productive pods. Thin stands also allow more weed competition to develop in the crop, and they encourage plants to branch and forms pod closer to the soil line, possibly adding to harvest losses.

Figure 3.4 shows seeding-rate responses from a series of recent Illinois trials. These trials were done using small plots, and plant establishment, as a percentage of seed planted, was high. Variety maturities used were MG II, III, and IV for northern, central, and southern Illinois, respectively. These results show little response from planting more than 100,000 seeds in northern and central Illinois, but some response from 100,000 to 150,000 in southern Illinois. These trials were conducted in 30-inch rows; other research has shown no consistent effect of row spacing on plant population responses in soybean when planting is relatively early. The leveling off at seeding rates above 100,000 in most of these trials is consistent with data from other recent research in Illinois and in other states. Of the 16 trials included in the northern and central regions, only one showed a yield response above 100,000 seeds per acre, and two showed some yield loss as seeding rate increased. Of the seven southern sites, three produced higher yields at 150,000 than at 100,000 seeds.

Soybean seed prices have increased a great deal in recent years, in part due to the fact that most varieties have patented GM traits for which licensing fees are charged. Thus some consideration might be given to applying economics to seeding rates, with increases or decreases in rates depending on the ratio of seed price to the price of soybeans. Soybean seeds are still sold mostly by weight (in 50-lb units), but some are beginning to be sold by number, in the same way that corn seed is sold. If a 50-lb unit of seed has 140,000 seeds (2,800 seeds per pound, which is typical for soybean seed) and costs $32, and the predicted price for soybeans at harvest is $13 per bushel, then calculations using the data in **Figure 3.4** show that the seed just pays for itself (that is, is at its economically optimal rate) at a seeding rate of about 90,000 in northern and central Illinois and about 160,000 in southern Illinois. If the same seed costs $50 per unit and the soybean price falls to $8 per bushel, the optimum seeding rates drop to about 80,000 in northern and central Illinois and about 130,000

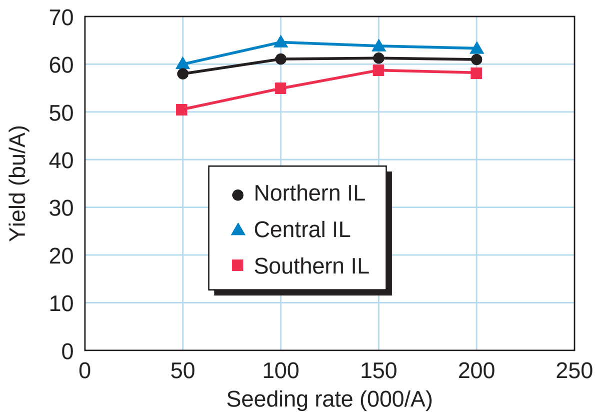

Figure 3.4. Seeding rate responses in Illinois trials, 2005 to 2007. Each region includes data from 7 to 9 trials. Rows were 30 inches apart. Trials were conducted by Ralph Esgar, University of Illinois.

in southern Illinois. While it helps to be aware of the fact that inputs such as seed should be used at rates that take into account costs and returns, it is also clear that having soybean plant populations too high for the conditions does not usually mean lower yield, just some seed cost that did not provide a return. On the other hand, having seeding rates too low, either purposefully or due to reduced emergence, costs both yield and profit. Thus it is unlikely that a seeding rate of only 80,000 should be used, despite the possibility that this will be enough in some cases.

Seed Quality and Testing

One important issue in choosing seeding rates is estimating how many of the seeds will germinate and emerge and how many of the emerged plants will survive to be productive. This number is affected by soil type, seed quality, type of planter used, and especially weather conditions after planting; it is not uncommon for good-quality soybean seed planted into good soil conditions to fail to produce adequate stands if heavy rain falls after planting and before emergence. Failure to produce a soybean stand is more common when planting is early, due to cooler soils and increased time to emergence. Planting too deep or just before heavy rain increases the chance of emergence problems due to soil crusting, and it can result in the death of seeds or seedlings due to lack of soil oxygen and increases in seedling diseases. It may also be useful to try to estimate how emergence might be affected by seed quality and planting conditions. The seed drop calculator at iah.ipm.illinois.edu/seed_drop_calculator can help with estimating and with calibrating planters.

In the research reported in **Figure 3.5,** drilling soybean seed in 7- or 8-inch rows produced stand counts of about 70% of the numbers of seeds planted, while planting with row units in either 15-inch or 30-inch rows produced about 80% stand establishment. The main reason for this is that drills tend not to place the seed at uniform depth in the soil and to firm soil around the seed as well as do row units. In soils that tend to form a crust, having seeds closer together in the row—as happens in wider rows—makes it possible for seeds to exert more force, per foot of row, to emerge through a crust. Seeds in narrow rows, which are typically planted 5 or 6 inches apart in the row, are too far from one another to "help" neighboring plants emerge.

Among agronomic crops, the seed of soybean is among the most difficult to produce and maintain with high quality. Germination percentages can be reduced by poor weather—especially wetting and drying several times—before harvest. And if the seed dries to below 10% moisture before harvest, even the most careful harvesting and handling can cause mechanical damage that reduces germination. Because of the potential for problems with quality, soybean seed is cleaned thoroughly to remove any seeds with unusual shapes, including splits (cotyledons that separate when the seedcoat breaks).

Soybean seed is tested to determine its emergence potential, and it often undergoes one or more "stress tests" that attempt to predict emergence under less-than-ideal conditions. The standard warm test, run on absorbent paper in the laboratory, is required on commercial seed containers; it estimates emergence under ideal conditions of moisture and temperature and of little disease. The "cold test" is the most common stress test; it is designed to see how well seed will germinate and emerge under cold, wet soil conditions. It includes the use of soil in an attempt to duplicate field conditions. Cold test scores vary some by laboratory, because soils and soil organisms differ among labs. Because of this, cold test scores need to be used with care; they are most helpful in comparing one lot of seed with

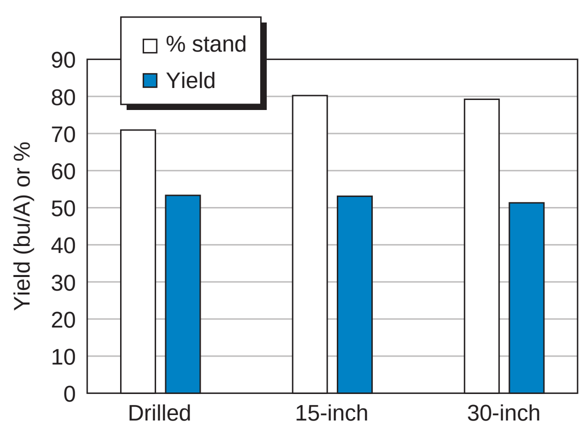

Figure 3.5. Effects of row spacing and planter on soybean yield and on percentage of seeds that produced plants, averaged over 7 Illinois sites. Data provided by Eric Adee, University of Illinois.

another tested in the same laboratory. Unlike warm tests, the results of cold tests need not be provided to the seed purchaser. Cold scores tend to be “worst-case” predictors; they are often considerably lower than warm scores and are usually lower than actual field emergence.

Another type of seed stress test is the accelerated aging test, in which seed is exposed to high temperatures and humidity before germination is tested. Such conditions are rarely encountered by seed before it is planted, but this test provides an estimate of seed vigor, which is the extent to which the seed has maintained intact its ability to germinate and produce a healthy seedling. Vigor is not exactly the same as germinability; over time, vigor typically starts to decline before germination percentage declines. A measure of vigor can thus be helpful in predicting whether good seed will remain good until it is planted.

Seed Size

The fragility of soybean seed compared to the seed of many crops is due to its relatively large size; its growth inside pods with thin walls that do not protect it particularly well from weather, insects, and diseases; and the ease with which it can be mechanically damaged. It is also subject to quality problems if conditions are very warm and humid during maturation. Fortunately, soybean seed develops its ability to germinate relatively early in the seed-filling process—by the time it reaches half to two-thirds its final weight—meaning that the inherent quality of soybean seed does not appear to depend on the final size of the seed. Thus seeds that end up smaller than normal due to dry conditions or some other stress during seed filling are very often as capable of germinating and establishing plants as are larger seeds of the same variety.

This means that, especially when seed quality tests show no problem with the smaller seed, the use of small seed represents little if any risk. Small seed may even have some advantages: some small-seeded varieties used in parts of the world have excellent seed quality and storability; small seeds need to take up less water in order to germinate and so may germinate faster; and smaller soybean cotyledons may be able to move up through the soil during emergence more easily than larger ones would. In fact, with most soybean seed sold by weight (as 50-lb units) and with seeding rates recommended by number and not weight, smaller seed may mean lower seed costs than larger seed.

Inoculation

Soybean is a member of the legume family of plants, most of which have relatively high protein content in their seeds and so need to take up a lot of nitrogen. Many of these plants have the ability to host bacteria in special structures, called nodules, on their roots. The plant forms nodules as a reaction to the infection of the root by these bacteria. Bacteria live in the nodules and are fed by sugars moving down from the leaves. In turn, the bacteria convert the nitrogen from air into forms usable by the plant. Active nodules have a pink color inside. Plants growing in soils with a lot of nitrogen from fertilizer usually do not have very many, or very active, nodules. So carryover N from a previous crop or N produced from soil organic matter can delay or reduce the fixation of N in nodules. On average, soybean plants take up about half of their N from the soil and the other half from N fixation. Somewhat surprisingly, even though N fixation requires energy from the plant and so would seem to detract from yield potential, using fertilizer to supply the N the crop needs very seldom increases soybean yield.

Scientists many years ago recognized that a legume such as soybean grown in a field where it did not grow before will form effective nodules only if some of the necessary bacteria are provided. Bacteria are formulated into an inoculant material, which is added to soybean seed or into the soil near the seed at planting. The type of bacteria needed to produce nodules persists for some years in the soil once a nodulated crop is grown. For this reason, it is rare to get a response to inoculation if soybeans grew in the same field previously. Research with some of the newer inoculants, including some that use newer, better strains of bacteria, has shown no consistent yield increase in fields where soybeans have been grown recently in rotation.

If soybean grew in a field more than five years earlier, or if soybean never grew in that field before, then inoculation with a high-quality inoculum is recommended in Illinois. Failure of soybeans to form nodules will usually reduce yields substantially, unless soils contain unusually large amounts of N. In cases where soybeans are planted on land with no recent history of soybean—for example, on land coming out of CRP—but inoculation is not done, it might pay to add N fertilizer, up to 200 or 250 pounds of N, with more on soils with less organic matter. In some such cases, however, no N has been added and soybean plants still seem to get enough N, either from N released from organic matter and stored in the soil or from active nodules, presumably from bacteria that persisted for a long time in the soil. One strategy in such a case is to watch the crop for signs of N deficiency and of nodule formation and to apply fertilizer N only if deficiency symptoms (lightening of green leaf color) develop and nodules fail to form. If needed, N should be applied before flowering begins. Applying half then and the rest at the beginning of pod filling might help assure the supply of N at critical stages.

Planting Depth

Emergence will be more rapid and stands will be more uniform if soybeans are planted at uniform depths of 1-1/4 to 1-3/4 inches. Deeper planting often results in slower emergence and poor stands, because soils are often cooler with increasing depth and because deep planting provides more time for unfavorable weather events and soil crusting to take place before emergence. Though there have been few if any measurements of the effects of uneven emergence on soybean yield, it is clear that uniform emergence, which is often related to uniform planting depth and soil conditions at the seed, is a good goal.

Varieties differ some in their ability to emerge when planted deeper than normal, though such differences may be less than they were among older varieties. If the description of a variety mentions an "emergence score," this score reflects the ability of the seedling hypocotyl to elongate to allow emergence when planting is deeper than recommended. This is a genetic trait, typically measured in sand, which may or may not be related to the vigor of the seed or its ability to emerge through soil crusts or under other poor conditions. So the main use of such scores may be to provide a warning not to plant too deep with some varieties (those with a high score, indicating low ability to emerge from depth). That's a good goal with all soybean seed, so such scores may not be very useful.

One ongoing issue with soybean planting depth is whether seeds should be planted deeper than normal to reach moister soil in order to germinate under dry conditions. The alternatives are to plant at normal depth, letting the seed wait until it rains to germinate, or to wait to plant until after it rains. There is not a clear answer to this dilemma, and every choice has drawbacks. In light soils such as sandy loams, planting to a depth of 2-1/2 or 3 inches to reach moisture might be a good strategy, since rainfall after planting on such soils poses little problem for emergence. In heavier soils, rainfall after planting will often mean failure of emergence, unless the rainfall amount and intensity are modest. Waiting to plant until after it rains can result in considerable delays in planting and emergence. One approach to this problem is to prevent it, by using less soil-drying tillage before planting and by planting faster so that soils don't dry out before planting.

Row Width

Recent survey data show that about 60% of soybean acres in Illinois are planted in 15-inch rows, with the rest split more or less equally between drilled (less than 10-inch) and 30-inch rows, and a few percent in rows wider than 30 inches. The increase in 15-inch rows has been rapid, rising from less than 20% of the acres in the late 1990s. Most of this increase has been at the expense of drilled soybeans, which occupied more than 50% of the acres in the mid-1990s. This rapid change followed the introduction of split-row planters, with 30-inch rows used for corn and row-splitting units to make 15-inch soybean rows. Wider planters (40 to 60 feet wide) help speed up soybean planting, and the use of row units often provides better seed metering and placement than can be achieved with drills.

Much research has been done on row width in soybean, with most studies showing that soybean yields increase when row width is decreased to less than 30 inches. Many such trials have shown that this yield increase tends to level off as rows reach 20 inches or less, though some, especially in environments where water limits yields, showed maximum yields at row spacings of 10 inches or less. **Figure 3.5** gives the results from a set of trials conducted in Illinois. In this study, drilled and 15-inch rows yielded the same, while 30-inch rows yielded about 2 bushels per acre, or about 4%, less. That study included different seeding rates, but there was no effect of seeding rate on yield, nor did seeding rate interact with row spacing to suggest that changing the row spacing calls for changing the seeding rate.

The yield advantage for narrow rows is usually greatest for earlier-maturing varieties, with full-season varieties showing smaller gains in yield as row spacing is reduced. To predict whether narrower rows will increase yield, follow this rule of thumb: If a full canopy of leaves is not developed by the time pod development begins in wide rows, then narrower row spacings may well produce higher yields. This helps explain why later-maturing varieties, which nearly always grow taller with more leaf area, usually respond less to narrow rows. It also helps to explain why narrow rows usually increase yield relatively more under dry conditions or late planting, both of which reduce plant growth.

Some seed companies describe the "growth habit" of their soybean varieties with regard to how wide the canopy spreads out when the plants grow in the row. While there are indications that some soybean varieties have longer petioles connecting leaves to stems and hence wider canopies, there is no solid evidence that this trait changes the way that a variety should be managed. Thus we see little or no reason why some "thin-line" varieties should always be in narrow rows while some "bush-type" varieties are better suited to wider rows. The main reason early-planted soybean plants fail to form complete canopies is most often related to dry weather that causes reduced growth of stems, leaves, and petioles, not to differences in growth habit.

Double-Cropping Considerations

Double-cropped soybeans, planted following harvest of winter wheat in mid- to late June, can be successfully produced most years in southern parts of Illinois, and sometimes in central Illinois as well, though the percentage of time we can expect good yields drops when moving north from Interstate 70. This practice is more successful in southern Illinois both because wheat harvest and soybean planting are earlier there and because warmer weather in the fall, with later frost dates, means that the crop matures more often there.

Development of soybean plants that are planted so late is typically shortened, due to the early onset and completion of the flowering process in relation to vegetative stages; to dry weather after emergence that often limits growth; and because high temperatures, especially at night, speed development. This effect is often greater when the soybean seeds are planted into dry soil and need to wait for rain to bring them up. The ripening wheat crop extracts water from the upper soil and may leave it very dry at the time of wheat harvest and soybean planting. An exceptionally early frost in the fall can damage the crop, which typically needs all of an average growing season to reach maturity. Yield potential of double-cropped soybeans is typically 40% to 60% of that obtained with full-season soybean planted in May, but double-cropped soybean yields vary widely.

Based on the fact that late planting makes the available growing season so short, many believe that using shorter-maturity varieties makes sense. That is not the case: If a variety that is early for a location is planted very late, vegetative development prior to flowering is extremely limited, and plants will often end up very short, with incomplete canopies and low node and pod numbers even in narrow rows. Instead, the best varieties for double-cropping yields are those that are classified as midseason to full-season for the area. If wheat harvest is early and planting can be done by June 15 to 20, then use varieties at least as late as those planted at the normal time. If planting is delayed into July or is into dry soil so the crop won't come up quickly, it might be slightly less risky, from the standpoint of avoiding frost at the end of the season, to plant a variety that is about half a maturity group shorter (say MG 4.0 instead of 4.5).

Despite sound management of double-cropped soybeans, it is quite common for the weather to turn dry after the crop has started to grow and for yields to be low. In some cases yields are too low to even pay to harvest the crop. The use of glyphosate-resistant varieties, while adding expense for seed, has greatly improved the flexibility of the double-cropping system, by delaying expenditures for weed control until it's clear whether there is good potential for yield. When wheat yields are good and the soybean receives enough water to do well, double-cropping can be very profitable.

Replanting Soybean

Though we recognize the potential loss in yield when soybean stands are incomplete due to poor emergence or to injury after emergence, replanting guidelines are somewhat difficult to develop and to put into practice. In many cases, due to the fragility of soybean seed, emerged stands are so poor that the decision to replant is an easy one. The fact that the yield losses with planting delays are more gradual in soybean than in corn also makes it easier to decide to replant soybeans that have poor stands. For example, many people would replant without much questioning a field with half a stand if this could be done by the end of May or even early June, knowing both that the reduced stand probably would not have produced full yields and that the date of replanting is not so late that it will result in large yield losses. One advantage to having soybean planting typically later than corn planting, and into warmer soil, is that stand problems appear more quickly and can be dealt with quickly. Still, replanting costs time and money, and it should be done only if the need for it is clear.

The answer to when an original stand should be replanted is often obvious—for example, when heavy rainfall or standing water reduces stands to zero in parts of fields or to very low levels in entire fields. Where there are no plants left in low-lying areas but the rest of the field has adequate stands, only the damaged areas need be replanted. Where stands vary across the field from low to high, then "repair planting" can be done in the more damaged areas. Wide planters now in common use make it necessary to plant wide strips in order to fix small problem areas, so some "repair" plantings turn into replanting most or all of a field.

Soybean stand reduction is often related to non-uniform field conditions, including topography and soil type differences. But some fields have stands uniformly reduced over the entire field. Seed of marginal quality, planting using the wrong planter settings, and planting too deep or too shallow might cause this in some cases. Such stands require counting in various spots to get a good average and then to decide whether replanting will pay. The response curves shown in **Figure 3.6** can give some guidance on whether to replant a uniformly reduced stand. Stand reductions in this study were made by removing randomly chosen 1-foot segments of row, resulting in some gaps in the row. The highest yield produced by replanted soybeans (the bottom curve) was about 88% of that produced by full stands planted early. This yield was equivalent to the yield produced by about half of the original stand. If the original stand was very uneven, with a lot of longer gaps, then it took more of the original stand to justify keeping it and not replanting. As a general rule of thumb, gaps of 16 inches or less in 30-inch rows have minimal effect on yield, as long as the overall stand is adequate.

Even when it's clear that a soybean stand should be replanted, there can be questions about how the replanting should be done. In particular, should the original stand be destroyed using herbicide or tillage before replanting, or should the drill or planter be used to "repair plant" without destroying the initial stand? Should replanting be done in narrow rows if the original planting was in wider rows? **Table 3.1** gives the results of a study done at two Illinois locations over three years (2003–2005). Planting dates were early May for the initial planting and 3 to 4 weeks later for the replanting treatments. Original stands were established as either drilled or 30-inch rows, with both full stands and deficient stands produced by different seeding rates. Low initial stands were left or were replanted using either a drill or 30-inch rows without tilling to destroy the original stand, or with a drill after tilling the original stand.

Results show that replanting low initial stands of 50,000 or less per acre was justified, especially when the low stand was in 30-inch rows. As expected, full, early-planted stands produced the highest yield, and about 3 bushels per acre more than 30-inch rows. But how the replanting was done—using the drill or row planter, and with or without tilling the initial stand—made no difference in the final yield. Note that replanting 30-inch row soybeans produced about the same yield as the full, initial stand produced in 30-inch rows, meaning that the benefit of narrow rows nearly cancelled out the advantage of earlier planting.

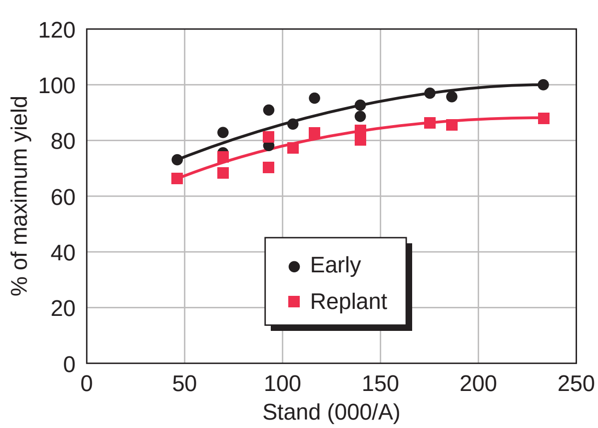

Figure 3.6. Response of early-planted and replanted soybeans to plant stand. Data from Gary Pepper, University of Illinois.

Table 3.1. Effect of replanting method on soybean stands and yields.

Original planting	Original stand	Replanted? (tillage/row spacing)	Final stand (000/A)	Yield (bu/A)
Drilled	High	Not replanted	171	58
Drilled	Low	Not replanted	54	50
30-in. rows	High	Not replanted	157	55
30-in. rows	Low	Not replanted	37	45
Drilled	Low	NT/drilled	163	54
Drilled	Low	NT/30-in. rows	161	53
30-in. rows	Low	NT/drilled	161	53
30-in. rows	Low	NT/30-in. rows	153	53
Drilled	Low	Tilled/drilled	183	54

Data are averaged over 3 years and two locations (Perry and DeKalb) and were generated by Mike Vose and Lyle Paul.

Specialty Types of Soybeans

There are several categories of specialty soybeans. Concerns over claims of health and environmental effects of genetically modified (GMO) varieties have translated into market demands in a number of countries and locales for non-GMO soybeans, mostly for processing into food. Other than requiring careful separation from soybeans carrying the gene for glyphosate resistance (e.g., Roundup Ready varieties) and some possible challenges in managing weeds without using glyphosate, many producers have the opportunity to help meet this demand. There are tests available that are often conducted at non-GMO soybean buying points to detect the presence of the glyphosate resistance gene, and loads with amounts above the limit (often 1%) of GMO presence are often prevented from entering the non-GMO market.

One concern is that the seed industry has concentrated its breeding efforts so much on GMO soybean that performance of non-GMO soybeans may not be keeping pace. Results available at the University of Illinois variety trial website (vt.cropsci.uiuc.edu/soybean.html) show that the number of conventional (non-GMO) varieties entered into the trials is much lower than the number of GMO entries and that, on average, non-GMO varieties have tended to yield less than the GMO varieties, especially in recent years. As with corn, seed companies have incentives to market GM varieties, and this may be showing up as lower performance of commercial non-GMO varieties.

There are a number of other different types of specialty soybeans produced to meet the needs of different markets. Tofu-type (clear hilum) soybeans are used for tofu production, with the colorless hilum desirable because small pieces of the seedcoat that might remain in the light-colored tofu product are not visible. Natto-type soybeans have very small seeds and are used in a fermented soybean food popular in some Asian countries, and in some cases for bean sprouts. High-oleic, low-linolenic, and low-saturated-fat soybeans are grown to produce edible oil considered to be better for health. More recently, trans fats, which are not found naturally but are produced when vegetable oil is hydrogenated to change its physical properties (for example, to produce margarine), have been identified as a serious threat to health, and their use is being banned in some places. Because saturated fats cannot be hydrogenated and so cannot form trans fats, there has also been some interest in high-saturated-fat soybean varieties. High-sucrose soybeans offer improved flavor and digestibility in foods such as soy milk, cheese, and meat analogs. Organic soybeans are in demand by consumers concerned about chemical inputs commonly used in soybean production.

High-Yield Soybeans

In 2007, Kip Cullers, a farmer in southwestern Missouri, produced soybeans that yielded more than 150 bushels per acre. This followed his yields of more than 130 bushels per acre in 2006, the first year he produced soybeans. These yields are much higher than any yields previously reported, and they are higher than many scientists believed to be likely from a physiological standpoint. Cullers's production practices include the use of poultry litter applied to the soil the previous fall, narrow or twin-row planting at populations above 250,000 seeds per acre, irrigation, nitrogen, micronutrient mixtures, plant growth hormones, and fungicide. The soil is well weathered but has good internal drainage and fair water-holding capacity.

A number of farmers and scientists have started work designed to duplicate conditions that produced such high yields. A study that we initiated at Urbana in 2008 produced the results given in **Table 3.2.** This was a relatively wet growing season, but August was dry, with only about an inch of rain. Irrigation increased yield by about 10%. Nitrogen fertilizer (90 lb N split into two applications) and foliar fungicide (applied twice) produced modest yield increases in irrigated soybeans, but micronutrients had no effect, and combining treatments did not give further yield increases. A similar study at Dixon Springs showed no response to irrigation or to any of a set of treatments similar to those used at Urbana. These are results from only one year, and this work will continue. But it clearly will not be easy to move yields up quickly through changes in management.

Table 3.2. Results from a "high-yield" trial with irrigation, nitrogen, fungicide, and micronutrients at Urbana, 2008.

Treatment	Irrigated (bu/ac)	Not irrigated (bu/ac)
Untreated	63	59
Nitrogen	71	59
Fungicide	68	59
Micronutrients	62	58
Nitrogen + fungicide	68	60
Nitrogen + fungicide + micronutrients	67	61
Average	66	59

4

Small Grains and Grain Sorghum

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Winter Wheat

Winter wheat is an important crop in Illinois, though its acreage in the state has recently been less than a tenth the acreage of corn. (Statewide yield trends for Illinois are shown in Figure 2.1, on p. 13.) The yield of wheat varies over years due to weather, but on a percentage basis this variability is no higher than for corn or soybean. Yields in recent years have been rising at the rate of 1.2 bushels per acre, or 2% to 3% per year. That is a faster rate, on a percentage basis, than the yield increases in corn over the same period.

Wheat grain is designated by marketing class, based on end uses for the wheat. Classes for most wheat include one of two kernel types (soft and hard) and one of two kernel colors (white and red). In addition, wheat can grow as winter wheat planted in the fall or as spring-planted wheat. These are not market classes, but nearly all spring wheat is in the hard wheat marketing class. Although all of these classes can be grown in Illinois, improved soft red winter wheat varieties are widely adapted in the state, and nearly all of Illinois wheat is of this type. The primary reasons for this are the better yields of soft red winter wheat and the sometimes-poor bread-making quality of hard wheat produced in our warm and humid climate. Because it may be difficult to find a market for hard wheat in many parts of Illinois, be sure to locate a market before planting hard wheat.

Wheat in the Cropping System

During the 1990s, wheat acreage in Illinois averaged about 1.4 million acres planted, with an average of about 1.2 million acres harvested. Since 2000, acreage has been below 1 million acres until recently; there were more than 1 million acres in 2007 and 2008. Because yields have continued to increase, the most likely explanation for the recent changes has been changing wheat prices, which have rebounded in recent years.

Most of the wheat acreage is in the southern half of the state, and a majority of the acreage south of I-70 is double-cropped with soybeans each year. Some of the crop in the northern part of the state is planted by livestock producers, who may harvest the straw as well as the grain and who often spread manure on the fields after wheat harvest. For those considering producing wheat, these points may help in making the decision:

1. State average yields have ranged from just under 50 to 67 bushels per acre over the past 10 years, with county average yields often correlated with average corn yields, reflecting the influence of soil productivity on both crops. Under very favorable spring weather conditions (i.e., dry weather in May and June), yields in some fields have exceeded 100 bushels per acre. As a rule of thumb, wheat yields average about a third those of corn, but they can be closer to half those of corn when weather is favorable for both crops. Because wheat's weather requirements differ from those of corn and soybeans, it helps spread weather risks.
2. Wheat costs less to produce than corn, but in most years gross and net incomes from wheat are likely to be less than for corn or soybeans. Added income from double-crop soybeans or from straw can improve the economic return from wheat. Wheat also provides income in midsummer, several months before corn and soybean income.
3. Wheat is one of the best annual crops in Illinois for erosion control because it is in the field for some 8-1/2 to 9 months of the year and is well established during heavy

spring rainfall. Wheat can also serve to break crop rotations that would otherwise lead to buildups in diseases or insects in corn and soybean. Some rotation research in western Illinois (see Chapter 5, "Cropping Systems") has shown that both corn and soybean yields benefit to a small extent when wheat is included in the rotation.

4. Wheat crop abandonment is higher than for other crops, but wheat acres not harvested can be planted to spring-seeded crops, usually at their optimal planting times.

Plant Development

Winter wheat typically emerges about a week after planting in the fall and grows mostly by forming tillers as the weather cools in late fall, reaching a height of only 3 to 4 inches. The growing point, or tip of the stem, remains underground through the dormant period. Growth resumes as air and soils warm in the spring, and growth becomes upright, followed by *jointing*, the point at which nodes of the stem start to become visible as the stem length increases. As the stem elongates, the developing head at the tip of the stem eventually emerges, flowering takes place, and grain fills. Growth stages in wheat are often described using a system known as the Feekes scale, illustrated in **Figure 4.1**. Some labels for inputs such as herbicides indicate at what Feekes stage the product should be applied.

Variety Selection

There has been considerable genetic improvement in wheat yield potential and standability in the past few decades, through efforts by both university and private breeders. The University of Illinois variety testing program in the Department of Crop Sciences annually tests dozens of varieties, with results available by mid-July each year at the website vt.cropsci.illinois.edu. Tests are grouped into two regions, one for northern Illinois and one for southern Illinois, each with three locations. Yield data are the most important, and height and test weight data are included as well. Test weight is an important grain quality indicator for wheat, and low test weight can result in lower prices paid for the crop. The main reason for low test weight is the presence of diseases, such as Fusarium head scab, that result in light kernels and lower kernel density.

There are occasional questions about the feasibility of producing wheat types other than soft red winter wheat in Illinois. Hard wheat classes, including hard red and hard white winter wheat, will grow well and produce good yields in Illinois, but they usually don't yield as well as soft wheat varieties and don't have the high quality needed to earn maximum price premiums over soft red wheat. Soft white wheat varieties also do well in Illinois, but the market for soft white wheat is limited, in part because soft white wheat grows so well in the Pacific Northwest and is exported from there. There is likely to be no premium for growing this type of wheat in Illinois, so there's no advantage to growing it unless a niche market can be located or developed.

Wheat producers who get a large part of their income from the crop by selling straw often choose varieties based on

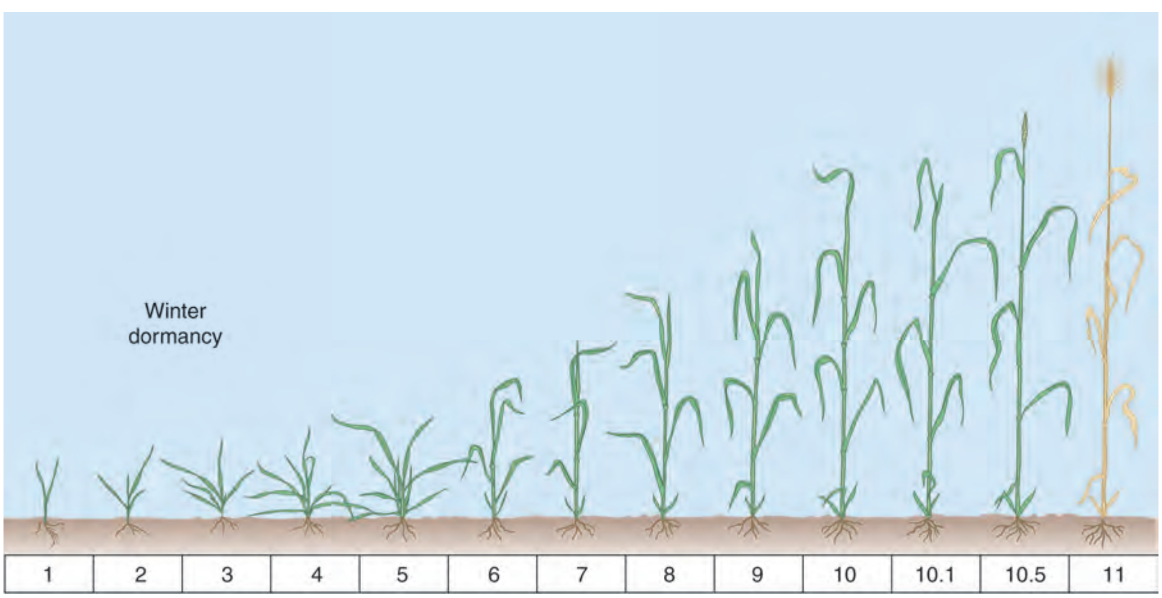

Figure 4.1. Growth stages of wheat, with Feekes' growth stage numbers indicated. Stages 1 through 3 are vegetative stages; 4 and 5 mark the start of stem growth; 6 and 7 are the "jointing" stages; 8 and 9 mark the appearance and full emergence of the flag (uppermost) leaf. Stage 10 is full "boot" stage just before head emergence, and stages 10.1 through 11 mark head emergence, flowering, and grain development through maturity.

their straw yield as much as on grain yield. In a study we did at DeKalb, we found that straw yield was affected both by plant height and by yield. The formula to predict straw yield based on height and grain yield was as follows:

Straw yield (tons per acre) = 0.018 × grain yield (bushels per acre) + 0.09 × height (inches) – 2.23

So a crop that produces 85 bushels per acre and is 35 inches tall before harvest might be expected to produce 2.45 tons of dry straw per acre (0.018 × 85 + 0.09 × 35 – 2.23). This worked well for the varieties we used in this trial, but it could be less accurate for other varieties. The important points are that higher-yielding varieties tend to have more heads per acre and so more straw and that height alone is not the best way to choose varieties, whether for grain or straw production.

Seeding Date

Hessian fly is a pest of wheat that lays its eggs in young plants in the fall; its pupae overwinter, and larvae of the next generation cause damage in the spring. Scientists found many years ago that waiting to plant wheat until after the adults of the fly died was an effective management technique. There is now genetic resistance to this pest in some wheat varieties, but the "Hessian fly-free date" was found to be a good time to plant wheat from an agronomic standpoint as well. The best time to plant wheat is the one that allows the crop to emerge and to grow for several weeks before low temperature brings on dormancy, but not so early that the crop makes excessive growth. The ranges of Hessian fly-free dates for different areas of Illinois are shown in **Figure 4.2**.

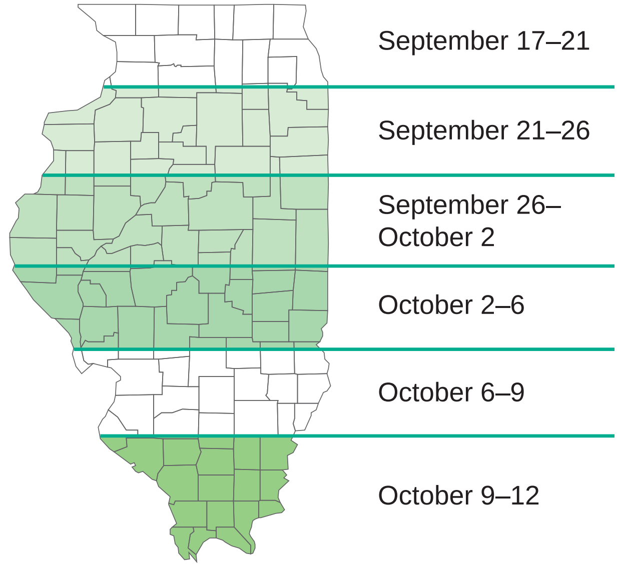

Figure 4.2. Ranges of Hessian fly-free dates in Illinois.

Wheat planted on or after the fly-free date is unlikely to be damaged by the Hessian fly, but a more important reason not to plant too early is that aphids that can carry barley yellow dwarf virus (BYDV) are much more likely to move into early-planted wheat. A crop planted at the correct time will also be less subject to damage in the fall from diseases such as Septoria leaf spot, which are favored by the excessive fall growth usually associated with too-early planting. Because the aphids that carry BYDV and the mites that carry the wheat streak mosaic virus are killed by freezing temperatures, the effects of the viruses will be less severe if wheat is planted a few weeks before the first killing freeze. Finally, wheat planted on or after the fly-free date will probably suffer less from soilborne mosaic; many varieties of soft red winter wheat carry resistance to this disease, but some show symptoms if severely infested.

Decreases in yield as planting is delayed past the fly-free date vary considerably over years and locations. In southern Illinois, the previous corn or soybean crop might be harvested several weeks before the optimum wheat planting time, and planting wheat too early is a more common mistake than planting too late. Fall aphid flights and volunteer wheat that serves as a reservoir for viral disease are more common in southern Illinois, and they add to the danger of yield loss if wheat is planted too early. Studies have shown that yields often decline little with planting delays for the first 10 days after the fly-free date. From 10 to 20 days late, yields decline at the rate of 1/2 to 1 bushel a day. The loss accelerates to 1 to 2 bushels a day from 20 to 30 days late, with sharper declines in the northern part of the state. Wheat planted a month after the fly-free date typically yields 2/3 to 3/4 of normal, and this is considered about the latest practical date to plant wheat.

Planting date has a major effect on the winter survivability of the wheat plant. It is best if the plant can grow to about the 3-leaf stage and form two or three tillers. Such plants should provide good ground cover by mid- to late November, when growth slows due to cold temperatures and dormancy sets in. Wheat may survive the winter even if planted so late that it fails to emerge in the fall, but reduced tillering and marginal winterhardiness often result in yield decreases, unless weather during the winter and spring is unusually benign.

By the time the plant reaches this growth stage, it has stored some sugars in the crown (lower stem). These sugars act as antifreeze, allowing the crown and new buds to survive soil temperatures at the crown depth down to 15 °F or so. Snow cover is very valuable, as it insulates the soil and keeps temperatures at this depth (about 1 inch) from falling this low. Late-planted wheat does not have time to produce and store as much sugar before soils freeze, while early planting tends to result in rapid plant growth with less storage of sugars. Freeze–thaw cycles during the winter tend to use up stored sugars, thereby decreasing winter-hardiness. Varieties also differ in the ability to survive low temperatures, but many of the higher-yielding varieties begin growth early in the spring, and this trait tends to be associated with less winter-hardiness.

Some are concerned that late-planted wheat or a crop that experiences a mild winter may not grow normally and produce grain in the spring. Winter annuals such as winter wheat usually require *vernalization*, which is a period of low temperatures during which biochemical changes in the plant make it able to elongate its stem and produce a head when the weather warms in the spring. This is how the crop avoids starting to head out in the fall if planted early or when the fall is unusually warm. Wheat needs temperatures down to only about 35 to 40 °F, and for only a few weeks after the seed takes on water, to undergo vernalization. This explains why even wheat planted so late that it fails to emerge in the fall almost always produces grain in the spring.

Seeding Rate

While seeding rate recommendations for wheat have typically been expressed as pounds of seed per acre, differences in seed weight means that rate in pounds does not translate well to number of seeds per acre. Research in Illinois has measured yields in response to varying the seeding from 20 to 50 seeds per square foot. Results given in **Figure 4.3** show that highest yields required seeding rates of 35 to 40 seeds per square foot, or about 1.5 to 1.7 million seeds per acre. This is somewhat higher than previous work has shown, due in part to a late spring freeze in 2007 that reduced the per-plant yield. Fewer seeds will be adequate in some years, but planting 1.5 million seeds is a reasonable goal if planting on time. If there are 15,000 seeds per pound, then 100 pounds of seed contain 1.5 million seeds.

Seed size in wheat varies by variety and by weather during seed production but usually ranges from about 10,000 to 17,000 seeds per pound. **Table 4.1** converts seed rates per square foot to those per acre and per linear foot of row in

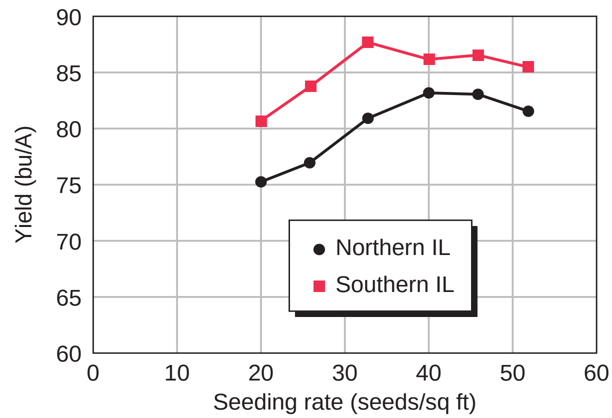

Figure 4.3. Response to seeding rate trials in northern and southern Illinois, 2007–2008.

7.5-inch rows. These numbers are useful for calibrating a drill. Many seed containers now list the number of seeds per pound for that seed lot. If not, you may estimate that large seed has 11,000 to 13,000 seeds per pound, medium 14,000 to 16,000 seeds per pound, and small 17,000 to 18,000 seeds per pound. **Table 4.1** gives the pounds of seed per acre needed for various seed sizes. The seed drop calculator at iah.ipm.illinois.edu/seed_drop_calculator will help with calculating seed rate and calibrating drills. Use the table to convert seeding rates from number per square foot to number per acre or per foot of row, and amount of seed needed to plant one acre at different rates and with different seed sizes.

A stand of 30 to 35 plants per square foot is generally considered optimal, and a minimum of 15 to 20 healthy plants per square foot is needed to justify keeping a field in the spring. If plants are weakened by winter weather and tiller numbers are low, then even 20 or 25 plants per square foot might not maximize yield. If in doubt, wait and count tillers. By jointing, wheat needs 40 to 50 fertile (head-bearing) tillers per square foot to ensure high yield potential.

If planting is delayed much past the fly-free date, then fall growth and spring tillering are likely to be reduced. To

Table 4.1. Conversion factors related to seeding rates for wheat.

Seeds/ sq ft	Seeds/A (millions)	Seeds/ft of 7.5-in. row	Lb of seed needed per acre: 10,000 seeds/lb	12,000 seeds/lb	14,000 seeds/lb	16,000 seeds/lb	18,000 seeds/lb
20	0.87	13	87	73	62	54	48
25	1.09	16	109	91	78	68	61
30	1.31	19	131	109	93	82	73
35	1.52	22	152	127	109	95	85
40	1.74	25	174	145	124	109	97
45	1.96	28	196	163	140	123	109

compensate, the seeding rate should be increased by 10% for each week of delay in planting, starting two weeks after the fly-free date.

Seed Treatment

Treating wheat seeds with the proper fungicide or mixture of fungicides is an inexpensive way to help ensure improved stands and better seed quality. Under conditions that favor the development of seedling diseases, the yield from treated seed may be 3 to 5 bushels higher than that from untreated seed. See Chapter 14, "Disease Management for Field Crops," for more information.

Seed treatment insecticides have been approved for use in wheat, and their use has become more common in recent years. The major benefit provided by seed treatment insecticide is control of aphids, especially those that fly into the crop in the fall. Controlling aphids provides control of BYDV, and yield increases of more than 10 bushels per acre have been found in trials where BYDV is a serious problem. In a series of studies from 2004 through 2008, insecticide used on wheat seed in southern Illinois trials increased yield by about 6 bushels per acre, while in northern Illinois this increase was only 1.7 bushels. Seed treatment insecticide should be used only if the cost of treatment is less than the value of the additional yield produced; using this input is much more likely to be profitable in southern than in northern Illinois. Early-planted wheat is more likely to have aphids move in, and thus is more likely to benefit from seed treatment insecticide than will late-planted wheat. Whether volunteer wheat is present in the area will also affect how much disease aphids might carry, but there are some other sources of disease inoculum besides wheat.

Tillage and Previous Crop

Wheat requires good seed-to-soil contact and moderate soil moisture for germination and emergence. Generally, one or two trips with a disk harrow or soil finisher will produce an adequate seedbed if the soil is not too wet. It is better to wait until the soil dries sufficiently before preparing it for wheat, even if that means planting is delayed.

While some producers prefer to use tillage to prepare a seedbed and to improve seed-to-soil contact for wheat, others have had good success drilling wheat without tillage. This approach requires adequate weight and covering mechanisms on the drill. Other considerations for no-tilling wheat include the following: residue from the previous crop must be spread uniformly to prevent seed placement problems; without tillage to destroy emerging weeds, herbicides may need to be considered in the fall; seed rates should be on the high side of the range used for wheat; and corn residue should be allowed to dry in the morning before drilling to prevent its being pushed down into the seed furrow and reducing uniformity of seed placement.

Table 4.2 shows the results from two long-term studies in western Illinois where different rotations (corn-soybean-wheat and soybean-corn-wheat) have been grown with or without tillage for a number of years. Compared to tilled plots, yields following no-till are slightly higher at Perry, where soils are lighter, but they are somewhat lower at Monmouth. Because no-till typically has lower costs than tillage systems, no-till might be cost-effective even with slightly lower yields. No-till may also result in less soil erosion than tillage, and untilled soils may experience less saturation with heavy rainfall. No-till wheat can suffer from lower stands associated with wheel traffic. This emphasizes the need to do whatever is needed for good seed placement and uniform emergence, regardless of the tillage system used.

Results in **Table 4.2** also indicate that yields at Monmouth were 3 to 4 bushels higher following soybean than following corn. There was no such difference at Perry. One concern is that corn residue from the previous crop can provide inoculum of diseases such as Fusarium head scab, especially when wheat is no-tilled. While this may have been a factor in these studies, tilled fields and wheat following soybean have also suffered from diseases when conditions are favorable for disease development. So tillage and previous crop are not the deciding factors in how much disease develops in most cases. Getting uniform seed placement and good stands is often more important than disease potential when considering previous crop and tillage.

Depth of Seeding

Wheat should not be planted deeper than 1 to 1-1/2 inches. A good seed drill is by far the best implement for placing seed at the right depth, and nearly all wheat acres are planted using a drill. Using a fertilizer spreader to seed wheat was once more common, but given high costs of seed and the variable success with broadcast seeding, this practice is not recommended. If it is done, success will be

Table 4.2. Previous crop and tillage effects on wheat yields in two Illinois locations.

Location	Previous crop	Tillage for wheat (bu/A)	
		Tilled	No-till
Perry	Soybean	77.9	79.8
	Corn	78.5	77.1
Monmouth	Soybean	86.0	80.2
	Corn	82.6	78.9

Data are from 3-year rotations with corn, soybean, and wheat and are averages over 6 years (2002–2007).

"Intensive" Wheat Management

Reports of very high wheat yields in northern Europe have increased interest in application of similar "intensive" management practice in the United States. Such practices have included narrow row spacing (4 to 5 inches); high seeding rates (45 to 50 seeds per square foot); high nitrogen rates, split into three or more applications; and routine use of foliar fungicides for disease control and plant growth regulators to reduce height and lodging. Interest in such practices in Illinois was high in the 1980s, and it has increased again following high yields in some areas in some years.

From research conducted in Illinois, it has become apparent that responses to these inputs are much less predictable in Illinois than in Europe, primarily because of the very different climatic conditions. Following is a summary of research findings to date:

1. Research in Indiana and other states shows that the response to rows narrower than 7 or 8 inches is quite erratic, with little evidence to suggest that the narrow rows will pay added equipment costs.

2. Seeding rates of 30 to 40 seeds per square foot generally produce maximum yields.

3. Increasing nitrogen beyond the recommended rates of up to 130 to 140 pounds per acre has not routinely increased yields. Splitting spring nitrogen into two or more applications has not increased yields in most cases, but it may do so if very wet weather after nitrogen application results in loss of nitrogen.

4. Although foliar fungicides are useful if diseases are found, routine use has resulted in yield increases of only 3 to 5 bushels per acre and is not always economically justified, unless disease levels are high.

5. Growth regulators are not needed to prevent lodging in modern varieties.

More recently, less intensive management packages have been promoted for higher yield and better grain quality. Some of these use tiller counting in the spring, and they tie nitrogen management to tiller counts. Foliar fungicides may also be used. While they are more likely to "work" than the European system described, these practices do not always increase yield or grain quality.

better using an air-flow fertilizer spreader for better distribution. Light tillage to incorporate the seed and to improve seed-to-soil contact may be needed, but it is often not very effective, especially if wide equipment is used that provides uneven tillage across its width. Plants that grow from shallow-placed seeds do not have as much winter-hardiness as deeper-seeded plants due to their shallow crown depth.

Row Spacing

Research on row spacing generally shows little advantage for planting wheat in rows that are less than 7 or 8 inches apart. Yield is usually reduced by wider rows, with a reduction of 1 to 2 bushels in 10-inch rows and 5 to 8 bushels in 15-inch rows. Wisconsin data show greater yield reductions in 10-inch rows, probably due to slower early growth than is common in Illinois.

Wheat Management for Best Yields in Illinois

Despite our best efforts at managing wheat, harsh winter weather, a spring freeze, or wet weather in the spring can spell disaster for the crop, and there may be little that can be done to maintain good yields. To help ensure good yields when the weather is favorable, follow these steps:

1. Choose several top varieties.
2. Apply some nitrogen and necessary phosphorus fertilizer before planting: 18-46-0 provides both nutrients.
3. Drill the seed on or near the fly-free date, using 35 to 40 seeds per square foot of good-quality seed.
4. Topdress additional nitrogen at the appropriate rate in late winter or early spring, at about the time the crop breaks dormancy and begins to green up and grow. Application to frozen soil is often done to avoid application to muddy fields. This may be unavoidable, but chances of loss are higher than when N is applied after growth resumes.
5. Scout for weeds, insects, and diseases beginning in early spring; treat for control only if necessary. Fall herbicide application, especially in no-till where weeds emerge soon after planting, might be helpful in some fields.
6. Hope for dry weather during the spring, especially during the time of heading and into the grain-filling period.

Double-Cropping and Intercropping

Much of the wheat in the southern half of Illinois is double-cropped with soybeans, and a small portion of wheat acreage is double-cropped with other crops, such as sunflower and grain sorghum. The following are a few management considerations for this cropping sequence:

1. To ensure that wheat will be harvestable as early as possible, choose a midseason or earlier wheat variety. There is not as much range in wheat maturity among available varieties as many people believe; in variety trials, the different varieties generally reach combine ripeness within the space of 3 to 4 days. Ironically, some of the more disease-resistant varieties stay green longer, and thus mature later, due to healthy leaves rather than to bred-in late maturity. Variety developers usually designate maturity according to time of flowering, which does not correspond exactly to time of harvest. We have also observed that varieties that flower 3 or 4 days earlier than average tend to yield less. It seems, therefore, that the best varieties should be chosen based on yield, only making sure that they do not mature later than average.
2. Plant wheat on time. A common rule of thumb is that for every 3 days of delay in planting time, harvest is delayed by 1 day. Do not, however, plant more than a few days earlier than the Hessian fly-free date.
3. Avoid excessive nitrogen application. Too much nitrogen can delay maturity and contribute to lodging, both of which make double-cropping more difficult.
4. Harvest as soon after combine-ripeness as the weather permits. Some producers successfully harvest at grain moisture contents up to 20%, taking care not to damage kernels. A few producers have stripper-headers that remove the grain without cutting plants, making early harvest easier. If the weather is dry and warm, "early" harvest may be only 2 to 4 days earlier than usual, but this can sometimes provide enough time to plant the double crop before wet weather sets in. Wheat at these moisture contents can usually be dried using unheated air, but watch stored grain carefully to make sure it is drying. If the weather is wet or cooler than normal, it may be necessary to raise the air temperature by 10 or 15 degrees to get the crop to dry without the grain heating up.
5. If straw is not harvested, it should be chopped and spread evenly to minimize interference with planting.

There continues to be some interest in a system called *relay intercropping*, in which wheat is typically planted in rows 14 or 15 inches apart and soybean seed is then planted between these rows before the wheat crop is harvested. Relay intercropping was developed during the 1970s but has never been widely used in Illinois. A polymer seed coating marketed to delay water uptake and germination of soybean seeds, thus allowing them to be planted between wheat rows earlier than uncoated seed could be, has not worked very well. Soybeans planted too early in this system grow up through the wheat, and these plants both interfere with wheat harvest and yield less if their tops are cut off when wheat is combined.

Relay intercropping is not in wide use, and the fact that most of the wheat in Illinois is grown where double-cropping is common will probably limit its adoption. Wheat yields in wide rows are reduced, weed control is an issue, and soils under a wheat crop are often very dry, limiting emergence and growth of soybean. The presence of the soybean crop may rule out straw harvest and manure application. It is possible to use uncoated seed and to plant after heading, but this can damage wheat yields even more. When it is wet in June and soybean grows up through the wheat crop, wheat cannot be harvested without damage to the soybean crop. In summary, Illinois producers need to be cautious when considering the relay-intercropping system. Some producers in Indiana and Ohio use it, but unlike Illinois, both of those states have considerable acreages of wheat on heavier soils in their northern areas, where double-cropping cannot normally be done successfully.

Spring Wheat

Spring wheat is not well adapted to Illinois. Because it matures more than 2 weeks later than winter wheat, it is in the process of filling kernels during the hot weather typical of late June and the first half of July. Consequently, yields average only about 50% to 60% of those of winter wheat. Livestock producers sometimes inquire about producing spring wheat if winter wheat could not be planted or if it was winter-killed, especially if straw production is a major reason for growing wheat. Straw yield of spring wheat is likely to be closer to that of winter wheat than is grain yield, but spring oats will often produce as much straw as spring wheat and will often produce more income from grain.

All available spring wheat varieties are of the hard wheat type, meaning that usefulness for breadmaking is an important quality (and price) consideration. Besides yield challenges for spring wheat in Illinois, getting price premiums based on high protein is unlikely in our soils and climate. Niche markets for hard wheat may exist, but in most cases the need for good-quality hard wheat is met by bringing wheat from drier areas such as the Great Plains or Canadian prairies.

With the exception of planting time, production practices for spring wheat are similar to those for winter wheat. Because of the lower yield potential, nitrogen rates should be 20 to 30 pounds less than those for winter wheat. Spring wheat should be planted in early spring—as soon as a seedbed can be prepared, at about the same time as spring oats is planted. If planting is delayed beyond mid-April, yields are likely to be low, and another crop should be considered.

Very little spring wheat is grown in Illinois, and there has been little recent testing of spring wheat varieties. Most spring wheat varieties that may grow reasonably well in Illinois were bred in Minnesota or other northern states, and so there is some risk when they are grown here. There are no varieties known to be clearly superior for either yield or quality when grown in Illinois, but those used widely in Minnesota are likely the best choices for growing in northern Illinois.

Rye

Both winter and spring varieties of rye are available, but only the winter type is suitable as a grain crop in Illinois. Winter rye is often used as a cover crop to prevent wind erosion of sandy soils. The crop is very winter-hardy, grows late into the fall, and is quite tolerant of drought. Rye generally matures 1 or 2 weeks before wheat. The major drawbacks to raising rye are the low yield potential and the very limited market. Rye is less desirable than other small grains as a feed grain.

The cultural practices for rye are similar to those for winter wheat. Planting can be somewhat earlier, and the nitrogen rate should be 20 to 30 pounds less than for wheat because of lower yield potential. Watch for shattering as grain nears maturity. Watch also for the ergot fungus, which replaces grains in the head and is poisonous to livestock. Ergot can develop when the weather is wet at heading.

There has been very little development of varieties specifically for the Corn Belt, and no formal yield testing has been done recently in Illinois. Much of the rye seed available in Illinois is simply called common rye; some of this probably descended from Balbo, a variety released in 1933 and widely grown many years ago in Illinois. More recently developed varieties that may do reasonably well in Illinois include Hancock, released by Wisconsin in 1979, and Rymin, released by Minnesota in 1973. Spooner is another Wisconsin variety that may be suitable.

Triticale

Triticale is a crop that resulted from the crossing of wheat and rye in the 1800s. The varieties currently available are not well adapted to Illinois and are usually deficient in some characteristic such as winter-hardiness, seed set, or seed quality. In addition, they are of feed quality only. They do not possess the milling and baking qualities needed for use in food products, though there are still some efforts underway to improve grain quality for this purpose.

Cultural practices for triticale are much the same as those for wheat and rye. The crop should be planted on time to help winter survival. As with rye, the nitrogen rate should be reduced to reflect the lower yield potential. With essentially no commercial market for triticale, growers should make certain they have a use for the crop before growing it. Generally when triticale is fed to livestock, it must be blended with other feed grains. Triticale is also used as a forage crop. The crop should be cut in the milk stage when it is harvested for forage.

A limited testing program at Urbana indicates that the crop is generally lower yielding than winter wheat and spring oats. Both spring and winter types of triticale are available, but only the winter type is suitable for Illinois. Caution must be used in selecting a variety because most winter varieties available are adapted to the South and may not be winter-hardy in Illinois. Yields of breeding lines tested at Urbana have generally ranged from 30 to 70 bushels per acre.

Spelt

Spelt is a very old type of wheat that was grown thousands of years ago. It has recently gotten some attention as a more nutritionally complete grain in comparison to regular wheat. It is grown like winter wheat and tends to be quite winter-hardy. It is used as livestock feed and is processed into food products. As in oats, the hull of spelt remains attached until the grain is processed for food. One advantage spelt has over wheat is that it will grow in a wider range of soil conditions, including droughty or wet soils. Yields are not likely to be as high as those of wheat, and the crop can suffer from a number of diseases. Niche markets for organic spelt exist in some places, and there are some small variety improvement programs underway.

Oats

Spring oats were once grown on more than 3 million acres in Illinois, primarily for use as horse and pig feed. In recent years less than 100,000 acres of oats has been grown in Illinois, and some of that is seeded with a legume to provide some cover during slow early growth of the legume, then is harvested as forage.

Even though oats has become a small-acreage crop in Illinois, the University of Illinois continues to develop varieties, which unlike wheat are still sold as public varieties. Oat yields in Illinois trials are reported along with wheat yields at the website vt.cropsci.illinois.edu/wheat.html. Test weight is an important grain quality trait for oats, especially for sale as horse feed. For processing into food products such as oatmeal, groat percentage—the percentage of hulled kernel compared to unhulled seed—may be more important than test weight.

To obtain high yields of spring oats, plant the crop as soon as you can prepare a seedbed. Yield reductions become quite severe if planting is delayed beyond April 1 in central Illinois and beyond April 15 in northern Illinois. After May 1, another crop should be considered unless the oats are being used as a companion crop for forage crop establishment and yield of the oats is not important.

When planting oats after corn, it is often desirable to disk the stalks; plowing may produce higher yields but is usually impractical. When planting oats after soybeans, disking is usually the only preparation needed, and it may be unnecessary if the soybean residue is evenly distributed. Make certain that the labels of the herbicides used on the previous crop allow oats to be planted; oats are quite sensitive to a number of common herbicides.

Before planting, treat the seed with a fungicide or a combination of fungicides. Seed treatment protects the seed during the germination process from seed- and soilborne fungi. (See Chapter 14 on disease management.)

Oats may be broadcast and disked in but will yield 7 to 10 bushels more per acre if drilled. When drilling, plant at a rate of 2 to 3 bushels (64 to 96 lb) per acre. If the oats are broadcast and disked in, increase the rate by 1/2 to 1 bushel per acre. As a companion seeding with forage legumes, use only 1 to 1-1/2 bushels per acre.

For suggestions on fertilizing oats, see Chapters 8 and 9.

Winter oats are not nearly as winter-hardy as wheat and are likely to survive mild winters only in the southern third or quarter of the state; U.S. Highway 50 is about the northern limit for winter oats. Because winter oats are not attacked by Hessian fly, planting in early September is highly desirable. Barley yellow dwarf virus may, however, infect early-planted winter oats, since the crop attracts aphids. Using seed-applied insecticide should provide protection against this insect and the disease it carries. The same type of seedbed is needed for winter oats as for winter wheat. The fertility program should be similar to that for spring oats. Seeding rate is 2 to 3 bushels per acre when drilled.

Development of winter oat varieties has virtually stopped in the Midwest because of the frequency of winter kill. Of the older varieties, Norline, Compact, and Walken are sufficiently hardy to survive some winters in the southern third of the state. All of these varieties were released more than 20 years ago. Walken has the best lodging resistance of the three.

Barley

Spring barley is damaged by hot, dry weather and so is adapted only to the northern part of Illinois. Good yields are possible, especially if the crop is planted in March or early April, but yields tend to be erratic. Markets for malting barley are not established in Illinois, and malting quality may be a problem. Barley can, however, be fed to livestock.

Plant spring barley early—about the same time as spring oats. Drill 2 bushels (96 lb) of seed per acre. To avoid excessive lodging, harvest the crop as soon as it is ripe. Fertility requirements for spring barley are essentially the same as for spring oats.

The situation with spring barley varieties is similar to that for spring wheat: most varieties originate in Minnesota or North Dakota and have not been widely tested or grown for seed in Illinois. Some of these varieties are Azure, Hazen, Manker, Morex, Norbert, Robust, and Excel. Seed for any of these will likely need to be brought in from Minnesota or the Dakotas.

Winter barley is not as winter-hardy as the commonly grown varieties of winter wheat and should be considered only in the southern third or so of Illinois. It is used almost exclusively as animal feed, and acreage in Illinois is very low.

Winter barley should be planted 1 to 2 weeks earlier than winter wheat. Sow with a drill and plant 2 bushels of seed per acre. Fertility requirements for winter barley are similar to those for winter wheat except that less nitrogen is required. Most winter barley varieties are less resistant to lodging than are winter wheat varieties. Winter barley cannot stand “wet feet,” and the crop should not be planted on land that tends to stay wet. The barley yellow dwarf virus is a serious threat to winter barley production.

There is no known commercial production of winter barley seed in Illinois, but a few newer varieties are bred and produced in states like Pennsylvania and Virginia. Pennco and Wysor are two varieties released in the 1980s, and they may survive the winter in southern Illinois.

Grain Sorghum

Although grain sorghum can be grown throughout Illinois, its greatest potential, in comparison with other crops, is in the southern third of the state. It is adapted to almost all soils, from sand to heavy clay. Its greatest advantage over corn is tolerance of moisture extremes. Grain sorghum usually yields more than corn when moisture is in short supply, but under better growing conditions it usually yields less than corn. Grain sorghum is also less affected by late planting and high temperatures during the growing season, but the crop is very sensitive to cool weather and will be killed by even light frost.

Although few side-by-side comparisons of corn and grain sorghum in southern Illinois are available, hybrid trials that were for some years conducted annually in southern Illinois offer some indication of relative yields. Averaged across six such trials, corn yielded about 40 bushels per acre more than grain sorghum, and much more than this when corn yields were high, as they have been in most years recently. In general, grain sorghum tends to yield more than corn only in fields where corn yields less than 100 bushels per acre. At the same time, average yields of grain sorghum in Illinois have been only 90 bushels per acre over the last decade and have exceeded 100 bushels only twice. In contrast, corn yields have averaged more than 150 bushels over the same period, and they have almost always exceeded grain sorghum yields, even in the same county.

It is common in many areas of the U.S. to refer to grain sorghum as "milo." Both are the same crop species, and "milo" technically refers to nonhybrid, more or less unimproved grain sorghum, grown for hundreds of years as a food crop, first in Africa, where it originated. In practice, the term *milo* is used interchangeably with *grain sorghum*. The term "sorghum" is also used to refer to sweet sorghum, used to make molasses, and to forage types of this crop, while milo refers to a crop grown for grain.

Fertilization. In general, phosphorus and potassium requirements of grain sorghum are similar to those for corn. The response to nitrogen is somewhat erratic, due largely to the extensive root system's efficiency in taking up soil nutrients. For this reason, and because of the lower yield potential, the maximum rate of nitrogen suggested is about 125 pounds per acre. For sorghum following a legume, such as soybean or clover, this rate may be reduced by 20 to 40 pounds.

Hybrids. The criteria for selecting grain sorghum hybrids are similar to those for selecting corn hybrids. Yields, maturity, standability, and disease resistance are all important. Consideration should also be given to the market class (endosperm color) and bird resistance, which may be associated with palatability to livestock. Performance tests of commercial grain sorghum hybrids are no longer conducted by the University of Illinois, so data need to come from seed companies. Much of their testing is done in states west of (and drier than) Illinois. Because of the limited acreage of grain sorghum in the eastern United States, most hybrids are developed for the Great Plains, and most have not been extensively tested under midwestern conditions. Illinois is farther north than most grain sorghum in the U.S., and so earlier-maturing hybrids tend to do better than later ones. Maturity of hybrids is expressed in days, but unlike corn, this refers to days to flowering, not days to maturity. So a "60-day" sorghum hybrid is not early, but rather midseason or even on the late side.

Planting. Sorghum should not be planted until soil temperature reaches 65 °F. In the southern half of the state, mid-May is considered the earliest practical planting date, while in northern Illinois planting should typically start only in late May. Such late planting, along with a shorter, cooler growing season, means that grain sorghum hybrids used in northern Illinois must be early maturing in order to mature before frost.

Sorghum usually emerges more slowly than corn and requires relatively good seed-to-soil contact. Planting depth should not exceed 1-1/2 inches, and about 1 inch is considered best. Because sorghum seedlings are slow to emerge, growers should use care when using reduced-till or no-till planting methods. Surface residue usually keeps the soil cooler and may harbor insects that can attack the crop, causing serious stand losses, especially when the crop is planted early in the season.

Row spacing. Row-spacing experiments have shown that narrow rows may produce more than wide rows, especially in dry years when plant growth is limited. Drilling in 7- to 10-inch rows works well if weeds can be controlled without cultivation, but if weed problems are expected, wider rows that will allow cultivation may be a better choice. Using a split-row planter to plant 15-inch rows is a good practice, providing weeds can be controlled.

Plant population. Because grain sorghum seed is small and some planters do not handle it well, this crop was historically planted based on pounds of seed per acre rather than number of seeds. This often resulted in overly dense plant populations that can cause lodging and yield loss. Aim for a plant stand of 50,000 to 100,000 plants per acre, with lower populations on droughtier soils. This is about 3 to 6 plants per foot of row in 30-inch rows at harvest and 2 to 4 plants per foot in 20-inch rows. Plant 30% to 50% more seeds than the intended stand, especially if planting early into cooler soils. Sorghum may also be drilled using 6 to 8 pounds of seed per acre if the drill cannot be calibrated more closely than this. Avoid excessive seed rates; plant stands when drilled should not be much higher than those in rows. Grain sorghum tillers extensively when plant populations are low. This increases yields, but tiller heads mature later, and it is usually better to have most of the harvested heads be primary heads, not tiller heads. Getting a uniform stand at high enough population is the way to reduce tiller formation.

Weed control. Because emergence and early growth of sorghum are slow, controlling weeds presents special problems. Suggestions for chemical control of weeds are given in Chapter 12. As with corn, a rotary hoe may be useful after the crop is rooted but before weeds become established.

Harvesting and storage. Timely harvest is important. Rainy weather after sorghum grain reaches physiological maturity may cause sprouting in the head, weathering (soft and mealy grain), or both. Harvest may begin when grain moisture is 20% or greater, if drying facilities are available. Sorghum often dries slowly in the field. Because sorghum plants do not die until frost, using a desiccant can reduce the amount of green plant material going through the combine, making harvest easier.

Marketing. Before planting, check on local markets. Because the acreage in Illinois is limited, many elevators do not buy grain sorghum.

Grazing. After harvest, sorghum stubble may be used for pasture. Livestock should not be allowed to graze for one week after frost because the danger is especially high for poisoning from prussic acid (hydrocyanic acid, or HCN). Tillers that can develop from the base of the plant after grain harvest can be very high in prussic acid after a frost.

5

Cropping Systems

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Two crops—corn and soybeans—have come to dominate the cultivated area of Illinois over the past 60 years, moving from 60% of cropped acres in 1950 to more than 90% in recent years (**Figure 5.1**). Wheat acreage declined by about half during this period, to about 1 million acres, while the number of acres used to produce livestock feed—oats and hay—has declined by almost 90%, down to less than 750 thousand acres. These shifts were due largely to the reduction in livestock numbers in Illinois. Much of the corn and soybeans produced in Illinois is exported to other states and to other countries.

Soybean acreage reached current levels during the 1970s, and though corn acreage has remained slightly higher than soybean acreage, most fields in Illinois have been managed as a 2-year corn–soybean rotation. In the past few years, corn acreage has increased at the expense of soybean acreage, and as a result there is more corn following corn in Illinois. Although there is little evidence to suggest that the 2-year rotation common in Illinois is less stable than cropping systems common elsewhere, some producers are interested in trying alternatives in an attempt to spread risks and to learn about other possible uses of the land they farm. So far, few alternatives have proven themselves to be economically viable, at least on large acreages.

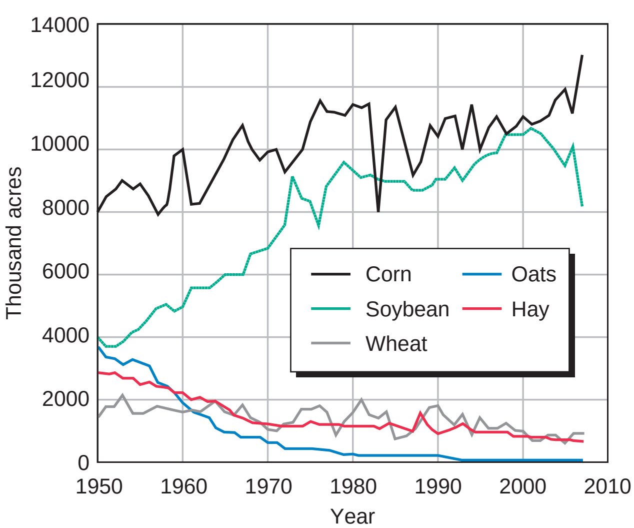

Figure 5.1. Crop acreage in Illinois, 1950 through 2007. Source: National Agricultural Statistics Service.

Cropping System Definitions

The term *cropping system* refers to the crops and crop sequences and the management techniques used on a particular field over a period of years. This term is not a new one, but it has been used more often in recent years in discussions about sustainability of our agricultural production systems. Several other terms have also been used during these discussions:

- **Allelopathy** is the release of a chemical substance by one plant species that inhibits the growth of another species. It has been proven or is suspected to cause yield reductions when one crop follows another of the same family—for example, when corn follows wheat. Technically, damage to a crop from following itself (such as corn following corn) is referred to as *autotoxicity*. In many cases the actual cause of such yield reduction is not well understood, but it is generally thought that the breakdown of crop residue can release chemicals that inhibit the growth of the next crop. So keeping old-crop residue away from new-crop roots and seedlings should help to minimize such damage.
- **Double-cropping** (also known as sequential cropping) is the practice of planting a second crop immediately following the harvest of a first crop, thus harvesting two crops from the same field in one year. This is a case of *multiple cropping*, which requires a season long enough and crops that mature quickly enough to allow two harvests in one year.
- **Intercropping** is the presence of two or more crops in the same field at the same time, planted in an ar-

rangement that results in the crops competing with one another.

- **Monocropping,** or **monoculture,** refers to the presence of a single crop in a field. This term is often used to refer to growing the same crop year after year in the same field; this practice is better described as *continuous cropping*, or continuous monocropping.
- **Relay intercropping** is a technique in which different crops are planted at different times in the same field, and both (or all) crops spend at least part of their season growing together in the field. An example would be dropping cover-crop seed into a soybean crop before it is mature.
- **Strip cropping** is the presence of two or more crops in the same field, planted in strips such that most plant competition is within each crop rather than between crops. This practice has elements of both intercropping and monocropping, with the width of the strips determining the degree of each.

Crop rotations, as a primary aspect of cropping systems, have received considerable attention in recent years, with many people contending that most current rotations are unstable and (at least indirectly) harmful to the environment and therefore not sustainable. Many proponents of "sustainable" agriculture point to the stability that accompanied the mixed farming practices of the past, in which livestock played a key role in utilizing crops produced and in returning manure to the fields. Such systems can still work well, but reduced livestock numbers, fewer producers, and increased crop productivity have meant that such systems are likely to work well for a relatively small segment of Illinois agriculture.

Corn and Soybean in Rotation

The corn–soybean rotation (with only one year of each crop) is still by far the most common one in Illinois. This crop sequence offers several advantages over growing either crop continuously. These advantages have been affected by the development of glyphosate-tolerant corn and soybean (which has tended to lessen the advantages of rotation with regard to weed control) and by the development of Bt-rootworm hybrids in corn (which has lessened the disadvantage in cost of control, and possibly in loss of yield, historically tied to rootworm control in continuous corn). The rotation with soybean reduces nitrogen fertilizer rate compared to continuous corn, but today the perceived disadvantage for continuous corn is less of an incentive to rotate than it has been in the past.

Even with the shifts in management options, most current data continue to suggest that yields of corn following

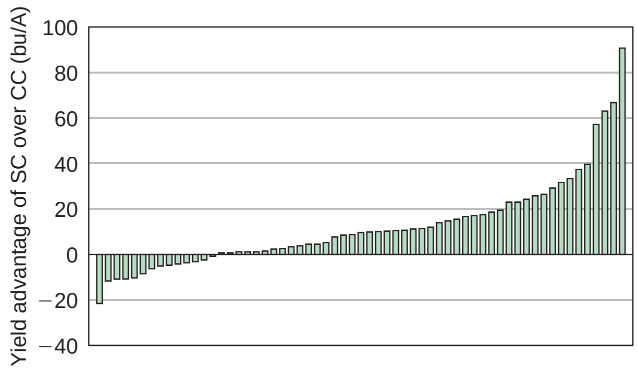

Figure 5.2. Yield advantage of corn following soybean over corn following corn in 62 trials in Illinois from 1999 through 2007.

soybean (SC) tend to be higher than yields of corn following corn (CC). **Figure 5.2** shows the yield difference between SC and CC over some 60 trials conducted over the past decade in different Illinois locations. While there is considerable variation over years and environments, CS averaged about 8% more yield than did CC. The four large yield differences in favor of SC on the right side of the figure are from locations where CC did relatively poorly, for reasons that might have included inadequate control of corn rootworm and a particular pattern of dryness. Such yield differences have diminished in the past four years, and it is possible that the use of Bt for rootworm, or of hybrids improved in other ways, will mean much less incidence of such loss. Without those four sites, SC yielded only about 5% more than CC.

Considerable effort has gone into trying to explain the yield increases found when corn and soybean are grown in sequence instead of continuously. One factor is the effect of residue on nitrogen (N) supply. Corn crop residue (stalks, leaves, and cobs) has low N content, so microbes take up N from the soil as they break down this residue from the previous crop, thus tying up some soil N and reducing the amount available to the next crop. Soybean residue is lower in quantity than corn residue, and it has a much higher N content. The breakdown of soybean residue, therefore, ties up little or no N, leaving more for the following corn crop.

Trials in which residues of previous crops have been removed or added back in different amounts have generally shown that removing corn residue after harvest partially removes the negative effects of corn as the crop that precedes corn (**Figure 5.3**). Removing the soybean residue before planting corn did not affect yield, and adding corn residue back after removing soybean residue decreased yield somewhat. Much of the positive effect of soybean on corn in the corn–soybean rotation seems to be related to the fact that soybean residue is low in quantity and, as measured by its relatively low C:N ratio, higher in quality

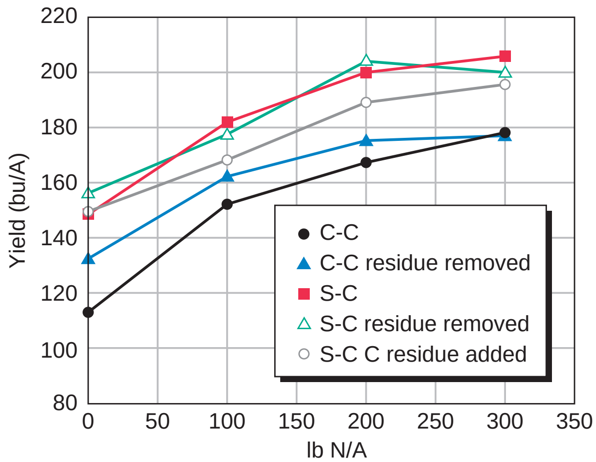

Figure 5.3. Effects of the previous crop and crop residue on corn yield and response to N rate. Data are from a 2-year study at Urbana.

than the residue from corn. Low amounts of residue mean less effect on soil temperature and moisture in the spring, and low C:N ratio means less tie-up of N as the residue breaks down. It is also likely that corn residue carries diseases to the following corn crop while soybean residue does not. Attempts to prove this with individual diseases, however, have not been very successful.

Soybean is usually grown following corn, but because of relatively better income expected from soybean or because of unusual circumstances such as very late planting or application of the wrong herbicide, soybean occasionally is grown following itself. In the rotation and residue study just described, soybean following soybean yielded 45 bushels per acre, while soybean following corn yielded 47, or about 2 bushels per acre more. Removing soybean residue increased the yield of the following soybean crop by less than 2 bushels per acre, but removing corn residue decreased yield of the following soybean crop slightly, as did adding corn residue back to soybean residue before planting soybean following soybean. From these results, we can only conclude that the causes of the "rotation effect" are complex, making it difficult to assign parts of the effect to specific causes.

Regardless of the mechanisms involved, the corn–soybean rotation has worked well during the time it has prevailed in much of the Midwest. From a standpoint of stability and optimal fit within a complex cropping system, a rotation as simple and short-term as this may not be ideal in the long run. Some contend that the growth requirements and other features of corn and soybean crops are so similar that the 2-year corn–soybean rotation does not constitute a crop rotation, at least in the normal sense of the word. Given the clear influence of each crop on the other, it is difficult to accept that conclusion. The corn–soybean rotation is, however, much less complex than are the multiple-crop rotations seen in many parts of the world. But most cropping systems develop problems over time, and there is little evidence that the corn–soybean system is more prone to problems than are longer-term, more complex rotations, especially rotations that do not include extended periods of forage legumes in the field.

The corn–corn–soybean (CCS) rotation represents one way for producers to increase corn acreage but still retain some benefits of the corn–soybean rotation. In fact, some research has shown that soybeans tend to yield more if they follow more than a single year of corn; in a study over three locations in Minnesota and Wisconsin, soybean following 5 years of corn yielded about 10% more than soybean rotated with corn in a 2-year sequence, which in turn yielded about 10% more than continuous soybean. **Table 5.1** gives the results of a 4-year study over six locations in Illinois. The second corn crop in the CCS rotation yielded 5 to 6 bushels per acre more than continuous corn, while the first year of corn in CCS yielded about the same as corn in the soybean–corn (SC) rotation in the northern locations, and due perhaps to variation among years, a little less than SC in southern Illinois. Soybean following 2 years of corn yielded about 3 bushels more than soybean following a single year of corn. As a result, the CCS rotation outperformed the SC rotation, at least at prevailing prices.

One frequent question is whether input costs can be reduced by using longer-term, more diverse crop rotations. Studies into this question have compared continuous corn and soybean and the corn–soybean rotation with rotations lasting 4 or 5 years that contain small grains and legumes either as cover crops or as forage feed sources. Like the

Table 5.1. Yields of corn and soybean in a study comparing continuous corn with corn–soybean and corn–corn–soybean rotations.

Crop and rotation	Yield (bu/A) 12 northern Illinois sites	7 southern Illinois sites
Corn		
Continuous corn	178	139
Corn–soybean	197	149
1st-yr corn in corn–corn–soy	196	144
2nd-yr corn in corn–corn–soy	184	145
Significance	*	NS
Soybean		
Corn–soy	54.9	53.0
Corn–corn–soy	58.3	56.0
Significance	*	NS

Data are from 2004 through 2007.

corn–soybean rotation, certain longer rotations can reduce pest control costs, while including an established forage legume can provide considerable nitrogen to a succeeding corn crop. At the same time, most of the longer-term rotations include forage crops or other crops with smaller, and perhaps more volatile, markets than corn and soybean. Lengthening rotations to include forages will be difficult unless the demand for livestock products increases. Such considerations will continue to favor production of crops such as corn and soybean.

Continuous Corn

With recent trends of corn yields increasing faster than soybean yields and with the price tending to favor corn slightly, the number of acres of corn following corn has risen in Illinois, and some producers have most, if not all, of their fields in corn every year. Though corn yields tend to be lower following corn than following soybean, many producers believe that they can manage continuous corn to produce yields as high as those of corn rotated with soybean. This is especially true in areas with the corn rootworm variant that lays eggs in soybean fields; in east-central Illinois, for example, many producers report yields of continuous corn as high as, or higher than, yields of corn following soybean.

To see whether increasing input levels might produce higher yields of continuous corn, we ran a study over several sites and several years on continuous corn. **Table 5.2** has data over years for these sites. In most cases, increasing the depth or amount of tillage had little effect on yield, though at Monmouth, where we used the modified mini-moldboard plow, it produced a yield increase. Added fertilizer sometimes increased yields, but seldom by enough to pay the added cost. And increasing the plant population from high (32,000) to very high (40,000) often decreased yield and seldom increased it. These results suggest that continuous corn, while it needs adequate inputs, does not typically respond very much to raising inputs to very high levels or to combinations of high inputs.

Corn residue can represent a challenge to corn that follows corn. With the possibility that corn residue might be harvested to produce cellulosic ethanol or other energy forms in the future, we initiated a study on the effects of residue removal on the response to tillage and N rate. **Figure 5.4** shows results averaged over 8 site-years in northern Illinois. Yields and the response to N rate were nearly identical in conventionally tilled plots, regardless of how much residue was removed. If all of the residue was left on and plots were no-tilled, then yields were reduced by about 10%, and it took some 20 pounds more N to reach the highest yield. Removing about half of the residue followed by no-till lowered the N requirement, but yields were still 4% (10 bushels per acre) less than yields of tilled plots. When complete residue removal was followed by no-till, yields were only about 2% less than in tilled plots, and N requirements were about the same. While it is not yet clear what will happen to soils if corn residues are removed for a number of years, it is clear that in the short term, removing some or even all of the residue will not decrease yields, and it may even increase yields under no-till.

Table 5.2. Effect of changing tillage, fertilizer amounts, and plant population on yield of continuous corn at four Illinois sites.

			Yield (bu/A)			
Tillage	Fertilizer	Plant population	DeKalb 2005–07	Monmouth 2003–07	Urbana 2003–06	Perry 2004–07
Normal	Normal	Normal	199	175	223	182
Normal	Normal	High	202	159	208	175
Normal	High	Normal	205	181	223	186
Normal	High	High	207	175	224	193
Deep	Normal	Normal	205	186	215	180
Deep	Normal	High	205	182	206	182
Deep	High	Normal	211	192	226	176
Deep	High	High	209	189	225	184
Significant effects ($P < 0.1$)			None	T, F, P	Fert	FxP

Normal and deep tillage used chisel plow and deep ripping or mini-moldboard plow, respectively. Normal and high fertilizer were normal P and K and 220 lb of N and additional N-P-K amounts of 100-80-120 lb per acre. Normal and high plant populations consisted of 32,000 and 40,000 plants per acre, respectively.

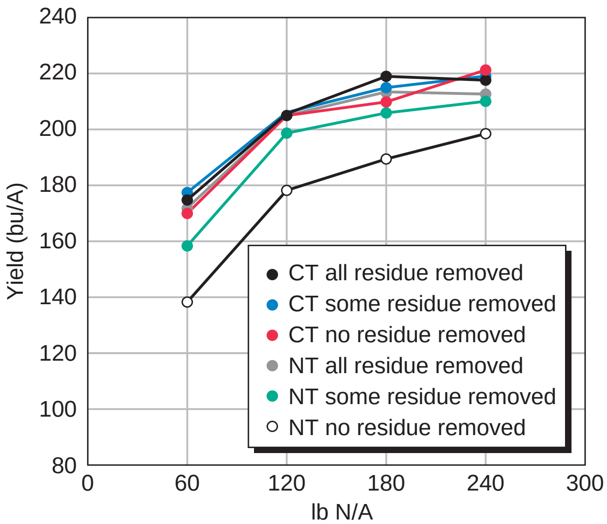

Figure 5.4. Effect of full and partial residue removal, tillage, and N rate on yields of continuous corn. Data are averaged over 8 site-years in northern Illinois from 2006 to 2008. CT = conventional tillage (chisel plow) and NT = no-till.

Corn–Soybean–Wheat Cropping Systems

While corn and soybean remain the primary crops of choice for most Illinois producers, there is still great interest in finding other combinations of crops that can provide similar or greater profits, more stability of yield and income, and some reduction in risks that corn and soybean crops share. One such system is a 3-year rotation that includes wheat along with corn and soybeans. While the double-cropping system in southern Illinois often includes these three crops, questions remain unanswered about the extent to which the wheat–soybean double-crop represents one or two crops, from a standpoint of effects on the next season's crop.

Over the past decade we have been conducting experiments at three sites in Illinois to see how adding winter wheat into the corn–soybean rotation affects yields and profitability. This experiment includes corn, soybean, and wheat grown in either of their two possible sequences (C–S–W or S–C–W), corn–soybean, continuous corn, and, at two of the sites, continuous soybean. Each crop is present in all possible phases each year. Double-crop soybean follows winter wheat harvest at the Brownstown site, but not at Monmouth and Perry, which are north of the normal double-cropping area in Illinois.

Results from the past three years of this study are presented in **Table 5.3**. Continuous corn yielded only 3% to 5% less than corn following soybean, and including wheat in the rotation improved corn yields by 3% to 7% at all locations. The sequence of corn, soybean, and wheat has had little effect on corn yield, though corn following soybean yielded slightly more than corn following wheat.

Continuous soybean yielded 4% and 2% less than soybean rotated with corn at Monmouth and Perry, respectively. Adding wheat into the rotation increased soybean yields by about 4% at Monmouth and 6% at Brownstown, but for some reason it tended to decrease soybean yields at Perry. Over 3 years of favorable double-crop conditions, double-crop soybean yielded about 90% of full-season soybean yields at Brownstown. Along with good wheat yields and good corn yields, the three-crop/double-crop system at Brownstown was highly productive and profitable. Wheat yields were little affected by crop sequence, though at Monmouth the wheat yield was about 4% higher when wheat followed soybean compared to wheat following corn.

Economic returns for these systems depend, of course, on crop prices and input costs. But results of this research indicate that three-crop rotations including wheat can be economically competitive at current crop price ratios. Drawbacks to the inclusion of winter wheat in northern Illinois include the occasional difficulty in getting the wheat crop planted on time following harvest of corn or soybean. The sequence in which the crops are grown does not affect yields much in most years, but it can be easier to plant wheat following soybean, both because of earlier harvest and because of less crop residue.

Table 5.3. Yields of corn, soybean, and wheat in cropping system trials at three Illinois sites (2006–2008).

Crop and sequence	Yield (bu/A)		
	Monmouth	Perry	Browns-town
Corn			
Continuous corn	197	180	146
Soybean–corn	208	188	151
Soybean–wheat–corn	217	192	160
Wheat–soybean–corn	220	196	161
Soybean			
Continuous soybean	68	45	—
Corn–soybean	71	46	35
Wheat–corn–soybean	74	45	37
Corn–wheat–soybean	74	42	37
Corn–soybean–wheat/ doublecrop soybean	—	—	31
Soybean–corn–wheat/ doublecrop soybean	—	—	22
Wheat			
Corn–soybean–wheat	90	75	67
Soybean–corn–wheat	86	76	69

Alternative Crops in Illinois

Many crops other than corn, soybean, and small grains will grow in Illinois, and many will grow quite well, but most have not been produced commercially. A few such crops have been produced on a limited scale and sold in limited quantities, either to local markets or for transportation to processing or export facilities. Many alternative crops are associated with high market prices and high potential income per acre, and thus they catch the attention of entrepreneurial producers who might hear about them. But such crops may have requirements (especially for quality) that can be difficult to meet under Illinois conditions, have high labor costs or other costs of production, or have very limited or inconsistent markets due to unpredictable production elsewhere.

Even though some alternative crops may grow quite well in Illinois, they may not enjoy a *comparative advantage* under Illinois conditions. If a crop is less profitable than other crops that grow or that could grow, then it is not economically advantageous, even if it grows well. For example, various types of edible dry beans grow well in Illinois, but these crops usually enjoy a comparative advantage elsewhere in the United States. This is not necessarily because they grow better elsewhere, but because they produce more income than most other crops in those areas. Some of this can be due to the proximity of processing facilities, which provides a large economic advantage in terms of transportation costs.

The most important consideration when deciding whether to produce a novel crop is its agronomic suitability. In some cases, the crop grows in areas with similar soils and weather, so we can easily learn about potential yields and problems. In other cases, the crop might not well grow in similar areas for very good reasons, and in most cases risks of growing such untested crops are very high. As an example, field (dry) pea was promoted as a crop in Illinois in 2004, with no prior production in most of the state. Thousands of acres were planted, using expensive seed imported from Canada. Field pea is a crop of dry areas, and it was basically destroyed by wet weather, with many fields abandoned and most of the rest yielding little. Illinois producers lost a great deal of money on a crop that was both untested and unsuitable, despite warnings about this.

After agronomic considerations, market availability, demand, and growth potential for any alternative crop need to be considered. Crops with relatively small, inflexible markets (that is, markets that require fixed quantities of only that crop, with the crop not readily used for other purposes) can easily become surplus in supply, quickly driving down prices or even making the crop impossible to sell. Unless alternative crops are desired by large populations, potential market expansion is limited. Delivery to a local market is desirable, but local markets often grow only slowly and with considerable expense, such as for advertising of "locally grown" products.

Some alternative crops can be used on-farm, perhaps substituting for purchased livestock feed. If production cost is sufficiently low, it may be possible to increase overall farm profitability with such a crop. The feeding value of the alternative crop should be included in such a consideration; while some crops can perhaps substitute for protein supplements, they may not result in equal animal gain or performance if protein quality is lower.

If specialized equipment and facilities or a large supply of inexpensive labor is needed to produce an alternative crop, the crop may not be very profitable or even feasible. Unless equipment or special facilities are used across many acres of a crop, the cost will be prohibitive. Large seasonal labor supplies are usually unavailable or are expensive in the Corn Belt; thus crops that require intensive hand labor, such as hand harvest, are typically not grown here.

Web Resources on Alternative or New Crops

There is a very good resource on alternative crops at the website www.hort.purdue.edu/newcrop. Here you can find information on virtually every crop that one would ever consider for Illinois, plus many crops that only grow elsewhere due to climatic restrictions in Illinois.

A research project at the University of Illinois resulted in a website (www.isws.illinois.edu/data/altcrops) that provides some estimates of suitability of crops, including many that are not grown in Illinois. Some of the data provided are incomplete, but the site provides information on a very large number of crops, and it does give some idea about production potential in Illinois.

Sunflower

Sunflower is an alternative crop that some Illinois farmers have produced profitably. Sunflower usually grows in areas of low humidity, and Illinois weather is often more humid than is ideal.

Two kinds of sunflowers can be produced in Illinois: the oil type and the confectionery type. Production practices are similar, but end uses of the grain differ. Oilseed sunflower produces a relatively small seed with an oil content of up to 50%. The hull on the grain is thin and dark colored and adheres tightly to the kernel. Oil from this type of sunflower is highly regarded for use as a salad and frying oil. Meal from the kernel is used as a protein supplement in livestock rations. Because sunflower meal is deficient in lysine, it must be supplemented for nonruminant animals.

Due to the distance to sunflower oil processors (most are in the upper Great Plains), most of the oil-type sunflowers produced in Illinois are used for products other than oil. In recent years, some producers have been producing sunflower as a double-crop following wheat harvest. While it is possible to get good yields in this short season, sunflower quality, as measured by oil content, is usually lower than industry standards. This, coupled with the low density (weight per bushel or per cubic foot) common in the Illinois crop, makes it prohibitive to ship out of state for oil extraction. Instead, most sunflowers produced in Illinois are packaged and used for birdseed.

Confectionery sunflowers usually have larger seeds and a striped hull. They are processed for use as snack foods, and some are used in birdseed mixtures to provide color. Tall plants with very large heads, often planted in gardens, are usually the confectionery type. Birds like all types of sunflower, and they will often eat seeds from the head with great enthusiasm.

Sunflower planting coincides with corn planting in Illinois. Many hybrids offered for sale will reach physiological maturity in only 90 to 100 days, so they can usually mature when planted following harvest of small grain crops. Use of sunflower as a double-crop may be a good choice if soybean cyst nematode is a pest, because sunflower is not attacked by cyst nematode.

Populations of 20,000 to 25,000 plants per acre are suitable for oilseed sunflower types produced on soils with good water-holding capacity. Coarser-textured soils with low water-holding capacity may benefit from lower stands. The confectionery-type sunflower should be planted at lower populations to help ensure production of large seed. Planting of seed should be at 1-1/2- to 2-inch depth, similar to placement for corn. Performance will tend to be best in rows spaced 15 to 30 inches apart.

A seed moisture of 18% to 20% is needed to permit sunflower harvest. Once physiological maturity of seed occurs (at about 40% moisture), a desiccant can be used to speed drying of green plant parts. Maturity of kernels occurs when the backs of heads are yellow, but the fleshy head and other plant parts take considerable time to dry to a level that permits combine harvest. A conventional combine head can be used for harvest, with losses reduced considerably by using special panlike attachments that extend from the cutter bar. Long-term storage of sunflower is feasible, but moisture levels of less than 10% need to be maintained.

Locating a market for sunflower is important before producing the crop. Because the head containing seed is exposed at the top of the plant, insects, disease, and birds can be pest problems. The location of sunflower fields relative to wooded areas will have an impact on the extent of bird damage.

Canola (Oilseed Rape)

Rapeseed, a member of the mustard family, is a crop that has been used as an oilseed in many countries for centuries. Canola is rapeseed that was genetically improved by Canadian scientists (hence, the “can” in “canola”), resulting in low erucic acid content in the oil and low levels of glucosinolates in the meal produced from the seed. These developments improved the quality of both edible oil and protein meal used in animal feed.

Types of canola with spring and winter growth habits are available, but the winter type is more likely to succeed in Illinois; when spring types are grown, hot weather occurs during seed production. Winter-hardiness and disease resistance under Illinois conditions have proven to be problems for the winter types, which are planted in the fall several weeks before winter wheat is planted.

Site selection is critical to successful production of canola because this crop cannot tolerate waterlogged soil. Only fields with good surface drainage should be used, and good internal drainage will help yields.

Planting 2 to 3 weeks before the normal wheat planting time is adequate for plant establishment, provided that cold temperatures do not arrive unusually early. The very small seeds need to be planted shallowly with a grain drill at a rate of only 5 to 6 pounds per acre. Canola needs adequate time to become established before fall temperatures decline, but it does not need to develop excessively. Plants with 6 to 10 leaves, with a lower stem about the diameter of a pencil, are considered adequate for winter survival. A taproot 5 to 6 inches deep generally develops with desired levels of top-growth in the fall.

Soil fertility needs for canola are similar to winter wheat, with a small amount of nitrogen applied in the fall to stimulate establishment and a larger topdress application in the early spring to promote growth. Too much nitrogen available in the fall can delay the onset of dormancy, putting the crop at greater risk for winter injury. Excessive amounts of nitrogen can increase lodging problems.

Growth of canola resumes early in the spring, with harvest maturity reached about the same time as that of winter wheat. Harvest needs to be done as soon as the crop is ready to reduce the amount of seed shatter. Only the top portion of the plant containing the seedpods is harvested.

Combining works well when seeds reach 10% moisture, but further drying of seeds (to 9% moisture or less) and occasional aeration are needed for storage. The tiny, round seeds tend to flow almost like water, so wagons, trucks, and bins used for transportation and storage need to be tight, with all cracks sealed.

There is no canola processing in Illinois, so locating a nearby delivery site is currently a problem. Problems with disease (especially *Sclerotinia*) and winter survival have also been common, and acreage of canola in Illinois is currently very low.

Buckwheat

Nutritionally, buckwheat is very good, with an amino acid composition superior to that of any cereal, including oats. Producing the crop as a livestock feed is possible, but markets for human consumption tend to be small. An export market exists in Japan, where noodles are made from the grain. This market requires large, well-filled seeds, which can be difficult to produce when the weather is hot and dry.

Buckwheat has an indeterminate growth habit; consequently, it grows until frost. Growth is favored by cool, moist conditions. In a short period (75 to 90 days), it can produce grain ready for harvest. High temperatures and dry weather during flowering can seriously limit grain formation. Little breeding work has been done to enhance yield potential; buckwheat is naturally cross-pollinated and cannot be inbred because of self-incompatibility. There are not many varieties available.

Because it produces grain in a short time, buckwheat can be planted as late as July 10 to 15 in northern Illinois and late July in southern parts of the state. Rapid vegetative growth of the plant provides good competition to weeds. Fertility demands are not high, so buckwheat may produce a better crop than other grains on infertile or poorly drained soils.

With the exception of those that can use the crop for livestock feed, producers should determine market opportunities before planting buckwheat. A few grain companies in the Midwest handle the crop for export, but buckwheat produced from late planting may often have small seeds and thus limited potential for the export market.

Specialty Corn and Soybean Production

Corn and soybeans with unique chemical or physical properties can perhaps be viewed as alternative crops, though production of these types is generally little different than production of "conventional" crops. Typically corn and soybean varieties with these special characteristics are used in the manufacture of food products, although some offer feeding advantages for livestock as well. A considerable portion of specialty soybeans is exported to Asian countries to be used in foods.

Organic production. Some of the fastest growing specialty markets are for organic corn and soybean. Companies are manufacturing increasing numbers of consumer food products based on organic grains, and demand for organic meat, milk, and other products is increasing rapidly. The USDA has produced a set of rather complex rules that govern the production of organic crops and the labeling of foods that contain such crops. These rules are much too extensive to list here, but persons interested in organic production can locate rules and other information at the USDA Agricultural Marketing Service (www.ams.usda.gov/AMSv1.0). In order to have products labeled as organic, producers need to have an agency certify that they are in compliance with the rules.

It takes three years without the use of prohibited inputs for a field to be certified as organic. Prohibited inputs include, among other things, manufactured forms of fertilizer, all synthetic pesticides, and genetically modified seed. Certain rotational sequences and intervals between crops must also be maintained. While it is neither simple nor easy to gain certification, organic crops often command prices that are much higher than those of nonorganic crops, so organic crops can be profitable even if production costs per unit are high. In a general sense, organic production that involves livestock tends to be easier than that which produces only grain crops. This is because forages in rotations can be grown for ruminants, and manure from livestock can be used to provide nutrients.

Special-use corn and soybean. Markets for specialty corn and soybeans domestically are often smaller than those for commodity corn and soybeans, but for some producers, growing specialty grains may be a means to enhance income. Specialty grain is usually produced under contract with a grain buyer, and the requirements for grain delivered may differ considerably from the requirements for that delivered to a local elevator.

One of the largest current specialty markets is for non-GMO corn and soybean. Other than needing to manage weeds and insects using conventional techniques and keeping harvested grain separate from that produced using GM seed, these are not generally difficult to produce. Many GM traits have strip tests that can be run at receiving points (elevators or terminals) to see if the grain meets the standard for presence of low levels of GM grain.

As the market for GM corn and soybean seed has grown, however, finding top-yielding varieties of these crops can be challenging. In the University of Illinois variety trials, conventional soybeans are tested in separate trials, while corn hybrids are in the same trial but identified as having no genetic (Bt or herbicide resistance) traits. Recent results confirm that most of the GM varieties that companies currently enter into these trials tend to yield more than conventional entries. However, the premium for non-GMO crops can make them still profitable.

Most specialty types of corn differ from conventional corn by having altered protein, oil, or starch in their grain. Some of these are described in Chapter 2. Specialty soybeans are also nutritionally altered, mostly by having different-than-normal types or ratios of fatty acids in their oil. Some demand for these products stems from the current health concerns regarding trans fats.

Biofuel Sources and Crops

Due to high petroleum prices and government mandates for production of "renewable" fuel (not from fossil fuel sources), interest in growing crops to convert to liquid fuel has been very high in recent years. By far the most common liquid fuel produced from renewable sources is ethanol, which can be produced by yeast grown in vats and fed by sugar. Sugar to feed this process is available in some countries from sugarcane, which is highly productive in terms of gallons of ethanol per acre. In the United States, where we grow limited acres of sugarcane due to limitations of temperature (it needs warm temperatures for at least 8 months to produce a crop), most of the sugar for ethanol production is produced by breaking down cornstarch into sugars in a process that uses enzymes. The byproduct is the non-starch parts of the kernel—protein, oil, and minerals, which together make up a useful livestock feed. In 2008, the U.S. will use about 30% of the corn crop to produce about 10 billion gallons of fuel ethanol. There are about a dozen ethanol plants in Illinois, and more than 130 plants in the U.S., most using corn grain as their major feedstock. Corn grown for grain is, and will remain for some time, our primary "biofuel" crop.

Increasing demands for ethanol and eventual limitations of corn supply and price will increase the production of ethanol using sources of sugar besides corn grain. Most experts believe that the real growth potential is in the production of *cellulosic ethanol*, which uses sugars produced by the breakdown of plant-based materials like wood waste, newspaper, cornstalks, and forage-type (non-grain) crops. Cellulose is a complex carbohydrate much like starch, and it is in nearly pure form in cotton fiber. It is more difficult to break cellulose down into sugars than to break down starch. But the real challenge is that cellulose in most plant materials is mixed with other chemical constituents that are not good sources of sugars, and extracting cellulose is difficult and expensive. While enterprises are under development to use plant materials such as cornstalks to produce ethanol, it will be some years before this is a major part of the supply. Compared to corn grain, cellulosic ethanol production creates not valuable livestock feed, but instead large quantities of sludgelike material that will present a disposal challenge.

In the event that cellulosic ethanol production becomes commercially viable, markets for crops and crop materials to be used as feedstocks will develop. One prominent source is likely to be corn crop residue, including stalks and cobs. There is about 1 ton (dry weight) of residue in the field after harvest for each 40 bushels of grain yield. So harvesting half of the corn residue in Illinois (12 million acres at 180 bushels per acre) would produce some 2.7 million tons, which at 80 gallons of ethanol per ton (such yields are not yet certain, but estimates range from 60 to 100 gallons per ton) would produce more than 2 billion gallons of ethanol. It is not yet clear what producers would be paid for such residue, but harvest, transportation, processing, and waste disposal costs will be high, and the replacement of nutrients removed in the residue will also represent a cost to the producer. As noted, removal of some of the corn residue should not present a problem, and it may even make it possible to do less tillage. The large challenges with this source may well turn out to be logistics of getting the residue harvested and transported, and then storing enough of the material to allow a plant to operate throughout the year, including during the growing season, when there would be no residue to harvest.

Corncobs make up about 20% of the weight of the ear, so a 200-bushel corn crop produces a little more than a ton of cobs. Efforts are under way to find ways to harvest cobs at the same time that grain is harvested. Cobs break down slowly and do less to protect the soil compared to stalks, so they may represent less loss to producers than would the loss of stalks. Challenges include getting cobs harvested without disrupting grain harvest, getting them dry enough to store (cob moisture may be similar to grain moisture at the time of harvest, unless harvest is delayed), and the fact that cobs may not be ideal sources of cellulosic ethanol due to their hardness and chemical composition.

While production of liquid fuel (ethanol, and perhaps a few others) is part of the renewable fuel mandate, it is also possible to burn various plant products directly to produce heat for generating electricity or for heating buildings. Direct burning is a less expensive way to extract energy than is the production of liquid fuel. It also means less waste, though ash—mineral content that doesn't burn—still has to be disposed of. Grass crops and other biological materials have been burned along with coal in power plants and have been compressed into pellets for burning in heating devices. Such material needs to be dry enough to burn well, and it is typically an advantage if it has low levels of nitrogen and other plant nutrients. This reduces the need to replace nutrients removed from the soil where the plant material grew, helps reduce pollution, and minimizes the amount of ash that needs to be disposed of after burning.

Dedicated Biofuel Crops

The amount of crop residue will, once processing is commercially viable, provide a great deal of material from which to make ethanol. If dry weight is the only important measure of value as a feedstock for ethanol production or burning, then it is possible that roadsides, interstate highway medians, waterways, and other unfarmed areas might become viable sources, to the extent that prices more than cover harvest and transportation costs. Wood processing wastes, recycled paper (paper has a high cellulose content), and other materials currently available at low cost might take on value as feedstock.

A great deal of effort is under way to find and develop crops that produce large quantities of harvestable dry matter that can be used as a source of cellulose. We call these "dedicated" biofuel crops because they typically aren't much good for anything else. Some such plants could be used as forages if harvested early, but getting maximum dry weight yields is possible only if the crop is grown to near maturity, when forage quality is not good.

The biofuel crop on which the most research has been done over the past two decades in the U.S. is *switchgrass* (**Figure 5.5**). This is a warm-season, perennial grass species native to the prairies of North America. It has very small seed and establishes somewhat slowly. Yields of more than 10 tons per acre have been reported from research, but yields of whole fields are likely to be less than that, perhaps 3 to 6 tons. Switchgrass can be used as a forage crop for livestock grazing, though its quality decreases as it matures.

Miscanthus, specifically the sterile natural cross called *Miscanthus* x *giganteus* (**Figure 5.5**), is being promoted as a biofuel crop based on high dry matter yields that have been reported in Illinois and other places. It is a perennial that can grow up to 13 feet tall, and it has underground stems called rhizomes that store materials to enable the plant to grow back quickly in the spring. Yields of more than 15 tons per acre have been reported from research trials. There is at present not enough grown in fields in the U.S. to be able to know what yields might be over years. Warm weather with relatively high rainfall and moderate soil drainage tend to improve yields, so it is possible that this plant will do well in some southern Illinois locations.

Figure 5.5. Switchgrass (foreground, left) and *miscanthus* x *giganteus* (right).

There is no established market and not enough seed stock to plant large acreages, so most plantings over the next few years will likely be for research and demonstration.

One of the major drawbacks to growing miscanthus is that, as a sterile plant that produces no seed, it has to be propagated vegetatively. This is usually done by planting pieces of rhizome harvested from an existing stand, typically using wide spacing between plants (3 ft in both directions) to minimize planting costs. Rhizome pieces sometimes fail to produce a viable plant from their buds, and so some may need to be replanted. Weed control during establishment is an issue as well. So establishing a stand is costly. After establishment, the plant needs to grow for three years before it reaches maximum productivity, and even then the stand may not be completely filled out. There is evidence that the plant responds to N fertilizer, at least after depletion of soil N supplies starts to limit growth.

Harvest of miscanthus plants as biofuel takes place in late fall or winter, after the leaf material has dried up and blown away and stems have dried. It can be harvested using forage equipment, either baled or chopped. Until cellulosic ethanol production begins, most harvested miscanthus will likely be burned directly. It is very coarse plant material, and so it has few if any uses other than as a fuel. The economics of miscanthus production are currently uncertain, given that no real market exists for the product and that yields in different field situations are largely unknown.

Cover Crops

Rye, wheat, ryegrass, hairy vetch, and other grasses and legumes are sometimes used as winter cover crops in the Midwest. The primary purpose for using cover crops is to provide plant cover for soil to help reduce erosion during the winter and spring. Winter cover crops have been shown to reduce total water runoff and soil loss by 50% or more, although the actual effect on any one field will depend on soil type and slope, the amount of cover, planting and tillage methods, and intensity of rainfall. A cover crop can protect soil only while it or its residue is present, and a field planted after cover crop residue has been displaced or buried by tillage may lose a great deal of soil if there is intense rainfall after planting. The use of winter cover crops in combination with no-till corn may reduce soil loss by more than 90%. Cover crops are promoted as a way to improve soil tilth, and they sometimes contribute nitrogen to the following crop.

The advantages of grasses such as rye as cover crops include low seed costs, rapid establishment of ground cover in the fall, vigorous growth, recovery of residual nitrogen from the soil, and good winter survival. Most research has shown, however, that corn planted into a grass cover crop often yields less than when grown without a cover crop. In one study at the University of Illinois research center near DeKalb, the negative effect of wheat and rye cover crops killed at different times before planting was closely related to the amount of cover crop dry matter that was present (**Figure 5.6**).

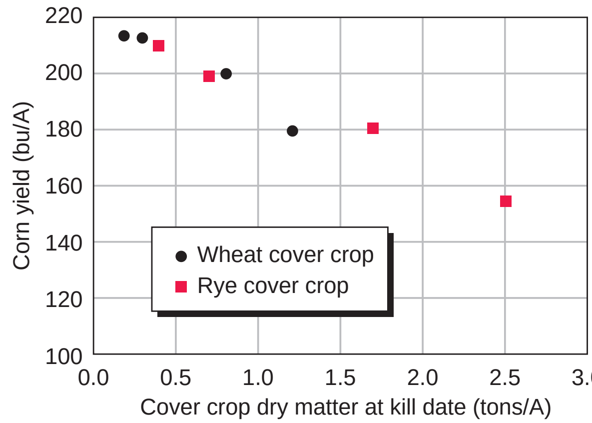

Figure 5.6. Effect of fall-seeded cover crop wheat and rye on the yield of corn. The cover crops were killed at 3, 2, and 1 week before planting using herbicide, and 2 days before planting with tillage. Earlier kill dates produced lower cover crop weights, and wheat produced about half the dry matter of rye by each date. Data are over three years (2007-2007) and are from a study conducted by Jim Morrison and Lyle Paul at the University of Illinois Northern Illinois Agronomy Research Center near DeKalb.

There are several reasons why grass cover crops might reduce yields of the following corn crop. Residue from grass crops, including corn, has a high carbon-to-nitrogen ratio, so nitrogen from the soil is tied up by microbes as they break down the residue. Second, a vigorously growing grass crop such as rye can dry out the surface soil rapidly, causing problems with stand establishment under dry planting conditions. When the weather at planting is wet, heavy surface residue from a cover crop can also cause soils to stay wet and cool, reducing emergence. Finally, chemical substances released during the breakdown of some grass crops have been shown to inhibit the growth of a following grass crop or of grass weeds. This is an example of allelopathy.

While grass cover crops can reduce yields of the following corn crop, most research has shown little or no effect of cover crops on a following soybean crop. In one Illinois study, rye cover crop was allowed to grow to reach a weight of about 2 tons per acre, and there was no effect of the cover crop on soybean yield. In that study, the rye took up as much as 100 pounds of N per acre. One cover crop grass that has gotten attention recently is annual ryegrass, especially for planting before soybean. It tends to grow fairly deep roots, which might improve soil structure some as they decay. But as with all cover crops, benefits to growing ryegrass need to be greater than the cost of planting and controlling it.

Figure 5.7 shows that in a 2-year study at Urbana, Illinois, using the legume hairy vetch as a cover crop resulted in higher yields than did using no cover crop or using rye or the combination of rye and vetch, at least at lower N rates. There are several reasons why legumes might be better cover crops than grasses. Legumes can fix nitrogen, so, providing that they have enough time to develop this capability, they may provide some "free" nitrogen—fixed from the nitrogen in the air—to the following crop. Most leguminous plant residues have a lower carbon-to-nitrogen ratio than those from grasses, so breakdown of their residue ties up little or no soil nitrogen. On the negative side, early growth by legumes may be somewhat slower than that of grass cover crops, and many of the legumes are not as winter-hardy as grasses such as rye. Legumes seeded after the harvest of a corn or soybean crop thus often grow little before winter, resulting in low winter survivability, limited nitrogen fixation before spring, and ground cover that is inadequate to protect the soil, particularly in northern Illinois.

Hairy vetch, at least in the southern Midwest, has often worked well as a winter cover crop. It offers the advantages of fairly good establishment, good fall growth, and vigorous spring growth, especially if it is planted early (during the late summer). When allowed to make considerable spring growth, hairy vetch has provided as much as 80 to 90 pounds of nitrogen per acre to the corn crop that follows. One disadvantage to hairy vetch is its lack of sufficient winter-hardiness; severe cold without snow cover will often kill this crop in the northern half of Illinois, especially if it has not made at least 4 to 6 inches of growth in the fall. The seed rate is moderately high, at 20 to 40

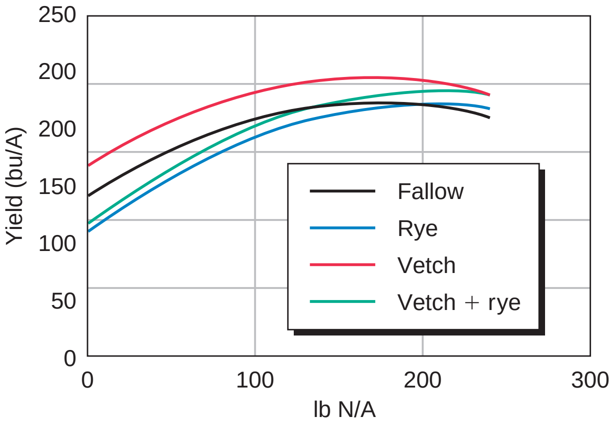

Figure 5.7. Effects of no cover crop, hairy vetch, rye, or hairy vetch plus rye on yield and N response of no-till corn grown following soybean. Data are from a 2-year study at Urbana, published by Fernando Miquez and Germán Bollero in *Crop Science* 46:1536–1545 (2006).

pounds per acre, and seed is currently priced at more than $2 per pound, so seed costs alone can be $50 to $80 per acre. The value of the nitrogen fixed under good conditions and provided to the next crop may return more than half of the seed cost, but there clearly need to be other benefits besides nitrogen supply to make the use of vetch profitable as a cover crop. Some producers grow their own seed to reduce the expense. Hairy vetch can also produce a considerable amount of hard seed, which may not germinate for 2 or 3 years, at which time it may become a serious weed in a crop such as winter wheat. Other legume species that may be used as winter cover crops include mammoth and medium red clovers, alfalfa, and ladino clover.

To get the maximum benefit from a legume cover crop, it must be planted early enough to grow for 6 to 8 weeks before the onset of cold weather in the late fall. The last half of August is probably the best time for planting such cover crops. They can be aerially seeded into a standing crop of corn or soybean, although dry weather after seeding may result in poor stands of the legume. Some attempts have been made to seed legumes such as hairy vetch into corn at the time of the last cultivation. This practice may work occasionally, but a good corn crop will shade the soil surface enough to prevent growth of a crop underneath its canopy, and cover crops seeded in this way will often grow very poorly or die during periods of dry weather. All things considered, the chances for successfully establishing legume cover crops are best when they are seeded into small grains during the spring or after small-grain harvest, or when they are planted on set-aside or other idled fields, well before the time of corn or soybean harvest.

There is some debate as to the best management of cover crops before planting field crops in the spring. A trade-off of benefits usually exists: Spring planting delays will allow the cover crop to make more growth (and to fix more nitrogen in the case of legumes), but this extra growth may be more difficult to kill, and it can deplete soil moisture. As discussed above, killing a grass cover crop several weeks before planting—or even earlier if cover crop growth is heavy—is preferable to killing it with herbicide or tillage just before planting the main crop. Legumes can also create some of the same problems as grass cover crops, especially if they are allowed to grow past the middle of May.

Research at Dixon Springs in southern Illinois has illustrated both the potential benefits and possible problems associated with the use of hairy vetch. In these studies, hairy vetch accumulated almost 100 pounds of dry matter and about 2.6 pounds of nitrogen per acre per day from late April to mid-May (**Table 5.4**). The best time to kill the cover crop with chemicals and to plant corn, however, varied considerably among the 3 years of the study. On average, corn planted following vetch yielded slightly more when the vetch was killed 1 to 2 weeks before planting (**Table 5.5**). Also, corn planted in mid-May yielded more than corn planted in early May, primarily due to a very wet spring in 1 of the 3 years, in which vetch helped to dry out the soil. Vetch also dried out the soil in the other 2 years, but this proved to be a disadvantage because moisture was short at planting. The conclusions from this study were that vetch should normally be killed at least a week before planting and that corn planting should not be delayed much past early May because yield decreases due to late planting can quickly overcome benefits of additional vetch growth.

Although the amount of nitrogen contained in the cover crop may be more than 100 pounds per acre, the rate applied to a corn crop following the cover crop cannot be reduced 1 pound for each pound of nitrogen contained in the cover crop. One study in Illinois showed that the economically optimal nitrogen rate dropped by only about 20 pounds per acre when a hairy vetch cover crop was used, even though the hairy vetch contained more than 70 pounds of nitrogen per acre. In the results shown in **Figure 5.7**, vetch cover crop increased yield over that without a cover crop, but the nitrogen response lines are nearly parallel to one another, meaning that the nitrogen rate required for maximum or optimum corn yield was not changed by the cover crop.

Whether to incorporate cover crop residue using tillage is debatable, with some research showing no advantage and other results showing some benefit. Incorporation may enhance the recovery of nutrients such as nitrogen under some weather conditions, it may offer more weed-control options, and it can help in stand establishment, both by reducing competition from the cover crop and by providing a better seedbed. On the other hand, incorporating cover crop

Table 5.4. Dry matter and N content of hairy vetch killed at different times using herbicide.

Kill date	Dry matter (lb/A)	Nitrogen (lb/A)
Late April	1,300	55
Early May	2,509	85
Mid-May	3,501	115

Data are from a 3-year study conducted by Steve Ebelhar at Dixon Springs.

Table 5.5. Corn yields from different corn planting dates and hairy vetch cover crop kill dates.

	Yield (lb/A)	
Corn planting date	Vetch kill 1–2 wk before planting	Vetch kill at the time of planting
Early May	1,300	55
Mid-May	2,509	85
Late May	3,501	115

Data are from a 3-year study conducted by Steve Ebelhar at Dixon Springs.

residue removes most or all of the soil-retaining benefit of the cover crop during the time between planting and crop canopy development, a period of high risk for soil erosion caused by rainfall. Tilling to incorporate residue can also stimulate the emergence of weed seedlings, and incorporated residue can cause problems in seed placement.

The danger of allelopathy caused by the release of chemical substances during the breakdown of cover crop residues can be minimized by physically moving cover crop residue from the crop row. This is difficult to do if tillage is used to kill the cover crop and to incorporate residue. If the cover crop is killed chemically long enough before crop planting, dried residue can usually be moved safely off the row by trash-moving planter attachments. This also helps with crop seed placement.

Cropping Systems and the Environment

In recent years a number of scientists have been studying the effects of cropping systems on the soil, water, and other natural resources located in and near fields where crops are grown. The approach to such studies is grounded in ecological sciences, and the general term *agroecology* has been coined to refer to this blend of ecology and agricultural sciences. *Ecological services* are means by which cropping systems can be shown to have positive effects on things like water quality or soils. Many ecological studies begin with the idea that unfarmed, unsettled, unused natural areas represent the most stable and resilient ecological systems. From that standpoint, any managed agricultural system represents an ecological negative. Thus ecological services from agricultural systems are usually considered in comparison with other agricultural systems, not with natural areas.

Carbon Sequestration

Crops take up carbon dioxide (CO_2) from the air and release oxygen (O_2). Because the continuous rise of atmospheric CO_2 concentration from the burning of fossil fuels (which started out as plant material, and before that as atmospheric CO_2 millions of years ago) has been blamed as a cause of global warming, there has recently been a lot of interest in claiming credit for growing crops as a means of removing carbon from the air, hence "sequestering" carbon. One visible example of carbon sequestration by plants is in forests, where the carbon in the woody part of trees has been removed from the air, at least until the wood burns or trees fall down and decay. In fact, the global atmospheric CO_2 concentration goes down during the northern hemisphere summer because photosynthesis removes it from the air.

While crop dry matter is indeed a store of sequestered carbon, most such carbon is sequestered only for a short time. Nearly all of the carbon in the grain used to feed livestock and people is respired to release its energy. Crop residue on or incorporated into the soil can take a long time to decay, but much of it eventually returns back to the atmosphere as CO_2. One form of carbon that remains sequestered, though, is the carbon in the stable fraction of soil organic matter. Soil organic matter is about 50% carbon, and 1 acre of topsoil 10 inches deep weighs about 3 million pounds, so if the topsoil has 4% organic matter it contains about 30 tons of carbon per acre. Though many soils are not this deep or do not have such high levels of organic matter, world soils contain huge quantities of carbon.

Illinois soils lost as much as half of their organic matter during the first 100 years or so of producing cultivated crops. Measurements indicate that this loss has slowed or stopped, and it may be possible, depending on crops and how they are grown, that soils could be made to gain *stable* soil organic carbon again. Organic matter is said to be stable only after it is in a chemical form that does not break down any further. Crop residue returned to the soil is not stable organic matter; in fact, 99% or more of it will disappear during the breakdown process in most soils, leaving less than 1% as added organic matter. Evidence is that roots break down more slowly and contribute considerably more to soil organic matter than do crop residues from above ground.

The breakdown process takes decades to complete, so changes in stable organic matter cannot be measured accurately after only 10 or 20 years of cropping. It is clear that cases where people claim that soil organic matter has increased by 1 percentage point or more over a few years do not reflect changes in stable organic matter, but rather changes in organic crop material or crop residues in various stages of breakdown. We also know that each percentage point of stable soil organic matter contains about 1,000 pounds of nitrogen per acre, so the long-term buildup of soil organic matter will require nitrogen above the needs of the crop.

While studies on carbon sequestration continue, it is in the best interest of most producers to keep crop residues in the field but perhaps not to drastically alter cropping practices. Proponents of sequestering carbon with annual crops often suggest that continuous corn is the best crop to use for this and that no-till is required, though strip-till is now often allowed as a variant of no-till. Continuous no-till corn is difficult to manage, especially in northern Illinois, due to buildup of large amounts of crop residue on the soil surface. Power companies may even pay for carbon "credits" if certain rules are followed. Because they can be easily monitored, it is likely that agronomic practices, not measured increases in soil carbon, will be the basis for such payments if they occur in the future. Early indications are that the amount of such credit payments may not be enough to cover added expenses or any crop losses that might occur from some of the practices that might be required.

Water Quality

Water quality in agricultural systems is associated with the amount of soil lost as runoff into surface water and with the amount of plant nutrients and pesticides that reach surface waters. A cropping system thus affects water quality to the extent that it keeps soil in place, releases little pesticide, and takes up nutrients that would otherwise leave fields in drainage or runoff water. Perennial cropping systems such as permanent pasture that are managed without use of excess nutrients or pesticides generally excel at preserving water quality. More common systems such as the corn–soybean rotation, even if managed well by using appropriate amounts and forms of nitrogen fertilizer, only those pesticides needed, and little or no tillage, will still in many cases lose more nitrogen to surface water than will perennial crops. Tile drainage, by making it possible for water to move out of a field to a stream or river, often increases nutrient loss from a field. But with proper care it is possible to produce crops with minimal effects on water quality.

Air Quality

Because higher CO_2 levels mean higher rates of photosynthesis, an increased atmospheric CO_2 level is itself a positive factor in crop production. Photosynthetic rates of well-managed crops are generally higher than those of natural systems, though the fact that forests and some perennial systems have active leaf area much longer during the growing season than do crops means that seasonal carbon uptake might be higher in some natural systems, even if the highest daily rates are less. Recent studies have shown that as the CO_2 level continues to rise, productivity of some crops will increase moderately, unless the increase in CO_2 is associated with hotter, drier conditions and so more stress.

The idea that plants, including crops, help to "restore" the air by taking in CO_2 and releasing oxygen for animals to breathe is a popular one, and it might be considered by some to be one of the ecological services provided by crops. Of course, natural systems do this as well. All photosynthesis is accompanied by release of large amounts of water vapor—each corn plant in a field loses about 5 gallons of water from its leaves over the course of a season, and the more a crop or system yields, the more water it uses. Some have linked crop production with increases in humidity levels, and even to the occurrence of thunderstorms. Another, more indirect link between cropping systems and air quality stems from the fact that engines that power farm equipment, as well as tillage and harvest operations, release particulate matter that can affect air quality.

Besides affecting air quality to some extent, plants can also be affected by the presence of pollutants in the air from sources such as automobile engines and factories. One such pollutant is ozone, a form of oxygen that is produced by the action of sunlight on engine exhaust gases. Ozone has been found in experiments to severely reduce yields of crops such as soybean. Because levels of such pollutants vary so much depending on windspeed and other conditions, it is difficult to know how much yield loss actually occurs. When plants take up ozone, there is presumably less for people and animals to breathe in, which might be a benefit.

Species Diversity

To many ecologists, any system with limited species diversity has low stability. Many thus see a corn field with low weed numbers and few insect or disease problems as lacking diversity, and hence a system with very low stability. According to principles of ecology, which generally deals with stability of systems left alone in nature, a corn field certainly is unstable: It will not stay a corn field unless people intervene to keep it as a corn field the next year. And this will require the use of extensive inputs such as new seed, methods of weed control, and nitrogen, all of which are not “natural” products or processes.

While the diversity within a corn field may not be very visible, there is a considerable amount of diversity in insects, disease organisms, and species that inhabit the soil. In general, though, the reason agronomists and ecologists would view the stability (and desirability) of a well-managed corn field quite differently is that the ecologist generally looks toward the long-term stability based on known principles, while the agronomists is looking at productivity in that year, without trying to predict whether such a crop will be possible in 10 or 20 years, or how things might need to be changed to maintain productivity. There is no good evidence that a corn field that produced a high yield in 2008 will be unable to do that in 2030, nor is there evidence that introducing more diversity through strip-intercropping or more diverse crop rotation will make it more productive over the long run.

Will Cropping Systems Need to Change?

Some who look at cropping systems in terms of ecological principles contend that current cropping patterns are so unstable that changes must be made soon to prevent disaster. There is historical evidence that some cultures have been destroyed as a consequence of depending too much on a single crop or a few crops, though it is not clear that the methods of production were the problem as much as lack of means to adequately manage insects and diseases. Yields of some major crops in major growing areas of the world have stagnated in recent years, in some cases without a clear cause, even as genetic potential of these crops continues to increase. Thus the answer to the question of whether cropping systems will need to change is “probably,” though there is very little evidence pointing to specific changes that will have to be made. As long as crops are produced using sound agronomic principles, with a minimum of pesticides, and with awareness of the need to preserve the soil and minimize effects on the environment, we will stay flexible enough to meet challenges to current crops as they come.

6

Hay and Pasture

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Illinois hay and pasture acres can contribute in many ways to the success of a farm enterprise. These crops offer opportunities for producers who decide to manage them properly. The information in this chapter is based on forage research from the University of Illinois and land-grant institutions in two adjacent states.

Vigorous, productive stands are the result of proven practices: selecting adapted species to your soils and forage need, choosing disease- and insect-resistant varieties that grow and recover quickly after harvest, following good seeding practices, using current soil tests as the basis for lime and fertilizer application, protecting stands from pests and traffic damage, and harvesting at the optimal time. Selecting species and varieties that are winter hardy and persistent also affects stand productivity. For guidelines on soil fertility management (including soil testing) for hay and pasture, see Chapter 8.

Evaluating Older Hay and Pasture Stands

Is maintaining an older, established stand better than reseeding or establishing a new stand? There are a number of factors to consider when making this decision.

In **pure grass fields**, a thick stand over the entire field is essential. Bare or open areas result because of diseases, winter kill, soil fertility, or other problems; they can quickly become infested with weeds, which can lead to further weakening of the stand. As a guide, if a 3-year-old bunch-type grass (such as orchardgrass or timothy) or sod-forming grass (such as smooth bromegrass or Kentucky bluegrass) has 50% or less ground cover, the stand should be renovated.

While stands that are relatively consistent in covering the soil may need only fertilizer and closer attention to other management practices, fields with large areas of weeds should be considered priorities for renovation.

In **pure legume fields**, a good uniform stand is also important. There are two common methods for making alfalfa stand evaluations:

- *Stem count.* Research has shown that the number of stems per square foot is a good indicator of potential yield. Stem counts can be taken when the plants are 4 to 6 inches tall. Simply count any stem the mower would cut. If there are fewer than 39 robust stems per square foot, consider tearing up the stand.
- *Plant count.* When evaluating a stand in the early spring, you will have to base your decision on the number of plants (crowns) per square foot since stems may not be tall enough to count. Use the following as a guide.

Season when counts are made	Suggested plants per sq ft
Fall of the seeding year	>20
Spring, 1st full production year	>12
Spring, 2nd production year	>8
Spring, 3rd production year	>5

Another guide for plant count in the spring is that 2-year-old stands with 6 or fewer plants per square foot or 3-year-old stands with 3 or fewer plants per square foot will not produce well.

Fall is the best time to evaluate stands. Include a health assessment of the alfalfa crown and root by digging up a number of plants from different areas in the field to properly determine crown and root vigor. Roots that exhibit disease or severe discoloration more than a couple of inches below the crown may not survive another season. If you are in doubt, take plants to your local extension office for further evaluation.

Establishing Hay and Pasture: Cool-Season Grasses and Legumes

Seeding date in Illinois, either spring or late-summer, depends to a great extent on the field's location (**Figure 6.1**).

Spring seedings tend to be more successful in the northern half of Illinois than in the southern half. Seeding can occur as soon as a seedbed can be prepared, usually late March to early April. Typically as seeding is delayed past mid-May, soil moisture becomes more limited, weed pressure increases, and soil temperature becomes higher. Lack of consistent success with spring seeding in the southern third of Illinois indicates that late-summer seedings may be more desirable.

Late-summer seedings for Illinois legumes should be completed 6 to 8 weeks prior to the first killing frost to ensure that plants become well established before winter: August 10 to 15 in the northern quarter, August 30 to September 4 in the central half, and September 5 to 10 in the southern quarter. Top growth of 4 to 6 inches is needed before dormancy. Cool-season grasses can be seeded 1 to 2 weeks later. A firm seedbed enabling seed-to-soil contact is critical for late-summer seeding, and adequate soil moisture must be present. Use the same seeding rate as in the spring, and do not include a companion or nurse crop.

Frost seeding, or overseeding, is one method of pasture renovation. A spinner-type seeder (**Figure 6.2**) is used to surface-broadcast seed into existing vegetation in late winter or very early spring while the soil is still frozen. Success of this method depends on soil freeze–thaw cycles, late snowfall, spring rain, and the management of existing vegetation before and after seeding. Frost seeding is more successful in a bunch-type grass than in a sod-forming grass. Due to lack of uniform germination and emergence, frost seeding is more suited to pastures than hay fields. Red clover and white clover are better adapted to frost seeding than other legumes. Lespedeza (annual) may also be considered for frost seeding in southern Illinois (see **Table 6.1**). Ryegrass (annual or Italian type) and orchardgrass are two cool-season grasses that have good seedling vigor and are adapted to frost seeding. Frost seeding will not be successful every year and is less successful on sandy soils.

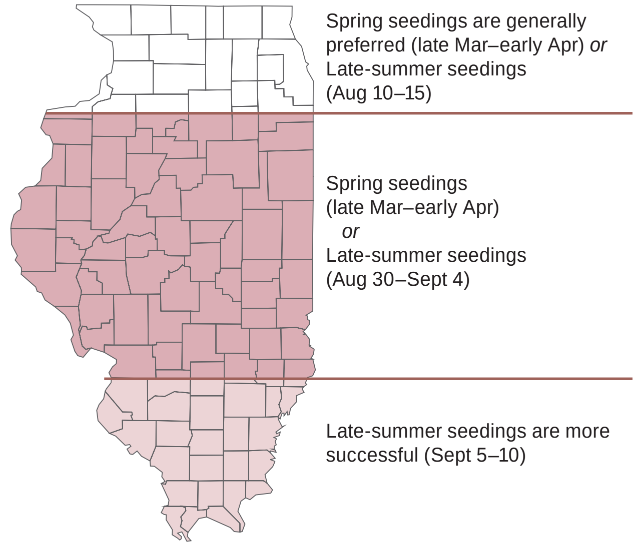

Figure 6.1. Suggested seeding dates for Illinois regions.

Figure 6.2. Spinner-type seeder for frost seeding mounted on an all-terrain vehicle.

Table 6.1. Forage seeding-rate recommendations for frost seeding (in pounds of pure live seed per acre).

Frost seeding of legume			
Moderately well to well-drained soils			
Northern and central IL		**Southern IL**	
Red clover	4–6	Red clover	4–6
		Lespedeza (annual)	20–25
Poorly drained soils			
Northern and central IL		**Southern IL**	
White clover	2–3	White clover	2–3
White clover Red clover	1–2 3–4	White clover Red clover	1–2 3–4

The table reflects recommendations from the University of Illinois, Purdue University, and Iowa State University. Characteristics, strengths, and weaknesses of legumes and grasses are described beginning on page 75. Species grouped between lines are to be planted as a mix.

Table 6.2. Forage seeding-rate recommendations for hay and pasture (in pounds of pure live seed per acre).

Moderately well to well-drained soils

Northern and central IL	
Alfalfa	12–15
Alfalfa[a] Smooth bromegrass	8–10 6–8
Alfalfa[a] Orchardgrass	8–10 4–6
Alfalfa[a] Tall fescue	8–10 8–10
Alfalfa[a] Timothy[b]	8–10 2–4
Alfalfa[a] Perennial ryegrass	8–10 4–8
Red clover White clover Orchardgrass	6–8 ½–1 4–6
Red clover White clover Tall fescue	6–8 ½–1 8–10
White clover Orchardgrass	½–1 6–8
White clover Smooth bromegrass	½–1 8–10
Birdsfoot trefoil Timothy[b]	5–7 2–4
Birdsfoot trefoil Orchardgrass	5–7 4–6
White clover Perennial ryegrass	½–1 4–8
Birdsfoot trefoil Perennial ryegrass	5–7 4–8

Southern IL	
Alfalfa	12–15
Alfalfa[a] Orchardgrass	8–10 4–6
White clover Orchardgrass	½–1 6–8
White clover Tall fescue	½–1 8–10
Alfalfa[a] Tall fescue	8–10 8–10
Alfalfa[a] Perennial ryegrass	8–10 4–8
Red clover White clover Orchardgrass	6–8 ½–1 4–6
Red clover White clover Tall fescue	6–8 ½–1 8–10
Lespedeza (annual) Orchardgrass	15 4–6
Lespedeza (annual) Tall fescue	15 8–10
White clover Perennial ryegrass	½–1 4–8
Lespedeza (annual) White clover Orchardgrass	15 ½–1 4–6

Poorly drained soils

Northern and central IL	
Birdsfoot trefoil Timothy[b]	5–7 2–4
Birdsfoot trefoil Smooth bromegrass	5–7 6–8
Alsike clover[c] White clover Timothy[b]	2–3 ¼–½ 2–4
Alsike clover[c] White clover Reed canarygrass[d]	2–3 ¼–½ 6–8
Alsike clover[c] White clover Tall fescue	2–3 ¼–½ 8–10
Alsike clover[c] Timothy[b]	3–4 2–4
Alsike clover[c] Reed canarygrass[d]	3–4 6–8
White clover Perennial ryegrass	½–1 4–8
Birdsfoot trefoil Perennial ryegrass	5–7 4–8

Southern IL	
White clover Tall fescue	½–1 8–10
Alsike clover[c] Redtop	3–4 4–6
Alsike clover[c] White clover Tall fescue	2–3 ¼–½ 8–10
Alsike clover[c] White clover Reed canarygrass[d]	2–3 ¼–½ 6–8
Alsike clover[c] Reed canarygrass[d]	3–4 6–8
Birdsfoot trefoil Timothy[b]	5–6 2–4
White clover Perennial ryegrass	½–1 4–8
Birdsfoot trefoil Perennial ryegrass	5–7 4–8

Droughty soils

Northern and central IL	
Alfalfa	12–15
Alfalfa Smooth bromegrass	8–10 6–8
Alfalfa Tall fescue	8–10 6–8
Reed canarygrass[d]	8–10

Southern IL	
Alfalfa	12–15
Alfalfa Tall fescue	8–10 6–8
Reed canarygrass[d]	8–10

The table reflects recommendations from the University of Illinois, Purdue University, and Iowa State University. Characteristics, strengths, and weaknesses of legumes and grasses are described beginning on page 75. Species grouped in the same box are to be planted as a mix.

[a]Red clover can be added at 4 lb/acre, but the alfalfa rate needs to be reduced by half; alternately, 6 to 8 lb/acre of red clover can be substituted for alfalfa.

[b]Timothy has questionable persistence long-term.

[c]Not to be used in horse pastures.

[d]Reed canarygrass is an invasive species.

Pure Live Seed

In **Table 6.2,** seeding rates are listed in pounds of pure live seed per acre. Pure live seed (PLS) is an indication of seed quality, but this information is rarely shown on seed tags.

Percent PLS is calculated by multiplying the purity of the bulk seed lot by the germination rate and dividing by 100. For example: If a bag of a species of seed is 90% pure and has a germination rate of 80%, the PLS would be 90.0 x 80.0 ÷ 100, or 72% PLS.

To determine how much seed is needed per acre, the PLS recommendation shown in **Table 6.2** would be divided by the PLS percentage and multiplied by 100. For example: If the seeding recommendation in the table is 12 pounds per acre PLS and the PLS is 72%, as in the previous paragraph, the amount of seed to purchase would be 12 ÷ 72 x 100, or 16.6 pounds per acre. In other words, you would have to plant 16.6 pounds of material from the seed bag of that species in order to plant 12 pounds of PLS per acre.

Table 6.3. Forage seeding-rate recommendations for horse pastures (in pounds of pure live seed per acre).

Moderately well to well-drained soils

Northern and central IL		Southern IL	
Kentucky bluegrass	15	Kentucky bluegrass	15
Alfalfa[a] Smooth bromegrass	8–10 6–8	Alfalfa[a] Orchardgrass	8–10 4–6
Alfalfa[a] Orchardgrass	8–10 4–6	Alfalfa[a] Tall fescue[b]	8–10 8–10
Alfalfa[a] Tall fescue[b]	8–10 8–10		

Poorly drained soils

Northern and central IL		Southern IL	
Kentucky bluegrass	15	Kentucky bluegrass	15
Red clover Timothy[c]	6–8 2–4	White clover Kentucky bluegrass	½–1 4–5
Red clover White clover Timothy[c]	4–6 ¼–½ 2–4	White clover Orchardgrass	½–1 4–6
Birdsfoot trefoil Timothy[c]	6–7 2–4	Red clover Orchardgrass	6–8 4–6
White clover Tall fescue[b]	½–1 8–10	White clover Tall fescue[b]	½–1 8–10
		Red clover Tall fescue[b]	6–8 8–10

The table reflects recommendations from the University of Illinois, Purdue University, and Iowa State University. Characteristics, strengths, and weaknesses of legumes and grasses are described beginning on page 75. Species grouped between lines are to be planted as a mix.

[a]Red clover can be added at 4 lb/acre, but the alfalfa rate needs to be reduced by half; alternatively, 6 to 8 lb/acre of red clover can be substituted for alfalfa. Red clover can cause some horses to salivate.

[b]If seeding tall fescue, plant "low" or "friendly" (novel) endophyte variety.

[c]Timothy has questionable persistence long-term.

Table 6.4. Forage seeding-rate recommendations for hog pastures (in pounds of pure live seed per acre).

For all soil types, anywhere in Illinois	
Alfalfa White clover	8 2
Alfalfa Red clover White clover	4 4 2
Forage rape Oats	4–6 32–64 (1–2 bushels)

The table reflects recommendations from the University of Illinois, Purdue University, and Iowa State University. Species grouped between lines are to be planted as a mix. Characteristics, strengths, and weaknesses of legumes and grasses are described beginning on page 75.

Seeding-rate recommendations for hay and pasture are shown in **Table 6.2** and are listed in pounds of pure live seed per acre (see the sidebar "Pure Live Seed" for more discussion). Specific recommendations for horse pastures are provided in **Table 6.3** and for hog pastures in **Table 6.4**. These rates are for seedings made under average conditions, either with a companion crop in the spring or without a companion crop in late summer. These tables are not meant to be all-inclusive; rather, they list commonly used species that have been researched and evaluated.

A spring seeding rate for alfalfa higher than that shown in **Table 6.2** has proven economical in northern and central Illinois when solo-seeded and when two or three harvests were taken in the seeding year. In northern and central Illinois, but not in south-central Illinois, seeding alfalfa at 18 pounds per acre (bulk seed) has produced yields 0.2 to 0.4 ton per acre higher than seeding at 12 pounds per acre (bulk seed).

A **companion crop,** or nurse crop, of oats has historically been used with spring forage seedings. With improvements in seeding equipment and herbicides, more alfalfa is direct-seeded (without a companion crop). Some dairy producers seed a small grain–pea mixture with spring-seeded alfalfa to increase crude protein and yield. The advantages of a companion crop are quick ground cover, additional forage, and reduced soil erosion and weed invasion. The disadvantages are competition with the perennial forage for moisture, nutrients, and light and the potential to smother the forage.

Two options for companion crops are spring oats (1 to 1.5 bushels per acre) and Italian ryegrass (2 to 4 pounds per acre). The use of fall-planted winter rye (cereal or grain rye) is not encouraged due to its aggressive growth. The decision to use a companion crop during spring forage establishment is site-specific. However, remember that the "money crop" is the perennial forage that is being established, not the companion crop.

Seeding on a prepared (tilled) seedbed. After the field has been tilled, seeding can be accomplished in one of two ways:

- *Broadcast seeding.* The seed is spread uniformly over a firm, prepared seedbed; then the seed is pressed into the seedbed surface with a corrugated roller (**Figure 6.3**). Fertilizer is applied during seedbed preparation. Typically, soil conditions are too loose (or soft) after tillage, and the soil should be firmed with a corrugated roller before seeding. The soil is firm enough if you don't leave a footprint any deeper than the sole of your shoe. The best tool for broadcast seeding is the double-corrugated roller seeder (**Figure 6.4**).

● *Band seeding.* A band of phosphorus fertilizer (for example, 0-46-0) is placed about 2 inches deep in the soil in rows 7 to 8 inches apart using a grain drill; then the seed is placed on the soil surface directly above the fertilizer band (**Figure 6.5**). Before the seeds are dropped, the fertilizer should be covered with soil, which occurs naturally when soils are in good working condition. A presswheel or packer wheel should roll over the forage seed to firm the seed into the soil surface.

Which is the better seeding method? Illinois studies have shown that band seeding often results in higher alfalfa yields for spring and late-August seedings. Seedings on soils that are low in phosphorus also yield more from band seeding. Successful early seeding on cold, wet soils is favored by banded phosphorus fertilizer. The greater yield from band seeding may be a response to abundant, readily available phosphorus from the banded fertilizer.

Broadcast seedings yield similarly to band seedings when soils are medium to high in phosphorus-supplying capacity and are well drained, so that they warm up faster in spring.

Seeding no-till. With this method, forage seed is planted, using a no-till drill, directly into a field with no additional tillage after harvesting the previous crop. Crop residues on the soil surface will reduce runoff and soil erosion and help conserve soil moisture. Fuel costs are lowered as a result of reduced trips across the field. The no-till drill must be adjusted correctly and be equipped with coulters, double-disc (or other suitable) seed placement units, and presswheels. The drill must open a seed furrow, place the seed at the correct depth, and cover and firm the soil over the seed. Weeds need to be controlled before forage establishment.

Seeding depth. Regardless of seeding method, small forage seeds should be placed 1/4 to 1/2 inch deep. On sandy soil, place seed up to 1 inch deep. A firm seedbed provides good seed-to-soil contact and enables the seed to absorb moisture. This is especially important with late-summer seedings.

Pasture establishment. If a new pasture is established from a prepared seedbed, it is suggested that it be harvested as hay the first year so that a "sod" can be formed to support livestock traffic.

Many pastures are established through a hay-crop program. If you intend for the hay crop to become a pasture, seed the desired mixture of legume(s) and grass(es). Whatever the method of establishment, consider factors such as the investment required (time, labor, money), the erosion potential, the length of time the field will be out of production, and access to equipment and pesticides. Pastures can also be renovated (p. 70) using reduced till or no-till methods or by frost seeding (p. 66).

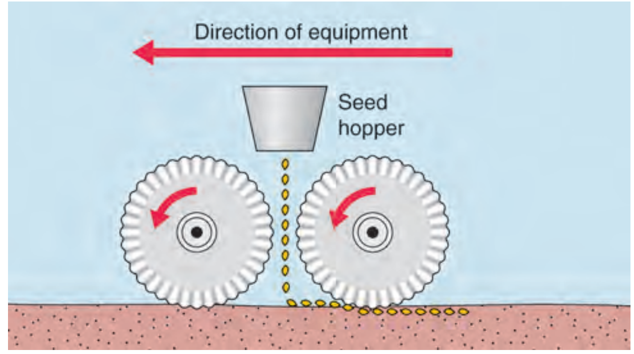

Figure 6.3. Schematic of broadcast seeding with a double-corrugated roller-seeder.

Figure 6.4. Double-corrugated roller-seeder (Brillion brand).

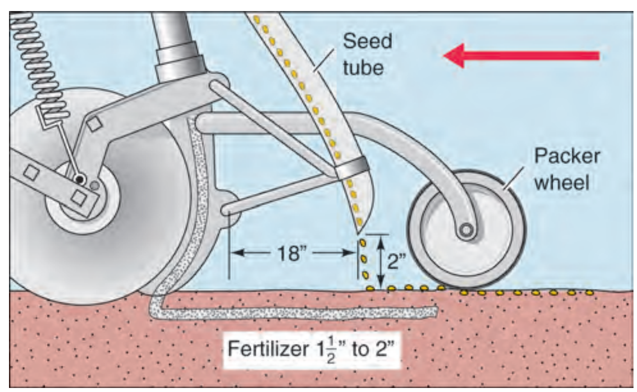

Figure 6.5. Placement of seed and high-phosphate fertilizer with grain drill.

Weed and insect control. Preplant, preemergence, and postemergence herbicides are available to help manage weeds when establishing hay and pasture. The specific herbicide and the time and method of application will depend on the forage species being planted (grass vs. legume vs. mixture), the weed species present, the age of the forage stand (seeding year vs. established stand), and other factors. Some pesticides have harvest, grazing, or other restrictions that need to be followed. Certain insects may reach damaging levels and may need to be controlled. Consult University of Illinois references for weed, insect, and disease identification and management suggestions. Follow label directions when using any pesticide.

Inoculation of legume seed. Legume seed should be inoculated with the proper strain of nitrogen-fixing bacteria before seeding (see p. 76 for additional discussion). Preinoculated seed should be stored in a cool, dry location from the time of purchase until it is planted. Be sure to observe the expiration date of the inoculant.

Pasture Renovation

Pasture renovation usually means changing the plant species, typically adding one or more legumes, in a pasture to increase quality and productivity. First identify the current species and evaluate the grazing management being used. A soil test will identify the need for lime, phosphorus, and potassium, all of which are very important in the establishment and stand life of forages. Be sure to take soil samples in advance so that if lime and fertilizer are needed they can be applied at least 6 months prior to seeding.

Before seeding new legumes or grasses into a pasture, reduce the competition from existing pasture plants. Tilling, overgrazing, and herbicides labeled for pasture renovation, used singly or in combination, have proven useful in subduing existing vegetation.

As mentioned, **frost seeding** is one method of renovation (see p. 66). **Interseeding** is a second method. The following steps are suggested for interseeding:

1. Where possible, graze the pasture heavily for 20 to 30 days before seeding to reduce the vigor of existing pasture plants. If overgrazing is not possible and if existing grasses are to be eliminated, consider applying a product containing glyphosate (a general-use pesticide) 2 to 3 weeks before the seeding date. In fields where a desirable grass species is to be subdued but not eliminated prior to planting, consider using a herbicide containing paraquat (a restricted-use pesticide) to suppress its growth.
2. Lime and fertilize, using a soil test as a guide. A minimum pH of 6.5 is suggested for legume–cool-season grass mixtures. Desirable phosphorus and potassium soil test levels vary with soil type and location in the state. Optimum phosphorus level is 40 to 50 pounds per acre, and optimum potassium level is 260 to 300 pounds per acre. See the information on soil testing in Chapter 8 for more details.
3. One or two days before seeding, consider applying a herbicide to subdue the vegetation *if a herbicide has not already been applied or if plant growth is excessive.* Paraquat and glyphosate are approved for this purpose. Follow label directions. Where an existing grass species is to be eliminated, use glyphosate at label rates. Where a desirable grass species is to be suppressed temporarily, use paraquat.
4. Seed the desired species, using high-yielding, adapted varieties (see **Table 6.5**). Alfalfa, red clover, white clover, and birdsfoot trefoil are legumes often seeded into pastures that have desirable grasses. To seed, use a

Table 6.5. Forage seeding-rate recommendations (in pounds of pure live seed per acre) for interseeding legume no-till into existing grass sod.

Moderately well to well-drained soils

Northern and central IL		Southern IL	
Alfalfa	7–8	Alfalfa	7–8
Red clover	4–5	Red clover	4–5
Red clover White clover	3–4 ½–1	Red clover White clover	3–4 ½–1
Birdsfoot trefoil	5–6	Lespedeza (annual)	15–20
		Birdsfoot trefoil	5–6

Poorly drained soils

Northern and central IL		Southern IL	
Red clover	4–5	Red clover	4–5
Red clover White clover	3–4 ½–1	Red clover White clover	3–4 ½–1
Birdsfoot trefoil	5–6	Lespedeza (annual)	15–20
Alsike clover[a] White clover	2 ½–1	Alsike clover[a] White clover	2 ½–1
		Birdsfoot trefoil	5–6

The table reflects recommendations from the University of Illinois, Purdue University, and Iowa State University. Characteristics, strengths, and weaknesses of legumes and grasses are described beginning on page 75. Species grouped between lines are to be planted as a mix.
[a]Not to be used in horse pastures.

Figure 6.6. No-till seeder (Tye brand).

no-till drill (**Figures 6.6 and 6.7**) that places the seed in contact with the soil at the proper depth.

5. Seedings may be made in early spring throughout the northern two-thirds of Illinois and in late August throughout the southern three-fourths.
6. Insects that eat germinating seedlings are more prevalent in southern Illinois than in northern Illinois, and an insecticide may be needed. Leafhoppers will usually appear on alfalfa foliage throughout Illinois in early summer and remain during most of the growing season. They must be controlled where alfalfa is seeded, especially in spring-seeded hay and pasture, because leafhopper feeding devastates new alfalfa seedlings. Leafhopper damage may be less where alfalfa is seeded with grass as opposed to a pure alfalfa stand. Leafhopper-resistant alfalfa varieties are available, and several insecticides are approved. Consult University of Illinois references for pest identification and management. Follow label directions when using any pesticide.
7. Management practices based on timely observations will help the new seedings become established (**Figure 6.8**). Rotational grazing will control competition from the sod, but do not allow newly emerged seedlings to be closely grazed. Clipping just above the new seedlings may be needed if weeds become a problem. New seedlings require light to maintain good growth. As a guide, about 5 weeks after spring seeding, the grass should be recovered from paraquat sod-suppression treatment, and managed grazing should be feasible. Close grazing should be avoided.
8. Late-August seedings should not be grazed until the following spring. Alfalfa and red clover seeded in late August should be in the late-bud to early flower stage when spring grazing begins. As with spring seedings, use rotational grazing and monitor the status of newly seeded plants.
9. Monitor and maintain soil fertility by soil testing on a regular basis.

Hay Harvest Management

Spring seeding year, with a companion crop. Spring-seeded forages for hay will benefit by early removal of the companion crop. The small-grain companion crop should be removed when the grain is in the boot to milk stage. If these small grains are harvested for grain, it is important to remove the straw and stubble as soon as possible to avoid smothering the perennial forage. Subsequent hay harvest of the perennial forage crop can be at 30 to 40 days, but follow the guideline below for last hay harvest.

Figure 6.7. No-till interseeding in April, northern Illinois.

Figure 6.8. Newly emerging red clover sown by no-till seeder.

Spring seeding year, without a companion crop (direct or solo seeding). Spring-seeded forages for hay should be ready for harvest 65 to 70 days after a late March–early April seeding. A second and perhaps a third harvest may follow the first harvest at 30- to 40-day intervals, but follow the guideline below for last hay harvest.

Last hay harvest during the growing season should be in late August or early September for the northern quarter of Illinois, by September 10 for the central half, and by September 20 for the southern quarter. The interval between last harvest date and the first killing frost allows food reserves (carbohydrates) to accumulate in the taproot and increases the chance for winter survival. Following harvest, root reserves decline as new growth begins. About 2 to 3 weeks after harvest, or when new regrowth is 6 to 8 inches tall, root reserves are depleted to a low level, and the top growth is adequate for photosynthesis to support the plant's need for carbohydrates. Root reserves are then replenished gradually until harvest or until the plant becomes dormant.

About 6 weeks of growth is required after a cutting to have enough food reserves produced and stored. This is the basis of the last harvest dates specified.

Dormant harvest is making a cutting of hay when the alfalfa is dormant or growing very slowly. Fall dormancy in alfalfa is a function of air temperature, duration of cool temperatures, and the fall dormancy rating of the variety. Alfalfa becomes dormant with an air temperature of 26 °F for a few consecutive days. Harvests in September and October affect late-fall root reserves of alfalfa more than summer harvests do. Dormant harvest may be taken after mid-October for northern Illinois, in late October for central Illinois, and in early November for southern Illinois.

Factors to consider if you are planning a dormant harvest include age of the stand, plant health status, soil-fertility level, soil drainage, and stubble height remaining after harvest. A spring-seeded stand should not have a dormant harvest taken that same year. If taking a dormant cutting, leave a 6- to 8-inch stubble height to catch snow to better protect the crop.

Established stands. Frequency of hay harvests is a trade-off among quality, yield, and stand persistence. The nutritional needs of the livestock consuming the hay need to be considered.

Maximum dry-matter yield and persistence from alfalfa and most forages are obtained by having the first cutting at nearly full bloom and harvesting every 40 to 42 days. Quality of this forage is lower.

High-quality forages should have the first harvest taken at the bud (for legumes) or boot (for grasses) stage. Subsequent harvests are taken at 28- to 32-day intervals. A very aggressive hay-cutting schedule may shorten stand life. For high-quality alfalfa, producers are encouraged to utilize the PEAQ technique described below.

A *compromise between quality and yield* is to make the first cutting at late-bud to first-flower stage and make subsequent cuttings at 32- to 35-day intervals.

See the sidebar for more discussion on forage quality, including forage testing.

Predicting first harvest for high-quality alfalfa. Producers desiring high-quality alfalfa hay at first cutting are encouraged to use the "Predictive Equations for Alfalfa Quality" (PEAQ) as a guide to determine the date for first harvest. This method provides an in-field estimate of

Forage Quality

Forage quality can be defined as all those characteristics that affect consumption, nutritive value, and performance of livestock. Forage quality is greatly affected by stage of maturity. As forage crops mature, their nutritive value declines.

Relative feed value (RFV) is an indicator of forage quality. The higher the RFV, the higher the quality. RFV, which declines with advancing maturity of the forage, can be calculated as follows:

1. Calculate digestible dry matter (DDM) of the forage on a dry-matter basis:

   DDM = 88.9 – (0.779 x acid detergent fiber)

2. Calculate dry-matter intake (DMI) of the forage as a percentage of body weight:

   DMI = 120 ÷ neutral detergent fiber

3. Calculate RFV:

   RFV = (DDM x DMI) ÷ 1.29

Relative forage quality (RFQ) is a new index to rank the quality of forages. Due to the digestible fiber component, RFQ appears to predict animal performance better than relative feed value. RFQ can be calculated as follows:

RFQ = (DMI, as % of body weight) x (TDN, as % of DM) ÷ 1.23

Forage Quality Definitions

Acid detergent fiber (ADF) is the percentage of cellulose, lignin, and ash in forage. ADF is used to calculate net energy values and indicates digestibility of the forage. As ADF increases, digestibility and energy content of forage decrease.

Neutral detergent fiber (NDF) is the percentage of cell wall material or fiber in the forage. It is inversely related to forage intake. As NDF increases, the amount an animal can consume decreases.

RFV is a calculated index that rates forage by potential intake of digestible dry matter. Average full-bloom alfalfa hay has an RFV of about 100. Higher quality forages would have an RFV above 100.

Crude protein (CP) is a measure of the true protein and nonprotein nitrogen portion of the forage. It is determined by multiplying the actual nitrogen content by a factor of 6.25.

RFQ provides a better quality estimate for grasses and legume–grass mixtures than relative feed value. RFQ can be used for all forages, including warm-season grasses and brassicas (turnips, rape, kale, etc.). However, RFQ should not be used for corn silage. It appears that RFQ and RFV average about the same, so RFQ can be substituted for RFV in pricing, contracts, and other uses.

Forage analysis or a forage test can supply useful information about the nutritional value of hay and pasture. The values described here are measured or calculated in a forage analysis. To find a list of forage testing laboratories, how to take a forage sample, where to purchase a hay probe, and other details, see the National Forage Testing Association website (www.foragetesting.org).

preharvest quality of standing alfalfa. It is not designed to balance rations and cannot account for harvest or storage losses.

The **PEAQ** method predicts relative feed value (RFV) and neutral detergent fiber (NDF) content based on plant maturity and plant height within a 2-square-foot area. With the use of either a table (see **Table 6.6** for University of Wisconsin PEAQ-RFV data) or a specially calibrated "measuring stick" (available from some alfalfa seed companies), estimates of RFV and NDF can be obtained directly from the field. PEAQ is designed for good, healthy stands of pure alfalfa.

Since about 15 RFV units are lost during harvest, alfalfa needs to be cut at 165 to 170 RFV using PEAQ to have 150 RFV of harvested forage.

More details about PEAQ can be found at the University of Illinois website peaq.traill.uiuc.edu.

Table 6.6. Relative feed value of standing alfalfa hay.

Height of tallest stem (in.)[a]	Stage of most mature stem		
	Late vegetative[b]	Bud[c]	Flower[d]
16	237	225	210
17	230	218	204
18	224	212	198
19	217	207	193
20	211	201	188
21	205	196	183
22	200	190	178
23	195	185	174
24	190	181	170
25	185	176	166
26	180	172	162
27	175	168	158
28	171	164	154
29	167	160	151
30	163	156	147
31	159	152	144
32	155	149	140
33	152	145	137
34	148	142	134
35	145	139	131
36	142	136	128
37	138	133	126
38	135	130	123
39	132	127	121
40	129	124	118
41	127	122	115
42	124	119	113

[a]From soil surface to stem tip.
[b]>12 in. with no buds visible.
[c]1 or more nodes with visible buds; no flowers visible.
[d]1 or more nodes with open flower(s).

Drying Agents and Preservatives for Hay

Drying agents or compounds to speed drying are sprayed onto hay at mowing to increase the drying rate. Drying agents contain potassium and sodium carbonates; they work only on legumes, not grasses. These products reduce drying time the most when drying conditions are good, so they tend to work better on second and third cuttings. Typical application rate is 5 to 7 pounds of active ingredient in 30 gallons of water per acre. Thorough coverage of the forage is important.

Preservatives are sprayed onto the hay as the bale is being formed to allow baling of hay that is wetter than normal without spoiling during storage. A commonly used preservative is "buffered" propionic acid. Acetic acid, another organic acid, is about half as effective as a preservative, so twice as much is needed. The application rate for propionic acid depends on the moisture content of the hay: for 20% to 25% moisture hay, the application rate is 0.5% to 0.9% propionic acid (10 lb per ton); for 26% to 30% moisture hay, the rate is 1.0% to 1.13% (20 lb per ton). These rates are for 100% propionic acid solution; if you are using a 50% propionic material, the rate needs to be doubled.

Hay-Making Practices

Various harvest management techniques and strategies will result in quality hay:

- Make hay harvest a top priority.
- Mow early in the day (start at 9:00 to 10:00 a.m.), after some, but not all, of the dew is gone.
- Rake when moisture content is higher than 40%.
- Bale when the moisture content for non-preservative-treated hay is 16% to 20%. Small square bales should be baled at 18% to 20%, medium squares at 16%, large squares (one ton, 8 x 4 x 4 feet) at 14%, and round bales at 16% to 18%.
- Research indicates no difference in drying rate and yield between a disk mower-conditioner and a sickle bar

mower. Impeller-type mower-conditioners dry grass hay quicker, while roll-type mower-conditioners dry alfalfa hay quicker (University of Wisconsin data).

- To get faster drying, always condition the hay, maintain proper roller clearance, and spread the swath as wide as possible.
- Ted only when necessary.
- Store hay in a barn or shed, or off the ground and under a cover.

Pasture-Grazing Management

Pasture management involves managing the interactions of plants, livestock, and soil. There are three basic types of grazing systems: continuous, rotational, and management-intensive.

Continuous grazing gives livestock unrestricted access to an area for an entire growing season. The grazier provides limited management; livestock graze when, where, and what they choose. Overgrazing, uneven manure distribution, and lower forage quality and yield often result.

Rotational grazing is a system in which livestock are moved regularly from one pasture to another. Pastures are allowed to rest and regrow, manure is more evenly distributed, and yield and forage utilization are increased. Watering and fencing costs are higher than with continuous grazing.

Management-intensive grazing is a system in which large pastures are divided into smaller areas called paddocks. Livestock are moved more frequently at high stocking rates from one paddock to another. Forage yield and manure distribution are higher than with continuous and rotational systems. Forages are able to rest and regrow before being grazed again. This system requires a higher level of management by the grazier and startup costs for fencing and watering.

To utilize excess forage in the late spring, it would be advantageous to make hay from one or more paddocks. Various crops (stockpiled pasture, oats, brassicas, warm-season annual grasses, corn residue, etc.) can be utilized to extend the grazing season, resulting in cost savings since less hay or other stored feed will be fed.

An example of a basic rotational grazing system is 10 days of grazing with 30 days of rest, requiring 4 paddocks. A more intensive rotational grazing system is 5 to 7 days of grazing with 28 to 30 days of rest, requiring 5 or 6 paddocks. An example of a management-intensive grazing system is 3 to 4 days of grazing with 30 to 33 days of rest, needing 8 to 11 paddocks. Dairy graziers typically utilize 12-hour grazing periods (moving cows twice a day to new forage), requiring more paddocks.

To determine the number of pastures (or paddocks) needed for either rotational or management-intensive grazing, use this formula: days of rest ÷ days of grazing + 1. However, livestock should be moved according to the forage and not by the calendar.

One of the principles of managed grazing, as compared with continuous grazing, is providing forages the time to rest between one grazing and the next. This rest period gives forages the time to grow, build root reserves, and maintain vigor. Many graziers follow the guideline of "graze half, leave half."

Recent developments in *fencing and watering techniques* have made management-intensive grazing more user-friendly. Polywire, polytape, and temporary fence posts can be used for interior, moveable fencing. High-tensile wire can be used for permanent perimeter fencing. Livestock should not have to travel more than 800 feet to access water. Ideally, water should be available in every pasture or paddock.

When adopting a rotational or management-intensive grazing system, consider the forage quality requirement of the livestock, estimate forage production and stocking density, determine the number of paddocks needed, remember to fence quantity and not acres, and remain flexible. The amount of forage growth that can be removed per grazing period and the needed rest period will vary with the forage species and season of the year and from year to year.

Weed control in pastures may be needed. An integrated approach using several different methods will be more effective than relying on a single practice: combine weed control methods that are mechanical (clipping, hand digging), chemical (herbicide), cultural (maintaining dense, active, and vigorously growing forages), and biological. Consult University of Illinois references for weed identification and management suggestions. Follow label directions when using any pesticide.

Selecting Hay and Pasture Species

The University of Illinois has conducted a testing program of public and private forages for many years. The 2008 field locations were Freeport (Stephenson County) and Urbana (Champaign County). The Freeport site is on a dairy farm, and the Urbana location is on the University of Illinois Crop Sciences Research and Education Center.

The Department of Crop Sciences publishes each year *Forage Crop Variety Trials in Illinois*, a report summarizing performance data of forage species and varieties grown at the test field locations by seeding year. The publication is available at extension offices and online at vt.cropsci.illinois.edu.

There is no one "best" forage species. All species, whether grown for hay or pasture, have strengths and weaknesses. Differences exist among species in winter-hardiness, ease of establishment, tolerance to various soil conditions (drought, wet, acidity), persistence, seasonal growth patterns, and antiquality factors (such as bloat, endophyte, and alkaloids). Major strengths and weaknesses of commonly grown legume and grass species for hay and pasture in Illinois are detailed in the following sections.

When selecting a variety within a species, consider yield potential, persistence, winter-hardiness, disease and insect resistance, and forage quality. Using certified seed assures genetic purity and trueness to variety name.

Even though a grass or legume species can be grown alone, mixtures of legumes and cool-season grasses often improve performance of pastures and multi-use pasture and hay fields. Each selected legume and grass in the mixture needs to be appropriate to the field and have a specific purpose. In most situations, a mixture of two to four well-chosen species is more desirable than a mixture of numerous species, some of which may not be particularly well suited to the soil, climate, or use. Generally, seeding prepackaged mixes of several legume and grass species is not encouraged.

See **Table 6.2** for seeding-rate recommendations.

Legume Species

Please note that the following discussion is not all-inclusive of legume species. The focus here is on the species most commonly adapted or evaluated for use in Illinois.

Alfalfa is the highest yielding and highest quality perennial forage suited to Illinois. It requires a well-drained soil with pH of 6.7 to 7.0. Grazing-tolerant, traffic-tolerant, and potato leafhopper–tolerant varieties are available. When deciding to purchase a leafhopper-tolerant variety, consider the frequency at which you scout for leafhoppers and the level of resistance of the variety you are considering (new generation varieties are 80% resistant). Diseases can affect all alfalfa plant parts and at different growth stages. Diseases can reduce yield, quality, and persistence. More information on alfalfa diseases is available at cropdisease.cropsci.illinois.edu. Resistance ratings to various diseases are listed in the current edition of *Winter Survival, Fall Dormancy and Pest Resistance Ratings for Alfalfa Varieties*, available through the National Alfalfa and Forage Alliance (www.alfalfa.org/publications.html).

Major strengths	Major weaknesses
Drought-tolerant	Not tolerant of wet, poorly drained soils
Excellent summer regrowth	Causes bloat in pure stands
Wide variety of uses	Potato leafhopper is major insect pest
	Not suited for frost seeding
	Requires rotational grazing to persist in pasture

Alfalfa produces a water-soluble toxin that moves into the soil and reduces the germination and growth of new alfalfa seedings. This phenomenon is called *autotoxicity*. At least half of the toxin is found in the aboveground plant parts; the balance is below ground.

When a stand is more than a year old, enough of the toxin may be present to cause damage to new seedings reestablished into that field. The main effect of autotoxicity is to limit the ability of root hairs to take up water and thus reduce development of the seedling. Alfalfa does not outgrow the initial effects of autotoxicity.

When the stand is more than a year old, alfalfa should not be reestablished in the field; instead, another crop (corn is best) should be grown for one year. This allows the toxin time to degrade and leach away from the root zone.

Research at the University of Missouri on reestablishing alfalfa found that when there were more than 1.3 plants per square foot, stands failed. Stands were successfully reestablished when there were less than 0.2 plant per square foot (1 plant per 5 square feet).

Alfalfa stands one year old or younger have produced very little of the toxin, so if necessary, alfalfa could be reestablished.

Red clover is the second most important hay and pasture legume in Illinois. There are two major types: medium (an early, two-cut type) and mammoth (a late, one-cut type). The medium type is preferred for Illinois. Red clover is generally considered a short-lived perennial (2 to 3 years); however, newer varieties are more disease resistant and may persist longer.

Major strengths	Major weaknesses
Easy and quick to establish	Not persistent; susceptible to root diseases
Tolerates wetter soil and lower pH than alfalfa	Not as drought-tolerant as alfalfa
Tolerates shade	Pubescent, so hard to dry for hay
High-yielding	Causes bloat
Reseeds easily	Can cause horses to salivate ("slobbers")
Adapted to frost seeding	Does not grow well on coarse-textured soil

White clover is commonly found in pastures and some hay fields. There are three types, or subspecies, of white clover. Ladino commonly refers to the large type of white clover that is higher yielding. White clover is generally considered a low-growing perennial legume, but new varieties have more upright growth.

Major strengths	Major weaknesses
Very high quality	Causes bloat
Prolific seed producer and self-seeding	Shallow-rooted
Tolerates lower soil pH than alfalfa and red clover	Low-yielding, especially for hay
Adapted to close grazing	Not drought-tolerant
Tolerates wetter, poorly drained soil	

Birdsfoot trefoil is a nonbloating, long-lived, winter-hardy perennial legume traditionally grown in northern Illinois pastures. It is more commonly grown for pasture than hay.

Major strengths	Major weaknesses
Does not cause bloat	Low seedling vigor; slow to establish
Adapted to poorly drained, acidic soils	Shallow-rooted; does not tolerate drought
Will reseed itself	Presence of tannins may reduce palatability

Alsike clover is a short-lived perennial that can be grown for hay and pasture. Because of fine stems that lodge, it should be grown with grass to help keep the legume erect. It should not be included in horse pastures, since this legume causes photosensitivity.

Major strengths	Major weaknesses
Well suited for wet, poorly drained soils	Not drought tolerant
Tolerant of acidic soils	Low-yielding
	Causes bloat and photosensitivity

Kura clover is a relatively new perennial, winter-hardy legume with a rhizomatous rooting system, well adapted to grazing. Evaluations of the species for pasture and hay, grown with and without grasses, are in progress. Seed may be difficult to obtain, and very slow stand establishment should be expected. Seed 6 to 8 pounds per acre in mixture with cool-season grasses.

Major strengths	Major weaknesses
Winterhardy	Poor seedling vigor
Very persistent once established	Slow to establish
Spreads by underground rhizomes	Causes bloat
Tolerant of poorly drained, acidic soils	Nonpubescent, attacked by potato leafhopper
	Requires special *Rhizobium* inoculum in order to fix nitrogen

Lespedeza (Korean) is a popular warm-season annual legume in the southern third of Illinois. The annual species is more palatable and higher yielding than the perennial type (Sericea).

Major strengths	Major weaknesses
Will tolerate low productive, eroded soils	Lower yielding
Easy to establish; can be frost seeded	Relatively shallow root system
Will reseed itself	Risk of rapid leaf shatter when harvested as hay
Does not cause bloat	Seed may contain considerable amount of hard seed

Sweetclover is now used mainly as a green manure crop and a forage crop for bees. Two common types of this legume exist in Illinois, yellow-flowered (biennial) and white-flowered (annual and biennial).

Major strengths	Major weaknesses
Biennials have deep taproot; drought-tolerant	Needs soil pH of at least 6.5
Biennial is winter-hardy	Not tolerant of poorly drained soil
Excellent for soil improvement	Contains coumarin, which may cause "bleeding disease" in cattle and reduced palatability
Good source of nectar and pollen for bees	Hay can get stemmy
	Grows prolifically on roadsides, etc., so is considered invasive

Hairy vetch is a winter annual legume most often grown for soil improvement or as a winter cover crop instead of a forage crop. It has a viney growth habit.

Major strengths	Major weaknesses
Can grow on a wide variety of soils	Less winter-hardy than alfalfa and red clover
Green manure crop providing source of nitrogen, especially in central and southern Illinois	Medium palatability
If grown for hay, should be seeded with small grain (winter rye, winter wheat, or winter triticale)	For best establishment, seed in August

Crownvetch is a well-known perennial legume used mainly as a soil conservation crop protecting erodible areas (such as road banks) and for land reclamation, rather than as a forage crop. It is a member of the pea family.

Major strengths	Major weaknesses
Deep-rooted	Slow to establish, low seeding vigor
Winter-hardy, long-lived	Low palatability
Drought-tolerant	Slow regrowth
Does not cause bloat	Difficult to harvest as hay due to prostrate growth habit
	Invasive

Inoculation of legumes. Legumes, such as the species just described, can meet their nitrogen needs from the soil atmosphere if the roots have the correct *Rhizobium* species and favorable conditions of soil pH, drainage, and temperature. *Rhizobium* bacteria are numerous in most soils; however, the species needed by a particular legume species may be lacking.

There are seven general groups and some other specific strains of *Rhizobium*, with each group specifically infecting roots of plants within its corresponding group and some specific strains infecting only a single species. The legume groups are alfalfa and sweetclover; true clovers (such as red, ladino, white, and alsike); peas and vetch (such as field pea, garden pea, and hairy vetch); beans (such as garden and pinto); cowpeas and lespedeza; soybean; and lupines. Some of the individual *Rhizobium* strains are specific to birdsfoot trefoil, crownvetch, cicer milkvetch, kura clover, and sainfoin. Legume seed should be inoculated with the proper *Rhizobium* bacteria before each planting.

Cool-Season Grass Species

Please note that the following discussion is not all-inclusive of cool-season grass species. The focus here is on the species most commonly adapted or evaluated for use in Illinois. **Table 6.2** lists seeding-rate recommendations for grass–legume mixtures. **Table 6.7** lists seeding-rate recommendations for pure grass stands for both perennial and annual grasses.

Table 6.7. Forage seeding-rate recommendations for cool-season grasses (in pounds of pure live seed per acre).

Cool-season perennial grasses (pure stand)	
Festulolium	20–25
Kentucky bluegrass	10–15
Meadow fescue	15–20
Orchardgrass	10–15
Reed canarygrass	6–10
Ryegrass, perennial	20–25
Smooth bromegrass	15–20
Tall fescue	10–15
Timothy	6–8
Cool-season annual grass (pure stand)	
Oats, seeded in mid-August	96 (3 bushels per acre)

The table reflects recommendations from the University of Illinois, Purdue University, and Iowa State University. Characteristics, strengths, and weaknesses of legumes and grasses are described beginning on page 75.

Timothy is a bunch-type perennial grass for hay and pasture that is best suited to the northern half of Illinois. Since it matures relatively late, timothy is commonly grown with red clover or birdsfoot trefoil. Timothy requires a long rest period after grazing or hay harvest for maximum productivity and persistence.

Major strengths	Major weaknesses
Winter-hardy	Poor tolerance to heat, drought, and traffic
Grows best in cool, moist soil conditions	Shallow-rooted
Compatible with legumes in mixtures, provided maturities are similar	Seedheads are constantly produced, thus stemmy
	Stand does not persist
	Limited production after first harvest

Smooth bromegrass is a winter-hardy, high-yielding, sod-forming perennial grass for northern and central Illinois hay and pasture. Smooth bromegrass works well in mixes with alfalfa or red clover.

Major strengths	Major weaknesses
Adapted to well-drained and droughty soils	Fluffy seed is hard to flow through seeder
Winter-hardy	Slow to establish, low seeding vigor
Highly palatable	Less summer production than orchardgrass
Responsive to nitrogen	Must be rested after harvest or stand will not persist. Hay harvests must be limited to 3 cuts a year.
Heat-tolerant	Not tolerant of close grazing

Orchardgrass is a high-yielding, bunch-type perennial grass adapted throughout the state for hay and pasture. Winter-hardy varieties need to be grown in northern Illinois. Orchardgrass grows best on soils with good moisture-holding capacity. Seed medium- to late-maturing varieties when grown with legumes.

Major strengths	Major weaknesses
Easy to establish and can be frost-seeded	Not drought-tolerant
Palatable	Varieties differ in susceptibility to rust and leaf spot diseases
Quick recovery after harvest	Varieties differ greatly in maturity
One of the most productive grasses in midsummer	Moderately winter-hardy for the northern quarter of Illinois
Grows in partial shade better than other grasses	

Reed canarygrass, a sod-forming, winter-hardy perennial grass, is not widely used, but it has growth attributes that deserve consideration. Low-alkaloid varieties should be sown, as they typically provide better animal performance and better intake. Keep in vegetative stage for best performance and to prevent seed escape to wetlands.

Major strengths	Major weaknesses
High-yielding	Slow to establish
Aggressive once established	Older varieties had low palatability due to presence of alkaloids
Persistent	Careful management needed for high quality
Can tolerate wet and dry soil conditions	Considered an invasive species, especially in wetlands
Deep-rooted	
Can utilize high soil fertility	

Tall fescue is a high-yielding, bunch-type perennial grass used for hay and pasture. Historically, it has been the predominant grass grown in the southern half of Illinois, but it can be grown throughout the state.

Major strengths	Major weaknesses
Widely adapted	Low palatability and quality of endophyte-infected varieties
Tolerant of livestock and vehicle traffic	Winterhardiness and disease resistance vary by variety
High-yielding	Fescue toxicosis caused by the endophytic fungus
Best grass for stockpiling (deferred grazing) since it maintains quality and palatability	
Moderately drought-tolerant	

"Endophyte" refers to a fungus living in the plant tissue; it contributes to plant persistence and other desirable characteristics, but it also has a negative influence on animal health and lowers the palatability and digestibility of tall fescue during the summer months. Varieties are available that are endophyte-free or low in endophyte. Recently, novel or nontoxic ("friendly") endophyte-infected tall fescue seed has been released. Preliminary data suggest that animal performance on novel endophyte can be excellent and similar to endophyte-free tall fescue. Novel endophyte appears to give tall fescue improved vigor, drought and grazing tolerance, and pest resistance. Research is continuing. If you are establishing tall fescue, consider seeding either low-endophyte or nontoxic endophyte varieties.

Tall fescue plant samples, taken at the vegetative stage, can be tested for the presence of the endophyte fungus by one of a number of commercial and university laboratories.

Kentucky bluegrass is a sod-forming, winter-hardy perennial pasture grass that tolerates close grazing and can be grown throughout Illinois. Production is greatest in the spring and fall.

Major strengths	Major weaknesses
Long-lived	Low-yielding
Fine-leaved and high quality	Shallow-rooted
Low maintenance	Poor drought tolerance
Compatible with white clover	Doesn't compete with more aggressive species
	Becomes dormant in summer

Ryegrass is a bunch-type, high-quality cool-season grass that consists of several species: annual, Italian, perennial, and hybrid crosses. For use in hay and pasture, select "forage"-type, not "turf"-type, varieties.

Major strengths	Major weaknesses
Quick establishment	Not tolerant of hot, dry conditions
High quality and palatable	Poor drought tolerance
Grows rapidly	Winterhardiness varies by variety
Grows best in fertile, well-drained soils	Varieties differ in susceptibility to stem rust and endophyte

Annual ryegrass, a weak perennial, can also used as a winter cover crop. It is lower-yielding. It is adapted to frost seeding but will produce seedheads in the seeding year. *Italian ryegrass* can be a perennial with a mild winter or snow cover. It can be used as a companion crop (seed at 2 to 4 pounds per acre) instead of oats for spring forage establishment. There are both heading and nonheading types. Nonheading types are preferred for frost seeding. Late maturity types have more uniform yield throughout the season. *Perennial ryegrass* is tolerant of close, frequent grazing and yields in the spring and fall.

New cool-season perennial grasses being evaluated. **Meadow fescue** is a bunch-type grass, adapted to cool, moist conditions and a "distant relative" of tall fescue. Initial data indicate that it is lower-yielding but has greater palatability than tall fescue. Ease of establishment, tolerance to close grazing, and rapid regrowth have been observed. Seed 8 to 12 pounds per acre in a mixture; see **Table 6.7** for the rate if seeded alone.

Festulolium is a bunch-type grass resulting from a hybrid cross between meadow fescue and Italian or perennial ryegrass. The intent is that drought, heat, and cold tolerance are transferred from fescue and ease of establishment and high quality transferred from ryegrass. Seed 4 to 10 pounds per acre in a mixture; see **Table 6.7** for rate if seeded alone.

Annual Forages

Please note that the following discussion is not all-inclusive of annual forage species. The focus here is on the species most commonly adapted or evaluated for use in Illinois; see **Table 6.8** for seeding-rate recommendations.

Annual forages are commonly grown as an emergency/supplemental forage crop, to fill the "summer slump" of cool-season perennial species, to work into a rotation, or to extend the grazing season. As the name indicates, these forages must be seeded yearly. Seed cost, cost of establishment, and risk of getting a stand must be considered.

Sudangrass, sudangrass hybrids, sorghum–sudangrass hybrids, and forage sorghum are warm-season, annual, bunch-type grasses that are very productive during the summer. They may be used for silage, green chop, or grazing. These tall-growing, succulent grasses are difficult to make into high-quality hay. They produce prussic acid (hydrogen cyanide), a compound toxic to livestock, when stressed by frost or drought. Since the concentration of prussic acid is greatest in young plants and in the leaves, to minimize prussic acid poisoning these grasses should not be harvested until they reach a "safe" height (see below). These crops should not be fed to any class of horse.

Seed of sudangrass and sorghum–sudangrass hybrids can be purchased that contain the brown midrib (BMR) trait. The BMR trait greatly improves the digestibility, palatability, and resulting daily gain of livestock, but the plant still has prussic acid potential. Warm soil temperature (65 to 70 °F) is required for ideal germination. Seed by late June and for southern Illinois by mid-July.

Sudangrass and sudangrass hybrids

Major strengths	Major weaknesses
Finer stems than sorghum–sudangrass hybrids	Do not harvest until 18 inches tall
Rapid regrowth	Prefers well-drained soil
Drought-tolerant	Possible nitrate toxicity with drought
Hybrids will yield slightly more than nonhybrid varieties	Must leave 6-inch stubble

Sorghum-sudangrass hybrids

Major strengths	Major weaknesses
Higher-yielding than sudangrass and sudangrass hybrids	Not as leafy as and more stems than sudangrass
Rapid regrowth	Do not harvest until 24 inches tall
Drought-tolerant	Prefers well-drained soil
	Possible nitrate toxicity with drought
	Must leave 6-inch stubble

Table 6.8. Forage seeding recommendations for warm-season grasses (in pounds of pure live seed per acre).

Warm-season annual grasses (pure stand)	
Sudangrass[a] and sudangrass hybrids[a]	25 drilled (30 broadcast)
Sorghum–sudangrass[a]	20 drilled (30 broadcast)
Forage sorghum[a]	12–15 drilled
Pearl millet	15 drilled (25 broadcast)
German (foxtail) millet, Japanese millet	12–15 drilled
Teff	4–6 drilled for uncoated seed
	8–10 drilled for coated seed
Warm-season perennial grasses[b]	
Single species	
Switchgrass[c]	6–9
Eastern gamagrass[c]	8–10
Big bluestem	10–12
Indiangrass	8–10
For mixtures, seeding rates should be reduced in proportion to the number of species. For example, if two species are used in a mixture, use half of the rate listed for each.	

The table reflects recommendations from the University of Illinois, Purdue University, and Iowa State University. Characteristics, strengths, and weaknesses of legumes and grasses are described beginning on page 75.
[a]Not to be used in horse pastures.
[b]Suitable for moderately to well-drained and droughty soils anywhere in Illinois. Not recommended for poorly drained soils.
[c]Will tolerate somewhat poorly drained soil.

Forage sorghum is an annual, tall-growing, warm-season, bunch-type grass belonging to the sorghum family. Some varieties are called "sweet sorghum" due to sweet and juicy stems.

Major strengths	Major weaknesses
Best as a silage crop	Not recommended for grazing or haying
Typically produces more silage dry matter yield than corn	Lower total digestible nutrients per acre than corn
	Matures late in the season
	Contains high level of prussic acid even late in the season
	High moisture content

Freeze on the sorghum family of crops breaks cell walls and allows *prussic acid* to be released within the plant. For this reason, it is advisable to remove grazing ruminant livestock from freshly frozen sudangrasses and sorghums. When the frozen plant material is thoroughly dry, usually after 3 to 5 days (following a "light" frost), grazing can resume. With a killing freeze (28 °F or colder), grazing should be delayed 8 to 10 days. After this drying period, observe the plants closely for new tiller growth, which is high in prussic acid. Livestock should be removed when there is new tiller growth that could be grazed.

Because the fermentation process from ensiling substantially reduces prussic acid potential, ensiling is the safest way to handle questionable feed. Harvesting as hay is the second safest way of using crops with questionably high levels of prussic acid potential.

Laboratory diagnostic procedures can determine relative potential.

Pearl millet is an annual, tall-growing warm-season grass that does not have prussic acid. It may be used for grazing, hay, green chop, or silage. Warm soil temperature (70 °F) is required for ideal germination. Seed by late June and for southern Illinois by mid-July.

Major strengths	Major weaknesses
Does not contain prussic acid	Slower regrowth after harvest than sorghum family of grasses
Fine-stemmed and leafy	Must leave 6 to 8 inches of stubble after harvest for regrowth
Higher leaf-to-stem ratio than sorghum family of grasses	Possible nitrate toxicity with drought
Higher yielding than other millets	

Other millets grown for forage include *German (Foxtail)* millet and *Japanese* millet. These warm-season annual grasses are usually seeded for an emergency hay crop, and to a lesser extent for pasture. Careful management is needed so they do not produce seed heads and become a weed problem.

Teff is a warm-season, summer annual grass, native to Ethiopia, and has the appearance of a bunch-grass. Indications are that teff is adapted to a wide range of soil conditions. Due to small seed size, a firm, well-prepared seedbed is needed for establishment. Use of teff as a forage crop in the Midwest has not been widely tested. Trials are in progress to identify adapted varieties and specific management practices.

Major strengths	Major weaknesses
Fine-stemmed	Small seed (1.25 M per pound)
Very palatable	Not tolerant of frost
Can be hayed, ensiled, or grazed	Not tolerant of cool soil temperatures (<70 °F) at planting

Brassicas (turnips, swedes/rutabaga, rape, and kale) are high-yielding, high-quality, fast-growing forbs belonging to the mustard family. They are low-fiber, high-moisture crops best utilized in a managed grazing system, not for hay or ensiling. Due to their high moisture content, they need to be supplemented with dry hay or pasture. The amount of dry matter yield in the tops (leaves and stems) vs. the roots (bulbs) varies by species and variety; see **Table 6.9** for seeding-rate recommendations. Seed by early June for summer grazing and by early August for fall and winter grazing. They can be seeded separately, or in a mixture with small grains.

Warm-Season Perennial Grass Species

Please note that the following discussion is not all-inclusive of warm-season perennial grass species; see **Table 6.8** for seeding-rate recommendations. The focus here is on the species most commonly adapted or evaluated for use in Illinois.

Also referred to as native prairie grasses, warm-season perennial grasses are commonly grown for conservation and wildlife purposes, but they can be an alternative forage for hay and pasture (especially with rotational grazing). In contrast to cool-season grasses, they grow primarily during the warm part of the summer and produce well under hot, dry conditions of midsummer. Seeding a single species is commonly preferred because mixed species are more difficult to manage. A mixture of warm-season and cool-season grasses is generally not recommended because of competition and differences in growth patterns. Typically, warm-season grasses are not compatible with legumes and have lower forage quality than cool-season grasses. They are more difficult and slower to establish than cool-season grasses, but once established they are persistent and vigorous.

Switchgrass is a tall, bunch-type grass with short rhizomes. It has long, broad leaves and grows 3 to 6 feet tall. Switchgrass becomes stemmy as it matures, so harvest before seed heads emerge for higher quality forage. See **Table 6.10** and **Table 6.11** for variety yield data.

Major strengths	Major weaknesses
Winter-hardy	Becomes stemmy as it matures
Drought-tolerant	Palatability and quality decline quickly after heading
Smooth seed can flow through most drills	
Will tolerate moist soils	

Big bluestem is a tall-growing (6 to 8 feet), bunch-type grass that may have short rhizomes. It is considered more palatable than switchgrass (especially after maturity), but it yields less. See **Table 6.10** for variety yield data.

Major strengths	Major weaknesses
More drought tolerant than other warm-season grasses	Seed should be debearded before seeding to enable even flow through the drill
Can tolerate low-water-holding soils	Lower-yielding than switchgrass
Winter-hardy	

Indiangrass is another tall-growing (4 to 6 feet), bunch-type grass with short rhizomes. The grass becomes stemmy if allowed to mature. It is especially adapted to deep, well-drained soils. See **Table 6.10** for variety yield data.

Major strengths	Major weaknesses
Winter-hardy	Yield potential less than switchgrass and eastern gamagrass
Drought-tolerant	Seed must be debearded for good seeding
Easier to establish than other warm-season grasses	

Eastern gamagrass, considered a relative of corn, is a bunch-type grass that produces short, thick rhizomes. It is best adapted to deep, well-drained soil. Corn planters are commonly used to seed this grass. See **Table 6.10** for variety yield data.

Major strengths	Major weaknesses
Winter-hardy	Not drought-tolerant
High palatability	Forms large clumps that make mechanical harvest difficult
	Large seeds are enclosed in a hard shell that contributes to dormancy; seed germination is improved by exposing seed to wet-chilling process

Establishment of warm-season perennial grasses. Warm-season perennial grasses are slower to establish than cool-season species. Seedings need to be made from early May to early June. Seeding in the early part of this range provides more time for seedlings to get well established. As seeding is delayed, grasses are slower to establish, yields are less, and weed pressure increases. Mowing at a height of 6 inches in the summer of the establishment year will help control weeds, but don't mow after the end of August so food reserves can build for the winter.

Seedings can be made on tilled, firm seedbeds using a drill or double-corrugated roller seeder. Seed of Indiangrass and big bluestem should be debearded. Eastern gamagrass is commonly seeded using a corn planter.

No-till seedings may be made into existing grass sods where the grass was previously killed with a herbicide. A no-till drill is needed to place seeds at the proper depth and ensure good seed-to-soil contact.

A seeding depth of 1/4 to 1/2 inch is suggested for all of the grasses described, except for eastern gamagrass, which should be seeded 1/2 to 1 inch deep.

See **Table 6.8** for suggested seeding rates, listed as pounds of pure live seed per acre.

Harvest of warm-season perennial grasses. Stands should not be harvested until they are well established and growing vigorously; this may require 2 to 3 years. Typically it is best not to graze these grasses during the seeding year. Established stands can be harvested when 18 to 24 inches high (late boot stage, before seed heads emerge), but leave 5 to 6 inches for regrowth.

Table 6.9. Forage seeding-rate recommendations for forbs.

Brassicas (pure stand)	
Turnip	2–3 drilled
Swedes (rutabaga)	2–3 drilled
Kale, rape	3–4 drilled

Table 6.10. Species and varieties of warm-season perennial grasses at Dixon Springs.

Species/variety*	2-yr avg dry matter (tons/A)
Switchgrass/Cave-in-Rock	5.47
Eastern gamagrass/Pete	7.20
Big bluestem/Roundtree	4.84
Caucasian bluestem	3.58
Indiangrass/Rumsey	6.03

*Each variety is harvested twice a year.

Table 6.11. Switchgrass variety trial at Shabbona (DeKalb County).

Variety	2002–04 avg dry matter (tons/A)
Blackwell	4.16
Cave-in-Rock	4.37
Pathfinder	3.81
Sunburst	3.67
WIP[a]	3.22
WSB[a]	3.82

The trial was a collaboration among the Northern Illinois Agronomy Research Center, the University of Illinois Department of Crop Sciences, USDA-ARS, and the U.S. Dairy Forage Research Center, Madison, Wisconsin. The trial was harvested once a year, generally in late August.
[a]Experimental variety, not currently available commercially.

Additional Information

These resources provide more details on hay and pasture management:

- North Central Region (NCR) Extension publication NCR547, *Alfalfa Management Guide*; contact your University of Illinois Extension office or see www.pubsplus.illinois.edu to order.
- Current edition of *Winter Survival, Fall Dormancy and Pest Resistance Ratings for Alfalfa Varieties*, available through National Alfalfa and Forage Alliance, www.alfalfa.org/publications.html.
- *Buying Horse Hay*, Extension publication A3772; contact your University of Illinois Extension office or see www.pubsplus.illinois.edu to order.
- *Grazing in Illinois* manual; copy available at University of Illinois Extension and Natural Resources Conservation Service (NRCS) offices and online at www.il.nrcs.usda.gov/technical/grazing/index.html#General
- University of Illinois *Illinois Livestock Trail* website, www.livestocktrail.illinois.edu
- Purdue University forage identification pictures, www.agry.purdue.edu/Ext/forages/ForageID/forageid.htm

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Water Quality

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Water quality in Illinois has improved significantly over the past 30 years. The most recent report from the Illinois Environmental Protection Agency rated 61% of the state's streams as good, 35% as fair, and 4% as poor. (For more information see the *Illinois Integrated Water Quality Report and Section 303d List—2008*, available online at www.epa.state.il.us/water/water-quality). Agriculture, however, continues to be identified as a primary source of water-quality impairment. Strategies for protecting water quality include voluntary approaches, incentive-based programs, and increased regulations.

Pesticides and fertilizers are often cited as examples of agricultural contaminants, but soil erosion continues to be a primary cause of water-quality problems. According to Natural Resources Conservation Service estimates, more than 900 million tons of agricultural soils were lost by sheet and rill erosion in 2003. In addition to minimizing agricultural chemical loss, sediment reduction should be a major component of water-protection efforts.

Illinois farmers have a great stake in protecting drinking-water quality because they often consume the water that lies directly under their farming operation. Their domestic water wells are often near agricultural operations or fields and thus must be safeguarded against contamination. In addition, surface water supplies, many of them sources of public drinking water, need to be protected. As a result, appropriate chemical selection and crop management decisions are needed to ensure good water quality.

Drinking-Water Standards

All public water supplies must sample quarterly for regulated contaminants, including several pesticides. Maximum contaminant levels (MCLs) have been established for more than 30 pesticides and pesticide metabolites. For example, the current MCL for atrazine is 3 parts per billion. Eventually, MCLs will be established for all pesticides. Compliance with the federal standards is based on an average of four quarterly samples. If standards are exceeded, water customers are notified by local media and subsequently on their water bills. If a water source is in violation, no additional water permit extensions can be issued until the problem is addressed. Solutions might include blending with an uncontaminated supply, extensive decontamination treatment, or finding an alternative supply. The additional water-treatment expense can be prohibitive to small communities, underscoring the importance of agriculture management practices that reduce the entry of herbicides and nutrients into the aquatic system.

Results from surface-water and well-water samples suggest that atrazine is the herbicide most likely to appear in surface water, but it does not appear to be widely found in well water at levels above drinking-water standards. Some of this is attributed to increased stewardship, but the decrease in violations also results from communities installing carbon filtration systems to meet water-quality standards. Nitrate contamination is often associated with shallow wells and surface water and may be an indication of movement of fertilizers, manures, and other wastes into these water supplies. In addition, tile drainage is a primary route for nitrate to reach surface water. The greatest challenge facing Illinois producers may be to keep herbicides and nutrients out of surface-water supplies. Management practices that reduce runoff concentration and volume may help.

Consumer Confidence Reports

Since 1999, all public water supplies have been required to provide customers with an annual report on drinking-water quality. These "consumer confidence" reports were developed by the U.S. Environmental Protection Agency (USEPA) in consultation with water suppliers, environmental groups, and individual states. They are intended to provide consumers with important information about the quality of their drinking water.

Each report includes information about the source of drinking water (for example, lake, river, or aquifer) and whether it meets federal drinking-water requirements. It indicates how susceptible this local drinking-water source is to contamination and identifies potential sources of contamination. It lists the contaminants detected in the water supply and outlines the potential health effects of any contaminant found in violation of an EPA health standard. Finally, the report tells consumers where they can go for more information on water quality and how to get a copy of the water system's complete source-water assessment.

In addition, any community water system that serves more than 100,000 people is required to make its consumer confidence report available to customers on a publicly accessible website. A listing by state is available at www.epa.gov/safewater/ccr/whereyoulive.html. More information can be found on the EPA's drinking-water website (www.epa.gov/ogwdw) or from the Safe Drinking Water hotline (800-426-4791).

Testing Private Wells

Although public water supplies are closely regulated and must meet EPA standards, private wells are not required to be tested. If the main source of your drinking water is a private well, it is your responsibility to test the water on a regular basis. Water testing can be done by the Illinois Department of Public Health or by private labs. A list of laboratories accredited by the Illinois EPA to test home drinking water is available at www.epa.state.il.us/well-water/list-accredited-labs.html.

A basic test analyzes water for two common contaminants, coliform bacteria and nitrate. The best time to test for these contaminants is during spring or summer following a period of heavy rainfall. The same testing should also be conducted after repairing or replacing an old well and after installing a new well or pump.

Coliform bacteria are an indicator of overall water quality. If they are detected in a water sample, there is some degree of contamination, and other organisms may also be present. A survey of private drinking-water wells in Illinois found that 44% tested positive for coliform bacteria. Although chemical disinfectants such as chloride tablets or bleach can be used to treat wells, it is important to identify potential sources of contamination. Contamination may come from soil or surface water, or there may be problems with well construction or location. Occasionally, public water supplies may issue a "boil order" if bacterial contamination is suspected. Five minutes of vigorous boiling is an effective way to kill most pathogens.

High nitrate levels in water are a concern for pregnant women and infants under 6 months of age. The standard for nitrate–nitrogen in drinking water is 10 parts per million. Boiling water does not reduce nitrate levels; in fact, it makes the problem worse because some of the water evaporates during boiling and the nitrate concentration in the remaining water increases. If tests show that nitrate–nitrogen levels exceed 10 parts per million, water should not be consumed by pregnant women or infants under the age of 6 months. Use an alternate water source, such as bottled water. Two publications about water testing are available from local University of Illinois Extension offices.

Planning Your Well: Guidelines for Safe, Dependable Drinking Water (Land and Water Publication #14) provides information about water quality, planning and installing a well, and understanding geologic conditions that affect groundwater.

Safe Drinking Water: Testing and Treating Home Drinking Water (Land and Water Publication #17) contains information about water testing, types of contaminants, and treatment devices that are available. Water testing is only part of a well owner's responsibility. Reducing risk from potential contaminants is also important. Septic systems, for example, should be properly maintained to minimize the chance of groundwater contamination.

In some studies, the highest levels of contamination are often from wells near chemical handling sites or known to have been contaminated directly by an accidental point-source introduction of the chemical, such as backsiphoning.

Protecting groundwater drinking sources is critical and achievable; it can be accomplished by attention to these four points:

- preventing point-source contamination of the well
- evaluating groundwater contamination susceptibility, as determined by soil and geologic conditions and the water-management system
- selecting appropriate chemicals and application strategies
- practicing sound agronomy, which uses integrated pest management principles and appropriate yield goals

Preventing Point-Source Contamination

Controlling point-source contamination is one of the most important actions for protecting a groundwater supply. A point source is a well-defined and traceable source of contamination, such as a leaking pesticide container, a pesticide spill, or backsiphoning from spray tanks directly into a well. Because point sources involve high concentrations of contaminants or direct movement of contaminants to the water source, the filtering ability of the soil is bypassed. The following handling practices, based largely on common sense, minimize the potential for groundwater contamination:

- Never mix chemicals near (within 200 feet of) wells, ditches, streams, and other water sources.
- Prevent backsiphoning of mixed pesticides from the spray tank to the well by always keeping the fill hose above the overflow of the spray tank.
- Store pesticides in a secure location a safe distance from both wells and surface waters.
- Triple-rinse pesticide containers and put rinsate back into the spray tank to make up the final spray mixture.
- Identify vulnerable areas and avoid applying pesticides or fertilizers near sinkholes.

Sealing Abandoned Wells

Although the total number of abandoned wells in Illinois is unknown, estimates range from 50,000 to 150,000. Every year, many wells are abandoned when they are replaced with new wells or when homes are connected to community water systems. Abandoned wells pose an immediate threat to human safety and provide a direct route for contaminants to pollute a water supply.

The risk of accidents for humans or domestic animals is greatest with large-diameter or dug wells, but any abandoned or unused well poses a threat to groundwater quality. The upper layers of soil normally act as a filter that effectively removes contaminants. Abandoned wells allow pollutants to bypass this filtering process and provide a direct path from land surface to groundwater.

What if you know there is an abandoned well on your land, but you are not sure of the exact location? Because abandoned wells are not always clearly visible, it may be necessary to contact former property owners or neighbors who might remember well locations. In addition, local well drillers often have site records of previous installations. If old photos are available, they may show windmills, houses, barns, or other buildings that have since been torn down where wells might be located. Finally, the Illinois State Water Survey maintains a database of well records.

Sealing an abandoned well is generally not an expensive process, but it must be done correctly, preferably by a licensed groundwater professional. Farmers have the right to seal their own wells, as long as they accept all responsibility for the sealing in compliance with the Illinois Well Construction Code and all pertinent county codes.

Before beginning any work, you must report the project to the local public health department and have a well-sealing plan approved. The Illinois Department of Public Health has a list of requirements and approved fill materials. After the work is done, you must complete a report and submit it within 30 days. Information on well sealing is also contained in *Sealing an Abandoned Well* (Land and Water Publication #4), 2003.

Groundwater Vulnerability

Site characteristics, including soil and geologic properties, water-table depth, and depth of the well, determine the potential of nonpoint contamination of groundwater. Differently from point sources, nonpoint sources of contamination are difficult to pinpoint, originate from a variety of sources, and are affected by many processes. Contaminants moving into groundwater from routine agricultural use are an example of a nonpoint source. Producers applying pesticides in vulnerable areas should pay strict attention to chemical selection and management practices.

Soil Characteristics

Water-holding capacity, permeability, and organic matter content are important soil properties that determine a soil's ability to detain surface-applied pesticides in the crop root zone. Fine-textured, dark prairie soils have large water-holding capacities and large organic matter contents, which reduce the likelihood of pesticide leaching due to reduced water flow or increased binding of pesticides. The forest soils that dominate the landscape in western and southern Illinois are slightly lower in organic matter and thus may be less effective at binding pesticides. The most vulnerable soils for groundwater contamination are the sandy soils that lie along the major river valleys. Sandy soils are highly permeable, have low organic matter content, and often are irrigated. All of these factors represent increased risks to groundwater quality. Extra precautions should be taken in these vulnerable soils regarding chemical selection and application methods. Irrigators, in particular, should pay attention to groundwater advisory warnings that restrict the use of some herbicides on sandy soils.

Geology

The geologic strata beneath a farming operation may be important in determining the risk of nonpoint-source contamination. One type of hazardous geology for groundwater pollution is the karst, or limestone region, that occurs along the margins of the Mississippi River and in the northwestern part of the state. Sinkholes and fractures that occur in the bedrock in these areas may extend to the soil surface, providing access for runoff directly to the groundwater. Water moving into these access points bypasses the natural treatment provided by percolation through soil. Karst areas should be farmed carefully, with attention to buffer zones around sinkholes to prevent runoff entry to the groundwater. Agronomic practices that minimize runoff reduce the potential for pesticide movement to the groundwater.

Groundwater and Well Depths

Deep aquifers that lie under impermeable geologic formations are the sites most protected from contamination by surface activities. In contrast, shallow-water-table aquifers are more vulnerable to contamination because of their proximity to the surface. Shallowly dug wells in sandy soils or areas with shallow aquifers are also more vulnerable, due to typically inadequate wellhead protection.

Precautions for Irrigators

Chemigation refers to the application of fertilizers and pesticides through an irrigation system. As a management tool, it has benefits and potential drawbacks for groundwater protection. The greatest benefit is for *fertigation*, which is the application of fertilizers, particularly nitrogen, through the irrigation system. Nitrogen can be more carefully applied during the vegetative growth period of grain crops, thereby minimizing the susceptibility to leaching. Chemigation systems must be equipped with devices to prevent backflow. These devices greatly reduce the threat of backsiphoning undiluted chemicals into the irrigation well. Backflow-prevention devices are mandatory on irrigation systems that inject fertilizers and pesticides.

Chemical Properties and Selection

The selection of agricultural chemicals is critical for producers on vulnerable soils and geologic sites. Herbicide selection is a complex task that must take into account the crop, the tillage system, the target species, and a host of other variables. Chemical properties of the herbicide are important to consider when evaluating their potential to leach to the groundwater. The three most important pesticide characteristics that influence leaching potential are solubility in water, ability to bind with the soil (adsorption), and the rate at which the pesticide breaks down in the soil. High solubility (a pesticide that dissolves readily), low binding ability, and slow breakdown all increase a pesticide's ability to move to the groundwater. Among the frequently used herbicides that have a greater potential to leach are those that contain acetochlor, atrazine, sulfentrazone, acifluorfen, dimethenamid, chloransulam, flumetsulam, simazine, metribuzin, and clopyralid (**Table 7.1**). These products are labeled with groundwater advisories.

Of all the herbicides used commercially on corn and soybean, more than 60% carry a groundwater advisory because they contain one or more of the components listed previously. Within this large group of herbicides, some contain only small quantities of a component that has a groundwater advisory. For the vast majority of dark-colored prairie soils in Illinois, leaching to potable groundwater is less common than on either sandy soils or over karst topography. For many of these vulnerable areas, herbicides with groundwater advisories are not labeled for use. Of the herbicides that have groundwater advisories, only atrazine has been detected in groundwater with any appreciable frequency.

Surface-Water Contamination

Although groundwater protection is an important priority, surface-water quality is generally at greater risk. Monitoring efforts have documented the temporary occurrence of high pesticide concentrations in surface water. Numerous studies have shown that chemical losses are often greatest when heavy rainstorms closely follow pesticide applications.

Similarly, state, regional, and national water monitoring efforts have identified elevated concentrations of nitrogen and phosphorus during periods of high rainfall in the spring. Addressing the impacts of agriculture on surface water continues to be one of the biggest challenges facing the industry.

Total Maximum Daily Loads

A total maximum daily load (TMDL) is the allowable amount of a single pollutant that a water body can receive from all contributing sources and still meet water-quality standards or designated uses. Although this definition seems fairly simple, determining "allowable amounts" and the steps needed to achieve "designated uses" are less clear. In addition, implementation plans, recommended practices, and the cost of establishing these TMDLs are still being examined. For a current map of the watersheds and expected completion dates, refer to the Illinois EPA website (www.epa.state.il.us/water/tmdl). Although the fi-

Table 7.1. Herbicides carrying label statements about groundwater contamination.

Trade name	Common name
2,4-D Amine (many)	2,4-D amine
AAtrex, Atrazine (many)	atrazine
Authority MTZ	sufentrazone + metribuzin
Balance Pro	isoxaflutole
Banvel	dicamba
Basagran	bentazon
Bicep II Magnum, Bicep Lite II Magnum	S-metolachlor + atrazine
Boundary	S-metolachlor + metribuzin
Breakfree	acetochlor
Breakfree ATZ	acetochlor + atrazine
Buctril + atrazine	bromoxynil + atrazine
Camix	S-metolachlor + mesotrione
Celebrity Plus	nicosulfuron + dicamba + diflufenzopyr
Clarity	dicamba
Define	flufenacet
Degree	acetochlor
Degree Xtra	acetochlor + atrazine
Distinct, Status	dicamba + diflufenzopyr
Dual II Magnum	S-metolachlor
Expert	S-metolachlor + atrazine + glyphosate
FieldMaster	acetochlor + atrazine + glyphosate
FirstRate	cloransulam
FulTime	acetochlor + atrazine
G-Max Lite, Guardsman Max	dimethenamid-P + atrazine
Halex GT	S-metolachlor + glyphosate + mesotrione
Harness	acetochlor
Harness Xtra	acetochlor + atrazine
Hornet WDG	flumetsulam + clopyralid
Hyvar X, XL	bromacil
IntRRo	alachlor
Keystone, Keystone LA	acetochlor + atrazine
Krovar	bromacil + diuron
Laddok S-12	atrazine + bentazon
Lightning	imazethapyr + imazapyr
Lumax, Lexar	S-metolachlor + atrazine + mesotrione
Marksman	dicamba + atrazine
Micro-Tech	alachlor
Northstar	primisulfuron + dicamba
Outlook	dimethenamid-P
Paramount	quinclorac
Pathway	picloram + 2,4-D
Prefix	S-metolachlor + fomesafen
Princep	simazine
Python	flumetsulam
Radius	flufenacet + isoxaflutole
Sencor	metribuzin
Sequence	S-metolachlor + glyphosate
Shotgun	atrazine + 2,4-D
Sim-Trol	simazine
Sonic, Authority First	cloransulam + sulfentrazone
Spartan	sulfentrazone
Spirit	primisulfuron + prosulfuron
Steadfast ATZ	nicosulfuron + rimsulfuron + atrazine
Stinger	clopyralid
Storm	bentazon + acifluorfen
SureStart	acetochlor + flumetsulam + clopyralid
Surpass	acetochlor
TopNotch	acetochlor
Tordon 101	picloram
Tordon K	picloram
Tordon RTU	picloram + 2,4-D
Ultra Blazer	acifluorfen
Yukon	halosulfuron + dicamba

nal TMDL rules may change, it seems very likely that any implementation strategies for improving water quality will include the use of "best management practices" (BMPs). Voluntary programs that adopt BMPs can be implemented today, without waiting for the final wording of a federal document.

Nutrient Standards

In 2000, the USEPA published ambient water quality criteria recommendations for rivers and streams and directed states to set water quality standards "to protect the physical, biological and chemical integrity of their waters." The recommended criteria were developed for 14 different ecoregions in the United States, and reference conditions were proposed for total phosphorus, total nitrogen, chlorophyll "a," and turbidity.

Since the reference conditions were based on the 25th percentile for all nutrient data, they did not account for local site conditions that may have significant impacts on water quality. Most streams in Illinois would exceed the proposed nutrient criteria, including some of the best waters that support a rich diversity of aquatic species.

Developing water quality standards for nutrients is a challenge facing Illinois and many other states. The USEPA did allow for individual states to adopt other scientifically defensible criteria or adjust them to better reflect state-specific conditions. In Illinois, a collaborative research program was organized to help provide the basis for standard development. This strategic research initiative (SRI) was funded by the State of Illinois through the Illinois Council on Food and Agricultural Research (C-FAR).

The C-FAR strategic research initiative has provided valuable insight on the development of nutrient standards. It has also raised additional questions and identified other factors that may have greater impacts on biotic integrity than nutrient concentration alone. Factors such as physical habitat, sediment, light availability, temperature, and hydrology are part of a complex relationship affecting biotic responses in rivers and streams.

Cause-and-effect relationships are sometimes difficult to establish because Illinois lacks a wide range of nutrient conditions, and nutrients are almost never the primary limiting factor to algal production. The challenge remains for regulators to adopt practical and effective nutrient standards, but developing partnerships with the research community is an important first step.

In October 2007, researchers in the Water Quality SRI participated in a Nutrient Standards Forum at the University of Illinois at Springfield. Each research team presented key findings and summarized their work. Information about the meeting and copies of all presentations are available on the C-FAR website (www.ilcfar.org/research/waterqualityforum.html).

Best Management Practices

BMPs are designed to minimize adverse effects of pesticide use on surface water and groundwater quality. In addition to protecting the environment, these practices must be economically sound. In most cases, a combination of BMPs is required to achieve water-quality goals, and the suggested practices may vary depending on soils, topography, and the individual farm operation.

Soil testing is a basic foundation for fertilizer recommendations. Testing manures for nutrient content allows accurate crediting for fertilizer replacement. A sound nitrogen-management program for grain crops that emphasizes appropriate yield goals and credit for prior legumes optimizes the amount of nitrogen fertilizer introduced to the field. Splitting nitrogen applications on sandy, irrigated soils is wise because it reduces the chances for excessive leaching that might occur with a single application. Use of a nitrification inhibitor on fine-textured soils where nitrogen is fall-applied may reduce leaching of nitrate–nitrogen. Adding nitrapyrin (N-Serve) to fall-applied nitrogen reduced nitrate leaching an average of 10% to 15% in a Minnesota study. Even less nitrate leaching occurred when nitrogen was spring-applied.

Integrated pest management (IPM) plays a vital role in protecting water resources. Regular monitoring of crop conditions and pest populations helps a producer make the most informed production decision about pesticide applications. Applications based on economic thresholds optimize grower profits while reducing environmental hazards. When possible, select the pesticide that is least likely to run off into surface water or leach to groundwater.

Proper handling and disposal of pesticides can reduce the potential for point-source contamination of water resources. Spills or improper disposal of excess spray can overload the soil's ability to hold and degrade pesticides, with resulting water contamination. If sprayers are dumped or washed out in the same place over the years, concentrated sources of herbicides may be created.

Conservation tillage practices reduce sediment loading and also reduce or slow water runoff. Because many herbicides can move from treated fields dissolved in runoff water, conservation tillage practices that increase water infiltration into the soil profile should help control herbicide runoff into surface water. Establish grass waterways in areas of concentrated water flow. These waterways will trap sediment and reduce the velocity of runoff flow, allowing greater infiltration of dissolved chemicals. Similarly, grass filter strips have been shown to effectively reduce the amount of herbicide runoff.

A cover crop such as a small grain or legume may provide water-quality benefits from several standpoints. The effectiveness of cover crops in controlling erosion is well documented, and controlling erosion is an important component of protecting the quality of surface water. Small-grain cover crops have shown some efficiency at retrieving residual nitrogen from the soil following fertilized corn or vegetable crops. This feature may be important on sandy irrigated soils where winter rainfall leaches much of the residual nitrogen. Match herbicide application rate to field characteristics and weed populations. Carefully review product labels, and follow setback requirements for perennial and intermittent streams and around tile inlets.

Consider a split application of soil-applied products to reduce the risk that heavy rainfall will cause extensive runoff. Select postemergence herbicides with physical and chemical characteristics that have less potential for surface runoff. Band-apply herbicides and use mechanical control when appropriate. Rotate crops and use a combination of weed management practices. In addition to helping achieve water-quality goals, these practices will reduce the chance for developing herbicide-resistant weeds.

Consider delaying herbicide application if heavy rains are forecast for the next few days. Research has shown that heavy rainfall shortly after herbicide application can cause significant chemical loss. Finally, some individual BMPs may not be appropriate as part of an overall cropping system. Incorporation of herbicides, for example, has been shown to decrease the amount of chemical runoff in surface water. Obviously, this practice is not compatible with a no-till system, and the balance between controlling soil erosion and reducing pesticide movement must be considered.

Local involvement at the watershed level is a part of any successful program. Some of the most effective water-protection efforts have been developed locally. Best management practices that are specific to a watershed appear to be more effective than treating every acre in a uniform way. Because most management practices need to be cost-effective before they are widely adopted, dealers and growers should be involved early in the planning process.

8

Managing Soil pH and Crop Nutrients

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The inherent complexity of crop production systems requires integrating many factors to ensure maximum crop yields with the least risk to the environment. Assessing present- and reserved-nutrient status of the soil, understanding its nutrient-release and nutrient-holding capacity, and knowing the plant and environmental factors that impact nutrient availability are necessary to guide fertilization rates, sources, and method of application of additional nutrients. The information here is intended to provide fundamental principles to help the reader understand what to do, and why, when making management decisions related to **phosphorus** (P), **potassium** (K), **secondary macronutrients** (calcium [Ca], magnesium [Mg], and sulfur [S]), **micronutrients** (boron [B], chlorine [Cl], copper [Cu], iron [Fe], manganese [Mn], molybdenum [Mo], and zinc [Zn]), and **pH**.

Factors Impacting Plant-Nutrient Availability

Nutrient availability can be impacted by soil chemical and physical properties, including parent material and naturally occurring minerals; amount of organic matter; depth to bedrock, sand, or gravel; and permeability, water holding capacity, and drainage. In addition, environmental conditions and crop characteristics have an important impact on nutrient availability. It is not unusual for crops in fields or portions of fields to show nutrient deficiencies during periods of the growing season, even where an adequate nutrient management plan is followed. The fact that nutrients are applied does not necessarily mean they are available. Plants obtain most of their nutrients and water from the soil through their root system. Any factor that restricts root growth and activity has the potential to restrict nutrient availability. This is not because nutrients are not plant-available in the soil, but because the ability of the crop to take up those nutrients is restricted. Understanding how these factors can cause nutrient deficiency in crops is important to avoiding excessive concern about the need for additional fertilization when a sound nutrient program is already in place.

Soil compaction can limit or completely restrict root penetration and effectively reduce the volume of soil, including nutrients and water, which can be accessed by the plant. To limit soil compaction, avoid entering fields that are too wet, and minimize the weight per axle by decreasing load weight and/or increasing tire surface area in contact with the soil. Planting when soils are wet can create a compacted wall next to the seed that will prevent the seedling from developing an adequate root system. Tilling wet soils will result in clods that become hard and dry out quickly on the surface, preventing roots from accessing resources inside the clod.

Soil water content is critical not only to supply the water needs of the crop but also to dissolve nutrients and make them available to the plant. Excess water in the soil, however, depletes oxygen (O_2) and builds up carbon dioxide (CO_2) levels. While O_2 is needed by roots to grow and take up nutrients, high CO_2 levels are toxic.

Temperature is important in regulating the speed of soil chemical processes that make nutrients available. Under cool soil temperatures, chemical reactions and root activity decrease, rendering nutrients less available to the crop. Portions of the plant nutrients are taken up as roots extract soil water to replenish water lost through the leaves. Cool air temperatures can lower evapotranspiration and reduce the convective flow of water and nutrients from the soil to the root.

Light intensity is low on cloudy days. Low light intensity reduces photosynthetic rates and nutrient uptake by the crop. Since low light intensity sometimes occurs when soils are waterlogged or temperatures are cool, cloud cover can exacerbate the capacity of the crop to take nutrients.

Diseases and pests can have an important impact on crop-nutrient uptake by competing for nutrients, affecting physiological capacity (such as reduction in photosynthesis rates), and diminishing root parameters through root pruning or tissue death.

Estimating Nutrient Availability

Soil Analysis

Soil tests are not perfect, so a soil test value should be considered not a single value, but rather a value within a range. There are multiple reasons why soil tests are not perfect: a soil test represents a measurement at one point in time, while a crop takes nutrients through an extended period, and typically under very different soil-water and temperature conditions than at the time of sampling; the information generated typically comes from a sample from the plow layer, but the crop roots extract nutrients below that layer; laboratory precision is typically within 5% to 10% of the true value. Despite these imperfections, soil testing is the most important guide to profitable application of phosphorus, potassium, and lime because it provides a framework for determining the fertility status of a field. In contrast, plant tissue analysis is typically more reliable than soil testing for secondary macronutrients and micronutrients. Since crop yield response to application of these nutrients has been very limited in Illinois, there is not a large enough database to correlate and calibrate soil-test procedures. Ratings in **Table 8.1** can provide a perspective on the reliability, usefulness, and cost effectiveness of soil tests as a basis for planning a soil fertility and liming program for Illinois field crops.

Traditionally, soil testing has been used to decide how much lime and fertilizer to apply to a field. With increased emphasis on precision agriculture, economics, and the environment, soil tests are also a logical tool to determine areas where adequate or excessive fertilization has taken place. In addition, they are used to monitor the impact of past fertility practices on changes in a field's nutrient status. Of course a soil test report can only be as accurate as the sample sent for analysis. In fact, the spatial variability of available nutrients in a field makes soil sampling the most common and greatest source of error in a soil test. To collect samples that provide a true measurement of the fertility of an area, one must determine the sampling distribution; collect samples to the proper depth; collect samples from precisely the same areas of the field that were sampled in the past; and collect samples at the proper time.

Table 8.1. Ratings of soil tests.

Test	Rating[a]
Water pH	100
Salt pH	30
Buffer pH	30
Exchangeable H	10
Phosphorus	85
Potassium	60
Boron: alfalfa	60
Boron: corn and soybeans	10
Iron: pH > 7.5	30
Iron: pH < 7.5	10
Organic matter	75
Calcium	40
Magnesium	40
Cation-exchange capacity	60
Sulfur	40
Zinc	45
Manganese: pH > 7.5	40
Manganese: pH < 7.5	10
Copper: organic soils	20
Copper: mineral soils	5

[a]On a scale of 0 to 100, 100 indicates a very reliable, useful, and cost-effective test, and 0 indicates a test of little value.

Field soil. A soil probe is the best implement for taking soil samples. An auger or a spade can also be used as long as care is taken to collect an exact depth with a constant slice thickness (**Figure 8.1**). A soil sample, or sampling point in the field, should be a composite of at least five soil cores taken with a probe from within a 10-foot radius around the sampling point. Composite samples should be placed in bags with labels identifying the places where the samples were collected.

Sampling distribution. The number of soil samples taken from a field is a compromise between what should be done (information) and what can be done (cost). The most common mistake is taking too few samples to represent a field adequately. Shortcuts in sampling may produce unreliable results and lead to higher fertilizer costs, lower returns, or both. Determine a soil sampling strategy by first evaluating cost, equipment to be used, past fertilization practices used, and the potential response to fertilizer application. Possible strategies include sampling for the following:

- *Whole-field uniform fertilizer applications.* For this approach, sampling at the rate of one composite from each 2-1/2-acre area is suggested (see **Figure 8.2**, diagram a, for sampling directions).

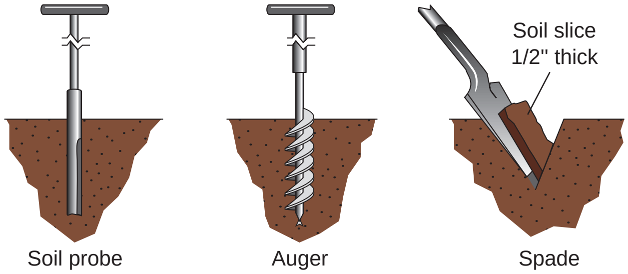


Figure 8.1. How to take soil samples with a soil probe, an auger, and a spade.

- *Site-specific applications for fields where large variations in test values over a short distance are suspected.* Under these conditions, collecting one sample from each 1.1-acre area (**Figure 8.2**, diagram b) will provide a better representation of the actual field variability. The greater sampling intensity will increase cost of the base information but allows for more complete use of technology in mapping soil fertility patterns and thus more appropriate fertilizer application rates.
- *Zones with common characteristics.* This is a directed sampling approach that is also known as "smart" or zone sampling. This method integrates information including such details as yield maps, crop canopy data, soil type or other characteristics, past management history, and the like. It defines sampling zones with common characteristics that may influence crop productivity and nutrient and water supplies. The size of such zones varies depending on field characteristics, but it seldom exceeds 10 acres.
- *Conservation tillage fields with fertilizer band applications.* There is not presently enough research data to define an accurate method for sampling these fields, so the following methods are given as suggestions. When the location of the band is known, collect the regular 7-inch depth sample 6 inches off the side of the band. Another approach would be to multiply a factor (0.67) by the distance (in inches) between bands to determine how many cores need to be collected from outside the band for each sample collected in the band. For example, in a 30-inch band distance, collect 20 cores from outside the band for each sample collected in the band. If the location of the band is not known, the best approach is to increase the number of samples (20 to 30) and to vary sampling position in relation to the row so the band does not bias test results.

Sampling depth. The proper sampling depth for pH, phosphorus, and potassium is 7 inches. This is because the fertilizer recommendation system in Illinois is based on crop response to fertility levels in the top 7 inches of the soil. For fields where conservation tillage has been used,

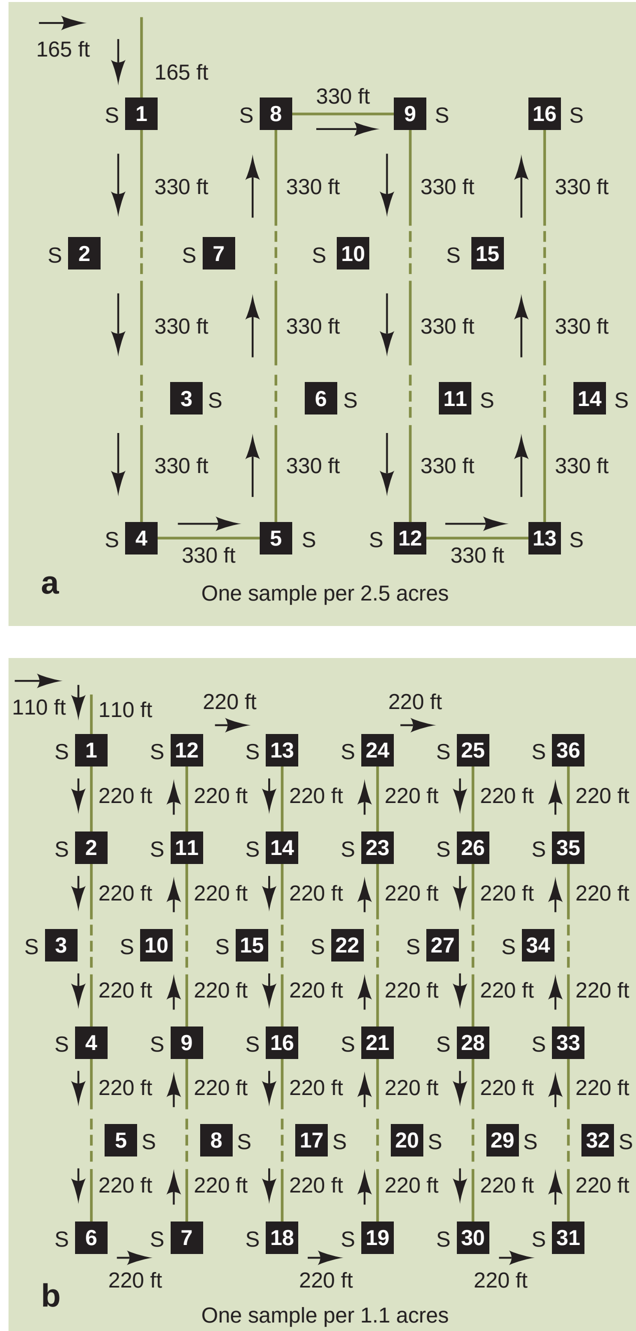


Figure 8.2. How to collect soil samples from a 40-acre field. Each sample (diagram a) should consist of five soil cores, 1 inch in diameter, collected to a 7-inch depth from within a 10-foot radius around each point. Higher frequency sampling (diagram b) is suggested for those who can use computerized spreading techniques on fields suspected of having large variations in test values over short distances.

accurate sampling depth is especially important, as such tillage results in less thorough mixing of lime and fertilizers than a tillage system that includes a moldboard plow. This stratification has not adversely affected crop yield, but misleading soil test results may be obtained if samples are not taken to the proper depth. Shallow samples will overestimate actual soil status, leading to underapplication of lime or fertilizers, while samples that are too deep or where some part of the top portion falls off during sampling will underestimate current soil status, causing overapplication of lime or fertilizers.

If surface soil pH is too high or too low, the efficacy of some herbicides and other chemical reactions may be affected. Thus, in addition to the regular 7-inch depth sampling, if either limestone (which raises pH) or nitrogen (which lowers pH) is applied to the soil surface and not incorporated with tillage, it is important to monitor surface soil pH by collecting samples to a depth of 2 inches from at least three areas in a 40-acre field. These areas should represent the low, intermediate, and high ground of the field.

Precise sample locations. Variations in values are often observed across soil tests in the same field. Given the inherent variability of soils over even short distances (related to soil forming factors) and management effects for which there is no record (such as non-uniform distribution of fertilizer), it is important to collect samples from precisely the same points each time a field is tested. Sample locations can be identified using a global positioning system (GPS) unit or by accurately measuring the sample points with a device such as a measuring wheel.

When to sample. Sampling every 4 years is strongly suggested when soils are at an optimum level of fertility. When maintenance levels are not being applied in cropping systems that remove large quantities of nutrients, such as hay or corn silage, soil testing should be done every other year. To improve the consistency of results, collect samples at the same time of year and, if possible, under similar soil-water conditions. Sampling done within a few months of lime or fertilizer treatment will be more variable than after a year.

Late summer and fall are the best seasons for collecting soil samples, because K test results are most reliable then. Results of the K test tend to be cyclic, with low levels in late summer and early fall and high levels in late January and early February. Phosphorus and pH levels are typically not seasonally affected in most soils in Illinois. In coarse-textured (sandy) soils with low buffer capacity, pH levels can increase as much as one unit under wet conditions.

Sending soils for analysis. Find information about commercial testing services available in your area at www.soiltesting.org, or contact an Extension office or a fertilizer dealer.

The best fertilizer recommendations are based on both soil test results and knowledge of field conditions that will affect nutrient availability. Because the person making the recommendation does not know the conditions in each field, it is important to provide adequate information with each sample.

The information needed includes cropping intentions for the next 4 years; the name of the soil type or, if not known, the nature of the soil (clay, silty, or sandy; light or dark color; level or hilly; eroded; well drained or wet; tiled or not; deep or shallow); fertilizer used (amount and grade); lime applied in the past 2 years; and proven yields or yield goals for all proposed crops.

The following tests should be performed:

- *pH*: The water pH test.
- *Phosphorus*: The Bray P_1 test for plant-available soil P. This test has been used to measure P availability in Illinois since it was developed in the 1940s. It was not developed to test alkaline soils, so it should be restricted to soils with pH less than 7.3. The Mehlich-3 test was developed in North Carolina for routine analysis of P, K, Ca, Mg, and several micronutrients. Research in Iowa has shown that the P results obtained with this test are nearly identical to those obtained with the Bray P_1 test on neutral-to-acid soils as long as the analysis is done by the colorimetric procedure. In soils or portions of a field where pH is above 7.3, the Bray P_1 test results in high test values. Under those soil conditions, yield response to P may be better correlated with the Mehlich-3 procedure. Samples extracted by the Mehlich-3 procedure and analyzed by inductively coupled plasma emission spectroscopy (ICP) result in higher values than those analyzed by the colorimetric procedure. The values obtained from ICP analysis cannot be adjusted to colorimetric values by a numerical conversion. A third procedure, referred to as the Olsen or sodium bicarbonate test, was developed for high-pH soils in western states and should not be used for acid soils. The results obtained with this test on high-pH soils are lower than those obtained with the Mehlich-3 procedure.
- *Potassium:* The ammonium acetate test has been the recommended test. Research in Iowa has shown that results from the Mehlich-3 extractable K test are similar to the ammonium acetate test.
- *Secondary nutrients and micronutrients:* Tests are available for most secondary nutrients and micronutrients, but interpretation is less reliable than with tests for lime, P, and K. Complete field history and soil information are especially important in interpreting results. Even though these tests are less reliable, they may be useful in two ways. First is troubleshooting, or diagnosing symptoms of abnormal growth; paired samples representing areas of good and poor growth are needed for analyses. Second

is "hidden-hunger checkup," or identifying deficiencies before symptoms appear. Soil tests are of little value in indicating marginal levels of secondary nutrients and micronutrients when crop growth is apparently normal. For this purpose, plant analysis may yield more information.

Interpreting soil test results and formulating soil treatment programs. A soil pH test reports soil reaction as pH units; phosphorus and K tests are typically reported in pounds of element per acre. Formulate a soil treatment program by preparing field soil test maps to observe areas of similar test levels that will benefit from similar applications. Areas with differences in soil test pH of 0.2 unit, P test of 10 pounds of P per acre, and K test of 30 pounds of K per acre are reasonable to designate for separate treatment. See page 96 for suggested pH goals, page 100 for P information, and page 103 for K information.

Spatial variability in soil test results. When soil test values vary across a field, there are two patterns and two possible ways to address the issue:

- *A definite pattern* of distinct high- and low-test values in different parts of the field. This likely indicates different soil types or different past management practices. Split the fertilizer or lime application to treat each area differently to meet the specific needs.
- *No consistent pattern* of high- and low-test values. Select the median test (the one that falls in the middle of a ranking from low to high). If no explanation for large differences in tests is found, consider taking a new set of samples.

Cation exchange capacity. Chemical elements exist in solution as cations (positively charged ions) or anions (negatively charged ions). In the soil solution, the plant nutrients hydrogen (H), Ca, Mg, K, ammonium (NH_4), Fe, Mn, Zn, and Cu exist as cations. The same is true for non-plant nutrients such as sodium (Na), barium (Ba), and metals of environmental concern, including mercury (Hg), cadmium (Cd), chromium (Cr), and others. Cation exchange capacity (CEC) is a measure of the amount of attraction for the soil with these chemical elements.

In soil, a high CEC is desirable, but not necessary, for high crop yields, as it is not a direct determining factor for yield. CEC facilitates retention of positively charged chemical elements from leaching, yet it gives nutrients to a growing plant root by an exchange of H. Cation exchange capacity in soil arises from negatively charged electrostatic charges in minerals and organic matter. The CEC of organic residues is low but increases as the residues convert to humus, which requires from 5 years to centuries. Thus, farming practices that reduce soil erosion and maintain soil humus favor the maintenance of CEC. It is influenced very little by fertilization, slightly decreased with soil acidification, and slightly increased with liming.

Depending on the amount of clay and humus, soil types have the following characteristic amounts of cation exchange (in units of milliequivalent per 100 grams of soil):

- Sandy soils: less than 4
- Light-colored silt-loam soils: 8 to 12
- Dark-colored silt-loam soils: 15 to 22
- Clay soils: 18 to 30

Plant Analysis

Plant analyses can be useful in diagnosing nutrient problems, identifying hidden hunger, and determining whether current fertility programs are adequate. Critical tissue-nutrient level (below which deficiency occurs) is the concentration needed for a crop to complete its life cycle. These concentrations are largely independent of soil or growing conditions, so the values typically apply across environments and provide a more reliable measurement for micronutrients and secondary nutrients than do soil tests.

How to sample. When diagnosing a fertility problem through plant analysis, select paired samples of comparable plant parts representing the abnormal and normal plants. Abnormal plants selected should represent the first stages of a problem. Samples taken at stages other than those described in **Table 8.2** might not correlate with the suggested critical nutrient levels.

After collecting the samples, deliver them immediately to the laboratory. Samples should be air-dried if they cannot be delivered immediately or if they are going to be shipped. Soil factors (fertility status, temperature, and moisture) and plant factors (cultivar and development stage) may complicate the interpretation of plant analysis data. The more information provided concerning a particular field, the more reliable the interpretation will be.

Soil pH

Effect of Soil Acidity on Plant Growth

Soil pH is a measure of the acidity or alkalinity of soil. Since pH is measured using a logarithmic scale, a decrease of 1 unit of pH means that the acidity increases by a factor of 10, so small changes in pH values can have important consequences. For most of Illinois, soil acidification is a concern, as acidity is created by removal of bases by harvested crops, leaching, and an acid residual left in the soil from N fertilizers. If surface soil pH is too high or too low, the efficacy of some herbicides and other chemical reactions may be affected. Also, soil acidity affects plant

Table 8.2. Suggested critical plant nutrient levels for various crops and stages of sampling.

Crop	Plant part	N (%)	P (%)	K (%)	Ca (%)	Mg (%)	S (%)	Zn (ppm)	Fe (ppm)	Mn (ppm)	Cu (ppm)	B (ppm)
Alfalfa	Upper 6 in. at early bloom	—	0.25	2.00	1.00	0.25	0.22	15	25	20	7	25
Corn	Leaf opposite and below the ear at tasseling	2.9	0.25	1.90	0.40	0.15	0.15	15	25	15	5	10
Soybean	Fully developed leaf and petiole at early podding	—	0.25	2.00	0.40	0.25	0.15	15	30	20	5	25
Wheat	Entire aboveground portion at tillering	4.7	0.22	3.20	0.36	0.12	0.15	15	25	25	5	10

N—nitrogen; P—phosphorus; K—potassium; Ca—calcium; Mg—magnesium; S—sulfur; Zn—zinc; Fe—iron; Mn—manganese; Cu—copper; B—boron.

growth in several ways. Whenever soil pH is low (and acidity is high), several situations may exist:

- The concentration of soluble metals, especially aluminum and Mn, may be toxic.
- Populations and the activity of the organisms responsible to transform N, S, and P to plant-available forms may be reduced.
- Calcium may be deficient. Usually this occurs only when the CEC of the soil is extremely low.
- Symbiotic N fixation in legume crops is greatly impaired. The symbiotic relationship requires a narrower range of soil reaction than does the growth of plants not relying on N fixation.
- Acidic soils—particularly those low in organic matter—are poorly aggregated and have poor tilth.
- The availability of mineral elements to plants may be affected. **Figure 8.3** shows the relationship between soil pH and nutrient availability (the wider the dark bar, the greater the nutrient availability). For example, the availability of P is greatest in the pH range between 5.5 and 7.5, dropping off below 5.5. In other words, for a given soil, if P is applied at pH 6, there will be more of it available than if the same amount is applied when the soil pH is below 5.5. Because the availability of Mo is increased greatly as soil acidity is decreased, Mo deficiencies usually can be corrected by liming.

Suggested pH goals. A soil test every 4 years is the best way to check pH levels. For cash grain systems and pasture grasses (not alfalfa or clover), maintaining a pH of at least 6.0 is a realistic goal. If the soil test shows that the pH is 6.0 or less, apply limestone. After the initial investment, it costs little more to maintain a pH at 6.5 than at 6.0. The profit over 10 years will be little affected because the increased yield will approximately offset the cost of the extra limestone plus interest. In contrast, a profitable yield response from raising the pH above 6.5 in cash grain systems is unlikely.

For cropping systems with alfalfa, clover, or lespedeza, aim for a pH of 6.5 or higher unless the soils have a pH of 6.2 or higher without ever being limed. In those soils, neutral soil is just below plow depth; it probably will not be necessary to apply limestone.

Raising soil pH (liming). In addition to soil test value and cropping system, liming rates are determined based on soil type, depth of tillage, and limestone quality. Suggested limestone rates for different soil types in **Table 8.3** are based on typical limestone quality and a tillage depth of 9 inches. For details on adjusting rates to specific conditions, see table footnotes.

Limestone quality is defined by its effective neutralizing value (ENV), a measurement of the neutralizing value and the fineness of grind. The neutralizing value of limestone is determined by its calcium carbonate ($CaCO_3$) equiva-

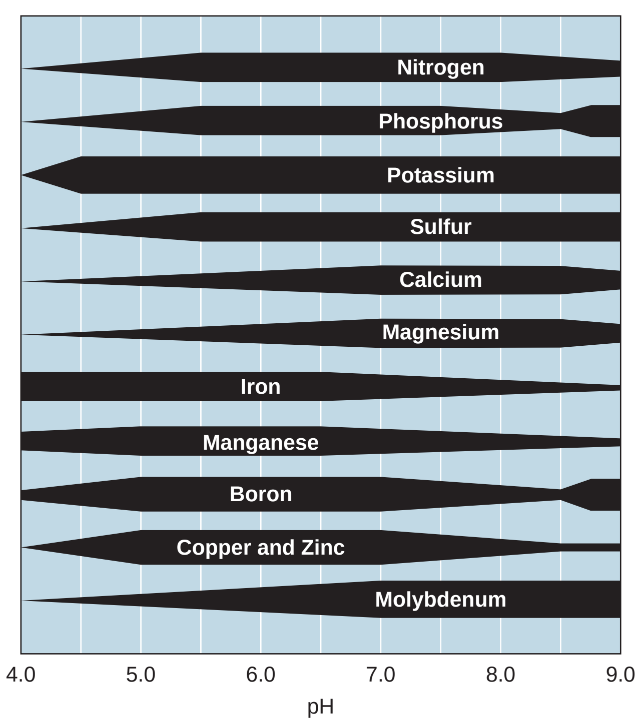


Figure 8.3. Available nutrients in relation to pH.

Table 8.3. Suggested limestone rates based on soil type, pH, cropping system, and 9-inch depth of tillage.

Soil type[a]	Soil pH value																					
	4.5	4.6	4.7	4.8	4.9	5.0	5.1	5.2	5.3	5.4	5.5	5.6	5.7	5.8	5.9	6.0	6.1	6.2	6.3	6.4	6.5	7.0
Tons of typical limestone[b] to apply to grain farming systems																						
A	8.0	8.0	8.0	8.0	8.0	8.0	7.8	7.0	6.3	5.5	4.8	4.0	3.3	2.5	1.8	1.0	Optional					
B	8.0	8.0	7.5	7.0	6.5	6.0	5.5	5.0	4.5	4.0	3.5	3.0	2.5	2.0	1.5	1.0	Optional					
C	6.6	6.3	5.9	5.5	5.1	4.8	4.4	4.0	3.6	3.3	2.9	2.5	2.1	1.8	1.4	1.0	Optional					
D	4.0	3.8	3.6	3.4	3.2	3.0	2.8	2.6	2.4	2.2	2.0	1.8	1.6	1.4	1.2	1.0	Optional					
E	4.0	3.6	3.2	2.8	2.4	2.0																
Tons of typical limestone[b] to apply to forage farming systems (alfalfa, clover, lespedeza)																						
A	11.0	11.0	11.0	11.0	11.0	11.0	11.0	10.3	9.6	8.9	8.1	7.4	6.7	6.0	5.3	4.6	3.9	3.1	2.4	1.7	1.0	Optional
B	11.0	11.0	11.0	10.4	9.9	9.3	8.8	8.2	7.7	7.1	6.6	6.0	5.4	4.9	4.3	3.8	3.2	2.7	2.1	1.6	1.0	Optional
C	10.0	9.6	9.1	8.7	8.2	7.8	7.3	6.9	6.4	6.0	5.5	5.1	4.6	4.2	3.7	3.3	2.8	2.4	1.9	1.5	1.0	Optional
D	6.0	5.8	5.5	5.3	5.0	4.8	4.5	4.3	4.0	3.8	3.5	3.3	3.0	2.8	2.5	2.3	2.0	1.8	1.5	1.3	1.0	Optional
E	6.0	5.4	4.9	4.3	3.8	3.2	2.7	2.1	1.6	1.0												

Note: If plowing is less than 9 in., reduce the amount; if it is more than 9 in., increase it. A chisel plow, disk, or field cultivator rather than a moldboard plow may not mix limestone deeper than 4 to 5 in.; for no-till or pasture systems, use the equivalent of a 3-in. tillage depth (one-third of the amount suggested).

[a]Soil A: Dark-colored silty clays and silty clay loams (CEC > 24). Soil B: Light- and medium-colored silty clays and silty clay loams; dark-colored silt and clay loams (CEC 15–24). Soil C: Light- and medium-colored silt and clay loams; dark- and medium-colored loams; dark-colored sandy loams (CEC 8–15). Soil D: Light-colored loams; light- and medium-colored sandy loams; sands (CEC < 8). Soil E: Muck and peat. Soil color is usually related to organic matter.Light-colored soils <2.5% organic matter; medium-colored soils 2.5–4.5% organic matter; dark-colored soils >4.5% organic matter.

[b]Typical limestone: 10% of the particles are greater than 8-mesh; 30% pass an 8-mesh and are held on 30-mesh; 30% pass a 30-mesh and are held on 60-mesh; and 30% pass a 60-mesh. A calcium carbonate equivalent (total neutralizing power) of 90%. Effective neutralizing value (ENV) of this material is 46.35 for 1 year after application, and 67.5 for 4 years after application. To correct the rate of application based on the ENV of the material available, follow calculations in the worksheet on page 98.

lent: the higher this value, the greater the limestone's ability to neutralize soil acidity. The fineness of grind determines the rate of reaction: finer limestone will neutralize soil acidity faster. Relative efficiency factors have been determined for various particle sizes (**Table 8.4**). If you are liming an acid soil just before seeding alfalfa, it is important to have highly reactive particles; the figures for 1 year are the best guide. If you apply lime before corn, the 4-year values are adequate.

The ENV can be calculated for any liming material by using the efficiency factors in **Table 8.4** and the $CaCO_3$ equivalent for the limestone in question. The Illinois Department of Agriculture, in cooperation with the Illinois Department of Transportation, collects and analyzes limestone samples from quarries that wish to participate in the Illinois Voluntary Limestone Program. These analyses, along with the calculated correction factors, are available from the Illinois Department of Agriculture, Bureau of Agricultural Products Inspection, P.O. Box 19281, Springfield, IL 62794-9281, in the annual publication *Illinois Voluntary Limestone Program Producer Information*. To calculate the ENV and the correction factor needed to determine rate of application for materials not reported in that publication, obtain the analysis of the material in question from the supplier and use the worksheet for lime-rate calculation on page 98 (or online at iah.ipm.illinois.edu/limestone_rate).

Table 8.4. Efficiency factors for various limestone particle sizes.

Particle sizes	Efficiency factor: 1 yr after application	Efficiency factor: 4 yr after application
Greater than 8-mesh	5	15
8- to 30-mesh	20	45
30- to 60-mesh	50	100
Passing 60-mesh	100	100

Examples of Rate Calculation

As an example, consider a limestone that has a $CaCO_3$ equivalent of 86.88% and a sample with 13.1% of the particles greater than 8-mesh, 40.4% that pass 8-mesh and are held on 30-mesh, 14.9% that pass 30-mesh and are held on 60-mesh, and 31.6% that pass 60-mesh. Assume that 3 tons of typical limestone are needed per acre (according to **Table 8.3**). The amounts of limestone with these characteristics that would be needed to meet the 3-ton recommendation would be 3.36 and 3.51 tons on a 1- and

Worksheet for Lime-Rate Calculation Based on ENV of Material

AFTER 1 YEAR

Step	Formulas	Completed Examples
1	% of particles greater than 8-mesh = $\frac{\quad}{100}$ x 5 = ... ☐	$\frac{13.1\%}{100}$ x 5 = ... 0.65
	% of particles that pass 8-mesh and are held on 30-mesh = $\frac{\quad}{100}$ x 20 =.......... + ☐	$\frac{40.4\%}{100}$ x 20 = ... + 8.08
	% of particles that pass 30-mesh and are held on 60-mesh = $\frac{\quad}{100}$ x 50 = ... + ☐	$\frac{14.9\%}{100}$ x 50 = ... + 7.45
	% of particles that pass 60-mesh = $\frac{\quad}{100}$ x 100 = ... + ☐	$\frac{31.6\%}{100}$ x 100 = ... + 31.60
	Total fineness efficiency............... ☐	**Total fineness efficiency**......... **47.78**
2	ENV = total fineness efficiency x $\frac{\text{\% calcium carbonate equivalent}}{100}$	ENV = 47.78 x $\frac{86.88}{100}$ = 41.51
3	Correction factor = $\frac{\text{ENV of typical limestone (46.35)}}{\text{ENV of sampled limestone (\_\_\_)}}$	$\frac{46.35}{41.51}$ = 1.12
4	Correction factor x limestone requirement (from Table 8.3) = ______ tons of sampled limestone needed per acre	1.12 x 3 = 3.4 tons per acre

AFTER 4 YEARS

Step	Formulas	Completed Examples
1	% of particles greater than 8-mesh = $\frac{\quad}{100}$ x 15 = ... ☐	$\frac{13.1\%}{100}$ x 15 = ... 1.96
	% of particles that pass 8-mesh and are held on 30-mesh = $\frac{\quad}{100}$ x 45 =.......... + ☐	$\frac{40.4\%}{100}$ x 45 = ... + 18.18
	% of particles that pass 30-mesh and are held on 60-mesh = $\frac{\quad}{100}$ x 100 = ... + ☐	$\frac{14.9\%}{100}$ x 100 = ... + 14.90
	% of particles that pass 60-mesh = $\frac{\quad}{100}$ x 100 = ... + ☐	$\frac{31.6\%}{100}$ x 100 = ... + 31.60
	Total fineness efficiency............... ☐	**Total fineness efficiency**......... **66.64**
2	ENV = total fineness efficiency x $\frac{\text{\% calcium carbonate equivalent}}{100}$	ENV = 66.64 x $\frac{86.88}{100}$ = 57.9
3	Correction factor = $\frac{\text{ENV of typical limestone (67.5)}}{\text{ENV of sampled limestone (\_\_\_)}}$	$\frac{67.5}{57.9}$ = 1.17
4	Correction factor x limestone requirement (from Table 8.3) = ______ tons of sampled limestone needed per acre	1.17 x 3 = 3.5 tons per acre

4-year basis, respectively (see the sample calculation in the worksheet).

How to apply limestone. Since limestone does not react with acidic soil very far from the particle, adjust application rates proportionally to the depth of tillage as explained in the footnote of **Table 8.3**. For pastures and no-till systems, when lime is broadcast on the soil surface, apply one-third of the needed rate to avoid creating extremely high pH at the soil surface. Consequently, liming may be required more often (but at lower rates) in these systems than in cultivated fields.

Similarly to a broadcast application of nutrients, make sure limestone is spread evenly throughout the soil surface by avoiding overlaps. If a mistake was made and very high rates were applied, scraping the material out of the field or increasing the amount of mixing by tillage would be a practical way to reduce negative effects. Limestone can be applied at any time, but fall applications are preferred to avoid soil compaction and concerns about spring planting delays. Fall application also allows more time for limestone to neutralize soil acidity.

If high initial cost is not a deterrent, rates up to 6 tons per acre may be applied at one time. If cost is a factor and the amount of limestone needed is 6 tons or more per acre, apply it in split applications of about two thirds the first time and the remainder 3 or 4 years later.

In no-till fields where lime is not incorporated in the soil, surface applications eventually neutralize acidity below the surface. However, this process is slow, so it is recommended to always maintain surface pH levels at adequate ranges. If pH levels in the surface are allowed to drop, lime applications will take a long time to start to neutralize acidity below the soil surface.

For hay and pastures, apply limestone several months ahead of seeding to allow time for the acidity to be neutralized. If rate requirements exceed 5 tons per acre, apply half the rate before the primary or intensive tillage and half before the secondary tillage (harrowing or disking). For rates of less than 5 tons, make a single application, preferably after primary tillage.

Fluid lime suspensions (liquid lime). Liquid lime products are created by suspending very finely ground limestone in water. Several industrial byproducts with liming properties also are being land-applied as suspensions, either because they are too fine to be spread dry or because they are already in suspension. These byproducts include residue from water treatment plants, cement plant stack dusts, paper mill sludge, and other waste products. These materials may contain as much as 50% water.

The chemistry of liquid liming materials is the same as that of dry materials. The rate of reaction and the neutralizing power for liquid lime are the same as for dry materials when particle sizes are the same. Application of liquid lime during the first few months after application will provide a more rapid increase in pH than will typical lime, but after that the two materials will provide equivalent pH levels in the soil. The rate of application calculated by using the equation below is adequate to maintain soil pH for at least 4 years at the same level as typical lime.

As an example, assume a lime need of 3 tons per acre (based on **Table 8.3**) and liquid lime that is 50% dry-matter and has a $CaCO_3$ equivalent of 97% on a dry-matter basis. The rate of liquid lime needed would be calculated as shown in the sample below.

Lowering Soil pH (Acidifying)

While soils with high pH (>7.4) result in reduced availability of several nutrients, particularly P, Zn, Fe, and Mn, decreasing soil pH has not been shown to be economical for producing agronomic crops. Acidifying soils to produce crops such as blueberries and cranberries is essential if the pH is high. Acidification can be accomplished by applying elemental S, aluminum sulfate, or iron sulfate. The amount of elemental S needed to reduce soil pH depends on the initial pH and the desired pH (see **Table 8.5**).

Calculating the Application Rate for Liquid Lime

$$\frac{\text{ENV of typical limestone [use 46.35]}}{\text{100 (fineness efficiency factor)} \times \dfrac{\text{\% calcium carbonate, equivalent, dry matter basis}}{100} \times \dfrac{\text{\% dry matter}}{100}} \times \text{tons of limestone needed per acre} = \text{tons of liquid lime needed per acre}$$

Sample calculation:

$$\frac{46.35}{100 \times \dfrac{97}{100} \times \dfrac{50}{100}} \times 3 = 2.87 \text{ tons of liquid lime needed per acre}$$

Table 8.5. Amount of elemental sulfur needed to reduce soil pH.

Soil pH	Soil group[a]			
	A	B	C	D
Elemental sulfur (lb/A) needed to reach pH 5.0				
6.4	2,700	2,100	1,400	700
6.2	2,400	1,800	1,200	600
6.0	2,150	1,625	1,075	550
5.8	1,925	1,450	950	475
5.6	1,700	1,275	850	425
5.4	1,225	925	625	300
5.2	775	575	375	200
Elemental sulfur (lb/A) needed to reach pH 4.5				
6.4	4,000	3,000	2,000	1,000
6.2	3,800	2,800	1,900	950
6.0	3,525	2,650	1,775	925
5.8	3,300	2,475	1,650	825
5.6	3,075	2,300	1,525	775
5.4	2,600	1,950	1,300	650
5.2	2,150	1,625	1,075	550
5.0	1,375	1,050	700	350

[a]Soil A: Dark-colored silty clays and silty clay loams (CEC > 24). Soil B: Light- and medium-colored silty clays and silty clay loams; dark-colored silt and clay loams (CEC 15–24). Soil C: Light- and medium-colored silt and clay loams; dark- and medium-colored loams; dark-colored sandy loams (CEC 8–15). Soil D: Light-colored loams; light- and medium-colored sandy loams; sands (CEC < 8).

Calcium–Magnesium Balance in Illinois Soils

Soils in northern Illinois usually contain more Mg than those in central and southern Illinois, both because of the high Mg content in the rock from which the soils developed and because northern soils are geologically younger. This relatively high level of Mg has caused speculation: is the level too high? Although there have been reported suggestions that either gypsum or low-Mg limestone should be applied, no research data have been put forth to justify concern over a too-narrow ratio of Ca to Mg.

On the other hand, concern is justified over a soil Mg level that is low, because of its relationship with hypomagnesaemia, a prime factor in grass tetany or milk fever in cattle. This concern is more relevant to producing forage than grain. Very high K levels (more than 500 pounds per acre) combined with low soil Mg levels contribute to low-Mg grass forages. Research data to establish critical Mg levels are very limited, but levels of soil Mg less than 60 pounds per acre on sands and 150 pounds per acre on silt-loams are considered low.

Ca and Mg levels of agricultural limestone vary among quarries in the state. Dolomitic limestone (material with appreciable Mg content, as high as 21.7% MgO or 46.5% $MgCO_3$) occurs predominantly in the northern three tiers of Illinois counties, in Kankakee County, and in Calhoun County. Limestone occurring in the remainder of the state is predominantly calcitic (high Ca), although it is not uncommon for it to contain 1% to 3% $MgCO_3$.

There are no agronomic reasons to recommend either that grain farmers in northern Illinois bypass local limestone sources, which are medium to high in Mg, and pay a premium for low-Mg limestone from southern Illinois or that grain farmers in southern Illinois order limestone from northern Illinois quarries because of Mg content.

For farmers with a livestock program or who produce forages in the claypan and fragipan regions of the south, where soil Mg levels may be marginal, it is appropriate to use a soil test to verify conditions and to use dolomitic limestone or Mg fertilization or to add Mg to the feed.

Phosphorus

Regional differences in P-supplying power shown in **Figure 8.4** were broadly defined primarily by parent material and degree of weathering factors. Within a region, variability in parent material, degree of weathering, native vegetation, and natural drainage cause differences in the soil's P-supplying power. For example, soils developed under forest cover appear to have more available subsoil P than those developed under grass.

High supplying power. The "high" region is in western Illinois, where the primary parent material was more than 4 to 5 feet of loess that was high in P content. The soils are leached of carbonates to a depth of more than 3-1/2 feet, and roots can spread easily in the moderately permeable profiles.

Medium supplying power. The "medium" region is in central Illinois, with arms extending into northern and southern Illinois. The primary parent material was more than 3 feet of loess over glacial till, glacial drift, or outwash. Some sandy areas with low P-supplying power occur. In comparison with the high-P region, more soils are poorly drained and have less available P in the subsoil and substratum horizons. Carbonates are likely to occur at shallower depths than in the high region. The soils in the northern and central areas are generally free of root restrictions, whereas soils in the southern arm are more likely to have root-restricting layers in the profile. The P-supplying power of soils of the region is likely to vary with natural drainage. Soils with good internal drainage are likely to have higher levels of available P in the subsoil and substratum. If

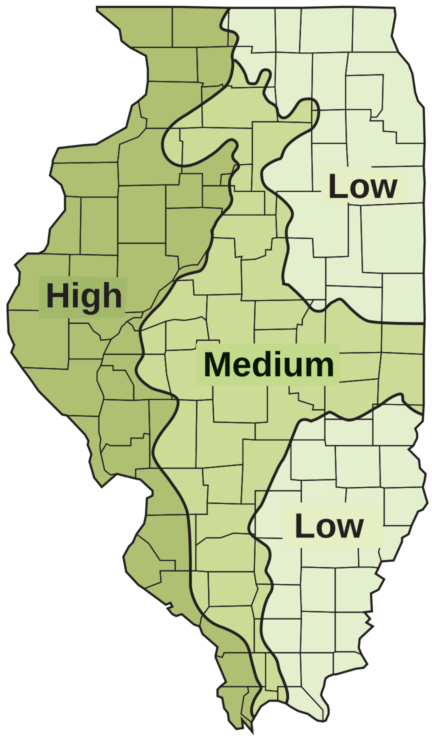
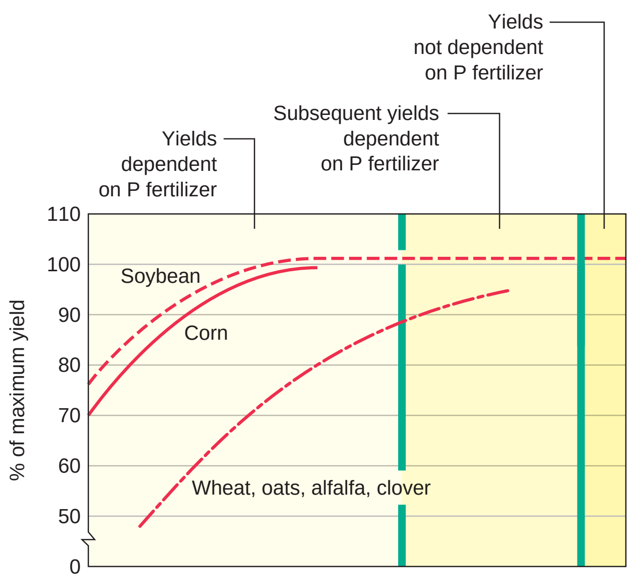


Figure 8.4. Subsoil phosphorus-supplying power in Illinois.



P test (lb/A) for different subsoil phosphorus-supplying power regions

High	7	15	20	40	60
Medium	10	20	30	45	65
Low	20	30	38	50	70

Figure 8.5. Relationship between expected yield and soil P, measured colorimetrically by the Bray P_1 or Mehlich-3 procedures on neutral-to-acid soils, or by the Mehlich-3 procedure on soils with pH > 7.3. These values should not be used for the Olsen (soil bicarbonate) test or for Mehlich-3 extractions analyzed by inductively coupled plasma emission spectroscopy (ICP).

internal drainage is fair or poor, P levels in the subsoil and substratum are likely to be low or medium.

Low supplying power. Soils in the "low" region in southeastern Illinois were formed from 2-1/2 to 7 feet of loess over weathered Illinoisan till. The profiles are more highly weathered than in the other regions and are slowly or very slowly permeable. Root development is more restricted than in the high or medium regions. Subsoil levels of P may be rather high by soil test in some soils of the region, but this is partially offset by conditions that restrict rooting.

Soils in the low region in northeastern Illinois were formed from thin loess (less than 3 feet) over glacial till. The glacial till, generally low in available P, ranges in texture from gravelly loam to clay in various soil associations of the region. In addition, shallow carbonates further reduce the P-supplying power of the soils of the region. Further, high bulk density and slow permeability in the subsoil and substratum restrict rooting in many soils of the region.

Phosphorus Recommendations

Minimum soil test levels required to produce optimal crop yields vary depending on the crop to be grown and the soil's P-supplying power (**Figure 8.5**). Near-maximal yields of corn and soybeans are obtained when levels of available P are maintained at 30, 40, and 45 pounds per acre for soils in the high, medium, and low P-supplying regions, respectively. Since these are minimal values, to ensure soil P availability will not restrict crop yield it is recommended that soil test results be built up to 40, 45, and 50 pounds per acre for soils in the high, medium, and low P-supplying regions, respectively. This is a practical approach because P is not easily lost from the soil, other than through crop removal or soil erosion.

Phosphorus soil test level required for optimal yields of wheat and oats is considerably higher than that required for corn and soybean yields (**Figure 8.5**), partly because of difference in uptake patterns. Wheat requires a large amount of readily available P in the fall, when the root system is feeding primarily from the upper soil surface. Phosphorus is taken up by corn until the grain is fully developed, so subsoil P is more important in interpreting the P test for corn than for wheat. To compensate for the higher P requirements of wheat and oats, it is suggested that 1.5 times the amount of expected P removal be applied prior to seeding these crops. This correction has already been included in the maintenance values listed for wheat and oats in **Table 8.6**.

No fertilization needed. There is no agronomic advantage in applying P when P_1 values are higher than 60, 65, and 70 for soils in the high, medium, and low P-supplying regions, respectively.

Maintenance fertilization needed. When soil test levels are between the minimum and 20 pounds above the minimum (40 to 60, 45 to 65, and 50 to 70 for the high, medium, and low P-supplying regions, respectively), apply enough to replace expected removal by the crop (and 1.5 times the removal for wheat and oats) using values from **Table 8.6**. At this test level, the yield of the current crop may not be affected by the fertilizer addition, but the yield of subsequent crops will be adversely affected if P is not applied to maintain soil test levels.

Buildup plus maintenance fertilization needed. When soil test levels are below the desired values (40, 45, and 50 for the high, medium, and low P-supplying regions, respectively), it is suggested that enough fertilizer be added to build the test to the desired goal and to replace what the crop will remove (as described in the previous paragraph). At this test level, the yield of the crop will be affected by the amount of P applied that year.

For perennial forage crops, broadcast and incorporate all of the buildup and as much of the maintenance as economically feasible after primary tillage and before seeding. On soils with low fertility, reserve 30 pounds of P_2O_5 per acre for band seeding. Warm-season perennial grasses prefer fertile soils but grow well in moderate fertility conditions. For establishment, fertilize with 24 to 30 pounds of P_2O_5. For these cropping systems, P rates beyond the year of establishment follow the regular maintenance or buildup plus maintenance program already described.

On average, Illinois soils require 9 pounds of P_2O_5 per acre to increase the P_1 soil test by 1 pound. The recommended rate of buildup for P is thus nine times the difference between the soil test goal and the actual soil test value. For a typical 4-year buildup program, divide the rate by 4 to determine the annual rate. Because the 9-pound rate is an average for Illinois soils, some soils will fail to reach the desired goal in 4 years with P_2O_5 applied at this rate, and others will exceed the goal.

Consequences of omitting fertilizer. The impact on yield and soil test level of eliminating P fertilizer will depend on the initial soil test and the number of years that applications are omitted. In a study in Iowa, eliminating P application for 9 years decreased soil test levels from 136 to 52 pounds per acre, but yields were not adversely affected in any year as compared to plots where soil test levels were maintained (**Figure 8.6**). In the same study, eliminating P for the 9 years when the initial soil test was 29 resulted in a decrease in soil test level to 14 and a decrease in yield to 70% of that obtained when adequate fertility was supplied. Eliminating P at an intermediate soil test level had little impact on yield but decreased the soil test level from 67 to 26 pounds per acre over the 9 years. These as well as similar Illinois results indicate little if any potential for a yield decrease if P application was eliminated for 4 years on soils that have a P test of 60 pounds per acre or higher.

Table 8.6. Maintenance fertilizer required for various crops.

	P_2O_5	K_2O
Grains		
Corn	0.43 lb/bu	0.28 lb/bu
Oats	0.38 lb/bu[a]	0.20 lb/bu
Soybean	0.85 lb/bu	1.30 lb/bu
Grain sorghum	0.42 lb/bu	0.21 lb/bu
Wheat	0.90 lb/bu[a]	0.30 lb/bu
Biomass		
Alfalfa, grass, or alfalfa–grass mixes	12.0 lb/ton	50.0 lb/ton
Corn silage	2.7 (0.53)[b] lb/ton	7.0 (1.4)[b] lb/ton
Corn stover	7.0 lb/ton	30 lb/ton[c]
Wheat straw	4.0 lb/ton	30 lb/ton[c]

To obtain total nutrient removal by the crop (maintenance rate), multiply value by the expected yield.
[a]Values given are 1.5 times actual P_2O_5 removal for oats and wheat.
[b]Values in parentheses correspond to pounds per bushel.
[c]Value will vary depending on amount of precipitation received between the time of physiological maturity and the time the material was baled and by the potassium fertility level of the soil.

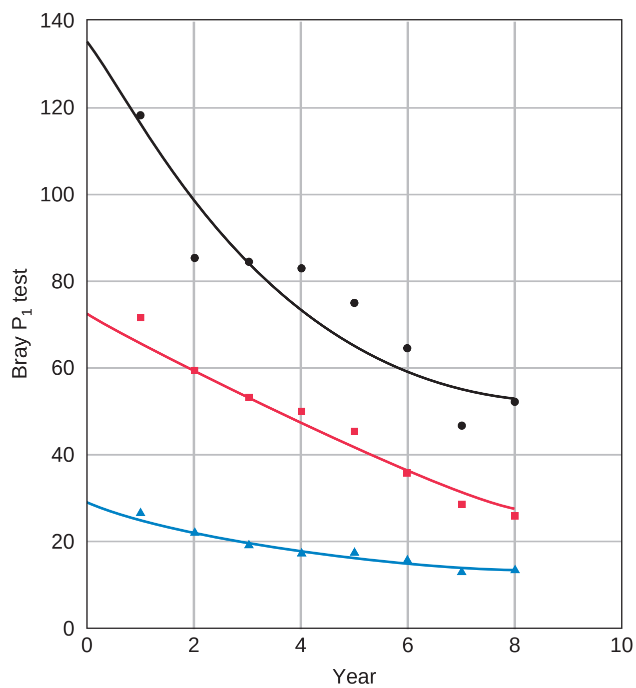


Figure 8.6. Effect of elimination of P fertilizer on P_1 soil test.

Potassium

Illinois is divided into two general regions for K, based on CEC (**Figure 8.7**). Soils with a CEC less than 12 milliequivalents per 100 grams are classified as having low capacity, while soils with values equal to or greater than 12 milliequivalents per 100 grams are considered to have high capacity. Important differences exist, however, among soils within these general regions because of differences in these factors:

- The amounts of clay and organic matter, which influence the exchange capacity of the soil.
- The degree of weathering of the soil material, which affects the amount of K that has been leached out.
- The kind of clay mineral.
- Drainage and aeration, which influence uptake of K.
- The parent material from which the soil was formed.

Low capacity includes sandy soils, because minerals from which they were developed are inherently low in K. Sandy soils also have very low cation exchange capacities and thus do not hold much reserve K.

Silt-loam soils in the "low" area in southern Illinois (claypans) are relatively older in terms of soil development; consequently, much more of the K has been leached out of the rooting zone. Furthermore, wetness and a platy structure between the surface and subsoil may interfere with rooting and with K uptake early in the growing period, even though roots are present.

Potassium Recommendations

Tests on soil samples that are taken before May 1 or after September 30 should be adjusted downward as follows: subtract 30 for the dark-colored soils in central and northern Illinois; subtract 45 for the light-colored soils in central and northern Illinois and for fine-textured bottomland soils; subtract 60 for the medium- and light-colored soils in southern Illinois.

Minimum soil test levels required to produce optimal crop yields vary depending on the crop to be grown and the soil's CEC (**Figure 8.8**). As with P, the only significant loss of soil-applied K is through crop removal or soil erosion, so to ensure that K availability will not limit crop yields it is recommended that soil test levels be slightly higher than that required for maximum yield. For corn and soybean it is recommended to have 260 and 300 pounds of exchangeable K per acre for soils in the low and high CEC regions, respectively.

Wheat is not very responsive to K unless the soil test value is less than 100 pounds per acre. Because wheat is usually grown in rotation with corn and soybeans, it is suggested that the soils be maintained at the optimal available K level for corn and soybeans.

No fertilization needed. No K additions are suggested if test levels are above 360 and 400 for the low and high CEC regions, unless crops that remove large amounts of K (such as alfalfa or corn silage) are being grown. When soil test levels are between 400 and 600 pounds of K per acre and corn silage or alfalfa is being grown, the soil should be tested every 2 years instead of every 4, or maintenance levels of K should be added to ensure that soil test levels do not fall below the point of optimal yields. Having adequate K in these systems is important to producing high-quality forage (K is important for the conversion of N to protein) and maintaining a vigorous stand (winter survival of legumes and stand longevity in grass-legume stands).

Maintenance fertilization needed. When soil test levels are between the minimum and 100 pounds above the minimum (260 to 360 and 300 to 400 for the low and high capacity, respectively), apply enough to replace what the crop to be grown is expected to remove using values from **Table 8.6**. At this test level the yield of the current crop may not be affected by the fertilizer addition, but the yield of subsequent crops will be adversely affected if K is not applied to maintain soil test levels.

Buildup plus maintenance fertilization needed. When soil test levels are below the desired values (260 and 300 for the low and high capacity, respectively), it is suggested that enough fertilizer be added to build the test to the desired goal and to replace what the crop will remove (as described in the previous paragraph). At this test level, the yield of the crop will be affected by the amount of K applied that year.

For perennial forage crops, broadcast and incorporate all of the buildup and as much of the maintenance as economically feasible before seeding. On soils with low fertility, it is safe to apply a maximum of 30 to 40 pounds of K_2O per acre along with the P band. Up to 600 pounds of K_2O per acre can be safely broadcast in the seedbed without damaging seedlings. Warm-season perennial grasses prefer fertile soils but grow well in moderate fertility conditions. For establishment, fertilize with 40 to 60 pounds of K_2O per acre. For these cropping systems, K rates beyond the year of establishment follow the regular maintenance or buildup plus maintenance program already described.

On average most Illinois soils require 4 pounds of K_2O per acre to increase the K exchangeable soil test by 1 pound. The recommended rate of buildup for K is thus 4 times the difference between the soil test goal and the actual soil test value. For a typical 4-year buildup program, divide the rate by 4 to determine the annual rate. In some soils, soil

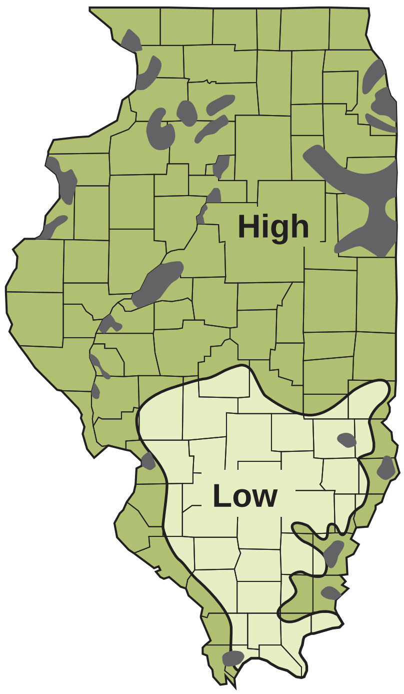


Figure 8.7. Cation-exchange capacity of Illinois soils. The darkest areas are sands with low capacity.

test levels do not build up as expected. Under the following conditions, an annual application approach (rather than buildup and maintenance) should be used:

- Soils for which past records indicate that soil test K does not increase when buildup applications are applied.
- Sandy soils that do not have a capacity large enough to hold adequate amounts of K.

Annual applications. When one of these conditions exists, or the land's expected tenure is short or unknown, continued monitoring of the level of K through soil testing every 4 years is recommended, along with the following:

- If soil test levels are below the desired buildup goal, multiply the maintenance value (K content in the harvested portion of the expected yield calculated from **Table 8.6**) by 1.5 and apply that rate annually.
- If levels are within the maintenance range, or only slightly below desired buildup levels (buildup and maintenance are less than 1.5 times removal), apply K maintenance amounts for the expected yield (**Table 8.6**).

There are advantages and disadvantages to buildup plus maintenance vs. annual application. In the short run, the annual option will likely be less costly. In the long run, the buildup approach may be more economical. In years of high income, tax benefits may be obtained by applying high rates of fertilizer. Also, in periods of low fertilizer prices, the soil can be built to higher levels that in essence

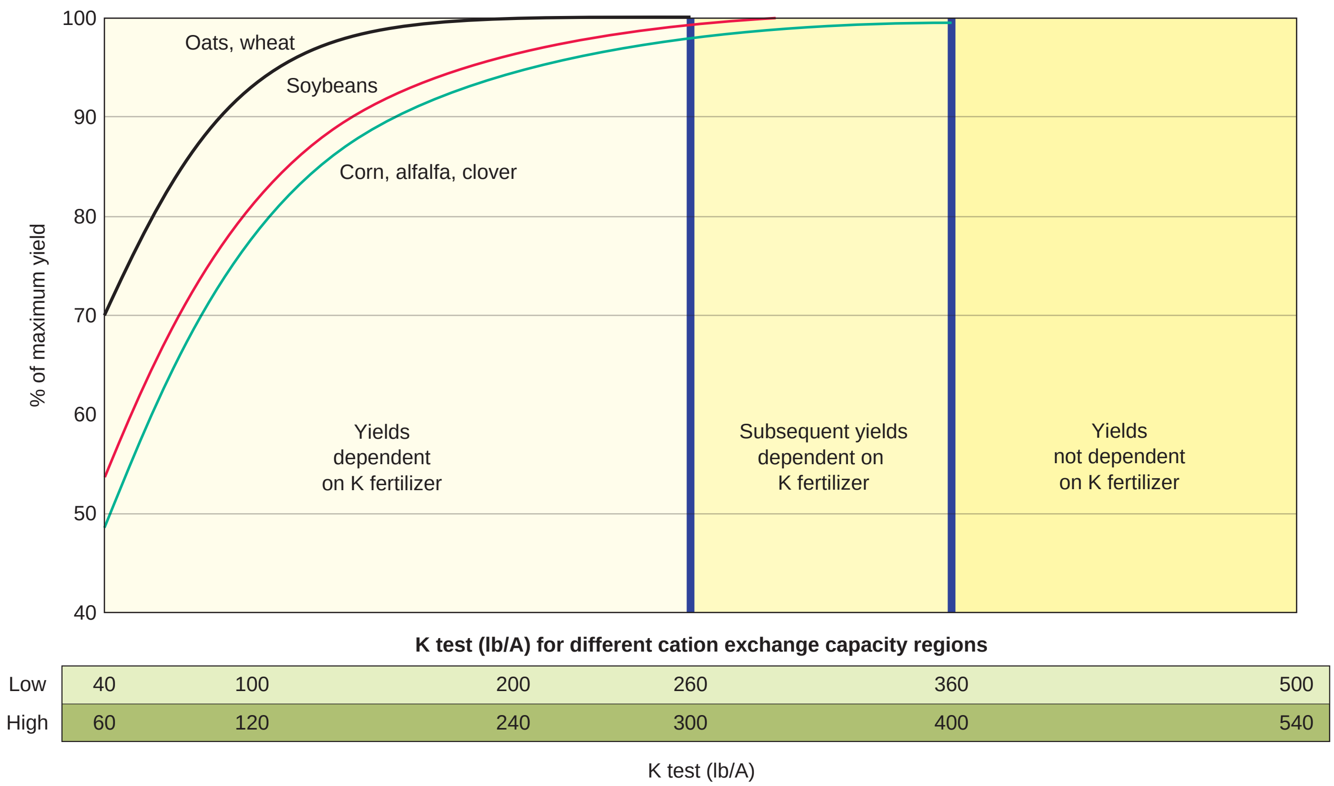


Figure 8.8. Relationship between expected yield and soil K, measured by the ammonium acetate or Mehlich-3 extractable K tests.

bank the materials in the soil for use at a later date when fertilizer prices are higher. Producers using the buildup system are insured against yield loss that may occur in years when weather conditions prevent fertilizer application or fertilizer supplies are not adequate. The primary advantage of the buildup concept is the slightly lower risk of potential yield reduction that may result from lower annual fertilizer rates. This is especially true in years of exceptionally favorable growing conditions. The primary disadvantage of the buildup option is the high cost of fertilizer in the initial buildup years.

Consequences of omitting fertilizer. The impact of eliminating K fertilizer on yield and soil test level will depend on the initial soil test and the number of years that applications are omitted. Although test levels tend to decline more rapidly for K than for P, there is little potential, if any, for a yield decrease if K application is eliminated for 4 years on soils that have a K test of at least 360 pounds per acre.

Applications of Phosphorus and Potassium

The following are examples of how to calculate P and K fertilizer rates for a 4-year program.

Example 1: Buildup plus maintenance needed

Continuous corn with a yield goal of 180 bushels per acre grown in a region of soils with high P-supplying power and high CEC. The soil test levels were 32 pounds of P and 250 pounds of K.

- Step 1: Calculate buildup rate.

  Phosphorus:

  The soil is 8 pounds below the desired level of 40 pounds per acre (**Figure 8.5**) (40 – 32 = 8).

  It takes 9 pounds of P_2O_5 to build the soil test level by 1 pound. 8 x 9 = 72 pounds of P_2O_5 over 4 years to bring soil P to the desired level, or 72 ÷ 4 = **18 pounds of P_2O_5** per year.

  Potassium:

  The soil is 50 pounds below the desired level of 300 pounds per acre (**Figure 8.8**) (300 – 250 = 50).

  It takes 4 pounds of K_2O to build the soil test level by 1 pound. 50 x 4 = 200 pounds of K_2O over 4 years to bring soil K to the desired level, or 200 ÷ 4 = **50 pounds of K_2O** per year.

- Step 2: Calculate maintenance (from **Table 8.6**).

  Phosphorus:

  0.43 pounds of P_2O_5 per bushel of corn x 180 bushels = **77 pounds of P_2O_5** per year.

  Potassium:

  0.28 pounds of K_2O per bushel of corn x 180 bushels = **50 pounds of K_2O** per year.

- Step 3: Sum buildup and maintenance values to determine yearly application rate.

  Phosphorus: 18 + 77 = **95 pounds of P_2O_5**

  Potassium: 50 + 50 = **100 pounds of K_2O**

Example 2: Maintenance-only needed

Corn and soybean with a yield goal of 180 bushels of corn per acre and 50 bushels of soybean per acre grown in a region of soils with medium P-supplying power and low CEC. The soil test levels were 55 pounds of P and 320 pounds of K.

- Step 1: Calculate maintenance (from **Table 8.6**).

  Phosphorus:

  0.43 pounds of P_2O_5 per bushels of corn x 180 bushels = **77 pounds of P_2O_5** for corn year.

  0.85 pounds of P_2O_5 per bushels of soybean x 50 bushels = **43 pounds of P_2O_5** for soybean year.

  Potassium:

  0.28 pounds of K_2O per bushel of corn x 180 bushels = **50 pounds of K_2O** for corn year.

  1.30 pounds of K_2O per bushel of soybean x 50 bushels = **65 pounds of K_2O** for soybean year.

  If a biennial application is preferred, sum the P and K rates for both crops to determine the rate of application.

Example 3: No fertilization needed

Corn and soybean with a yield goal of 180 bushels of corn per acre and 50 bushels of soybean per acre grown in a region of soils with high P-supplying power and high CEC. Soil test levels were 90 pounds of P and 450 pounds of K.

Example 4: Annual application

Corn and soybean with a yield goal of 160 bushels of corn per acre and 40 bushels of soybean per acre grown in a region of soils with low P-supplying power and low CEC. The soil test levels were 75 pounds of P and 180 pounds of K. The K test levels fail to increase as expected.

Since P levels are high, there is no need to apply P. The soil does not respond to buildup rates, so following an annual application approach is recommended.

- Step 1: Calculate maintenance (from **Table 8.6**).

  0.28 pounds of K_2O per bushel of corn x 160 bushels = **45 pounds of K_2O** for corn year.

  1.30 pounds of K_2O per bushel of soybean x 40 bushels = **52 pounds of K_2O** for soybean year.

- Step 2: Adjust for annual application approach.

  45 pounds of K_2O x 1.5 = **68 pounds of K_2O** for corn year.

  52 pounds of K_2O x 1.5 = **78 pounds of K_2O** for soybean year.

Determining Removal in Forage Systems

As mentioned, P and K needs are assessed by soil testing. If testing is not being done in a pasture system, the second best option is to apply what is removed by the crop using values from **Table 9.6**. Very productive pastures yield 5 to 6 tons of dry matter per acre, moderately productive pastures 3 to 5 tons, and less productive pastures 1 to 3 tons. Recycling of nutrients from urine and manure reduces the total nutrients removed from a pasture by 60% to 80%, varying with the intensity of grazing management (continuous vs. rotational vs. management-intensive) and the resulting distribution of manure. Managed grazing improves the distribution and utilization of P and K. Thus, usually less of these two nutrients is needed on pastures than on hay fields. It is important to test soil every 4 years to monitor changes in the fertility status of pastures.

Determining Removal by Baled Stover or Straw

Baling corn stover and wheat straw has a direct impact on P and K removal from the field. This removal needs to be included in fertilization plans for the following crop. The best method to determining nutrient removal is by directly measuring tons of residue baled and chemically analyzing samples collected from those bales.

If that method is not feasible, follow these guidelines to determine nutrient removal through an indirect approach: The amount of residue produced depends on several factors, but for corn and wheat typically a general value is 1 pound of residue per pound of grain produced (dry weight basis). The amount of actual removal will depend on harvest method. Traditional harvest methods remove anywhere from 50% to 80% of the total residue. To determine the amount of P and K removed with the residue, multiply the values in **Table 8.6** by the tons of residue removed.

The actual amount of nutrients present in the residue can vary significantly from the table values dependent on several factors such as growing-season conditions, hybrid, and general fertility of the soil. Further, while P has low mobility because it is present in organic forms, K is present in a highly soluble inorganic form. Thus, K amounts can be largely influenced by the amount and frequency of precipitation in the time elapsed since the crop reached maturity and the time the residue was removed from the field.

In determining nutrient removal and the actual value of crop residue, it is important to realize that there are components in addition to P and K. Crop residue also includes N, secondary macronutrients, and micronutrients, as well as organic carbon. The impacts of increased removal of these nutrients and organic carbon from residue removal are not as obvious in the short term as for P and K, but they will definitely carry consequences in the long term. While secondary macronutrients and micronutrients are not typically provided through fertilization in Illinois, greater removal can accelerate deficiency of these nutrients in the soil. Removal of basic cations (such as K, Ca, and Mg) can lead to an increase in the need to lime soils to maintain adequate pH levels. Nitrogen reserves, as well as organic matter depletions, can lead to less crop availability of N through the process of mineralization (conversion of organic N to inorganic forms). Diminishing organic carbon contents can also result in negative impacts on soil physical, chemical, and biological properties. Thus, all factors, including nutrient removal and soil resources, should be carefully considered when estimating the actual cost of crop residue removal.

Fertilizer Sources

MAP vs. DAP. Monoammonium phosphate (MAP) and diammonium phosphate (DAP) are the most common P sources. The main difference between these two products is the amount of P and N present in the fertilizer and the initial chemical reaction that takes place in the soil when they are applied. Both products are made by ammoniation of phosphoric acid. The grade for MAP varies (11-51-0, 10-50-0, 11-55-0, etc.) because the phosphoric acid quality for MAP is lower than for DAP (which can be sold only as 18-46-0). As phosphate rock quality declines in the mines, MAP production is favored. When applied in the soil, MAP produces an acidifying reaction that can prevent the formation of toxic levels of ammonia, while DAP produces an alkaline reaction and the formation of ammonia. However, these initial differences diminish within a month or two, and no agronomic differences are typically observed between the two P sources.

Solubility of phosphorus. The water solubility of the P_2O_5 listed as available on the fertilizer label is of little importance under typical field crop and soil conditions on soils with medium to high levels of available P when recommended rates of application and broadcast placement are used. Due to rapid interaction of P fertilizer with iron and aluminum, P is tightly bound in the soil, so water solubility does not imply great movement or leaching.

For some situations, water solubility is important:

- For band placement of a small amount of fertilizer to stimulate early growth, at least 40% of the P should be water-soluble for application to acidic soils, and preferably 80% for calcareous soils. As shown in **Table 8.7**, the P in nearly all fertilizers commonly sold in Illinois is highly water-soluble. Phosphate water solubility above 80% has not been shown to increase yield any further than water solubility of at least 50%.
- For calcareous soils, a high degree of solubility in water is desirable, especially on soils that are shown by soil test to be low in available P.

White vs. red potash. Both red and white potash are muriate of potash (potassium chloride, or KCl). When the ore is mined it is reddish in color due to iron impurities. Depending on the processing and recovery method, the iron impurities are either removed or are left on the final product. Red potash is produced by grinding and flotation, while white potash is produced by dissolution and recrystallization in which iron is removed from the final product. Red potash is 0-0-60, and white potash is slightly more pure 0-0-62. Both forms are highly soluble and contain approximately 47% chloride. The difference in the amount of sodium is significant enough to produce any differences in the crops. Red potash contains approximately 4% sodium and white potash about 1%; there are no agronomic differences between the two products.

Noncommercial fertilizer sources. Livestock manure, sewage sludge, and some industrial waste materials are effective sources of plant nutrients. Since many of the nutrients in these materials are in the organic form and since the ratio of N to P is often not in the same proportion as removed by the plants, these materials require special management to ensure that an adequate supply of plant nutrients will be available. Whenever possible, the allocation of these products should be based on P, not N, needs of the crop to minimize the potential for long-term buildup of P in the soil. The amount of nutrients present in these products is animal- and management-specific. In order to apply adequate nutrient rates, the quantities contained in these materials need to be determined through chemical analysis, if details are not already provided by the supplier. Table 9.6 (p. 132) shows average nutrient values that can be used as a general reference for different materials. In equivalent bases of commercial fertilizer, P and K availability from these sources is normally 80% and 85%, respectively. A large percentage of both P and K will be available the first year after application, and approximately 10% of the original amount will be available the second year.

Table 8.7. Water solubility of some common processed-phosphate materials.

Material	% P_2O_5	% water-soluble
Ordinary superphosphate 0-20-0	16–22	78
Triple superphosphate	44–47	84
Mono-ammonium phosphate 11-48-0	46–48	100
Di-ammonium phosphate 18-46-0	46	100
Ammonium polyphosphate 10-34-0, 11-37-0	34–37	100

Placement of Fertilizers

Selecting the proper application technique for a particular field depends at least in part on the inherent fertility level, the crop to be grown, the land tenure, and the tillage system. On fields where the fertility level is at or above the desired goal, method of placement is often irrelevant. In contrast, on low-testing soils and in soils with high P- and K-fixing capacity, placement of the fertilizer within a concentrated band can be beneficial, particularly at low rates of application. On higher-testing soils, plant recovery of applied fertilizer in the year of application is usually greater from a band than a broadcast application, though yield differences are unlikely. Finally, there is no evidence suggesting that fertility levels can be maintained if fertilizer rates are reduced in a band application.

Broadcast fertilization. Broadcast and incorporation by plow or disk is an effective method to apply buildup and maintenance rates of P and K on soils with adequate fertility. This system, particularly when the tillage system includes a moldboard plow every few years, distributes nutrients uniformly throughout the entire plow depth. As a result, roots growing within that zone have access to high levels of fertility. Because the nutrients are intimately mixed with a large volume of soil, opportunity exists for increased nutrient fixation on soils having high fixation ability. Fortunately, most Illinois soils do not have high fixation rates for P or K.

Relatively immobile materials such as limestone, P, and K move slowly in most soils unless they are physically mixed by tillage operations. Broadcast applications of these materials in no-till or other forms of conservation tillage (including chisel plow) cause vertical stratification of nutrients, with higher concentrations developing near the surface. Such stratification has not been shown to reduce yields of corn or soybeans in Illinois. Among other factors, this is likely because crops develop more roots near the soil surface in conservation tillage systems, due apparently to both the improved soil-water conditions caused by the surface mulch of crop residues and the higher levels of available nutrients.

When doing a broadcast application it is important to maintain uniformity across the application width, do the correct amount of overlap, and have an applicator control system that maintains application rate per unit of soil surface constant independent of ground speed. When using dry bulk blends, ensure that materials are as uniform as possible in size, density, and distribution in the fertilizer bin. For liquids, maintain solution well mixed in the tank, and check nozzles for clogging.

Starter or row fertilization. This is an application below and to the side of the seed (typically 2 inches below and 2 inches to the side, also known as 2x2 placement). Other techniques to attain a starter response include application in direct contact with the seed ("pop-up" fertilization, described later) and placement on the soil surface near the seed row. These methods have not shown the consistency of crop response observed for the 2x2 technique. On soils of low fertility, 2x2 placement of fertilizer has been shown to be an efficient method of application, especially when the rate of application is markedly less than that needed to build the soil to the desired level. Producers who are not assured of having long-term tenure on the land may wish to consider this option. The major disadvantages of row fertilization are the additional time and labor required at planting time, limited contact between roots and fertilizer, and inadequate rate of application to increase soil levels for future crops.

Wet and cool soil conditions early in the season can limit plant growth and nutrient uptake. This is typically a greater concern in no-till fields where the high surface residue content has a mulching effect. Row fertilization promotes rapid and uniform corn growth when cool and wet soil conditions are present, even in soils with high fertility. At high soil test levels, the early growth response to starter seldom results in increased yield at harvest. This early growth response to starter occurs because the fertilizer band provides a high nutrient concentration when uptake demands are high relative to the small size of a root system with reduced growth and nutrient uptake capacity due to unfavorable soil conditions. For this reason, even when a large amount of fertilizer is being added by broadcast, starter applications are recommended on soils with low to medium fertility to ensure adequate nutrient supply to corn seedlings.

The greatest response to starter in corn is given by N, followed by P. Potassium produces the smallest response, and typically only when K test levels are low or when soil conditions are limiting nutrient uptake. Nitrogen in the band can increase P uptake by maintaining this nutrient in a more available form. Also, roots proliferate in response to N and P, so a band containing these two nutrients can increase nutrient availability by producing more roots to absorb the nutrients. The use of urea in the band, however, is not recommended since its hydrolysis produces ammonia, which inhibits root growth and thus negatively impacts P uptake. Since salt content can also injure roots, it is recommended not to exceed 75 and 100 pounds of salt (N plus K_2O) per acre in a starter application for soybean and corn, respectively. However, research has shown that under some conditions as much as 200 pounds of N per acre can be applied in a 2x2 placement without injuring corn. Although rarely done, a 2x2 placement can supply all the P and K maintenance for one crop.

In contrast to corn, soybean response to starter is unlikely if soil fertility is medium to high or if an adequate broadcast application of P and K was done in a low-testing soil. The difference is likely related to the distinct root system of both crops and the fact that soybeans are planted later, when soil conditions are less limiting for nutrient uptake.

Seed placed, or "pop-up," fertilization. With this method a small amount of fertilizer is applied directly with the seed. The term "pop-up" is misleading. Corn does not emerge sooner; in fact, it may be delayed a few days with this kind of application. While corn may grow more rapidly during the first 1 to 2 weeks after emergence, seldom will there be a yield difference compared to a 2x2 placement.

Some advantages for this placement method include lower equipment cost, faster planting (fewer fertilizer fill-up stops during planting), and the possibility for early cultivation for weed control due to faster growth of the crop. However, seed-placed fertilization is a risky operation. Under normal moisture conditions, the maximum safe amount of salt (N plus K_2O) for pop-up placement is about 10 or 12 pounds per acre. In excessively dry springs, or sandy soils with very low CEC (less than 8), even these low rates may result in damage to seedlings and/or reduction in germination. Urea or urea-containing fertilizers as well as micronutrients should not be used in direct contact with the seed.

Soybean is more sensitive to salt than is corn, so pop-up fertilization is not recommended for soybean.

Wheat is very responsive to P, especially under low-test levels. Because of narrow rows in wheat, there are fewer options for starter fertilizers than in corn. For this reason, starter P (normally 10-34-0, 18-46-0, or 11-52-0) is often placed with the seed. The small amount of N in the fertilizer can also help the crop when no pre-plant N was applied or when little carryover N is available from the previous crop.

For perennial forage crops, 30 pounds of P_2O_5 and up to 30 to 40 pounds of K_2O per acre can be applied safely when using a band seeder. This large amount of K is safe because the rate per acre is distributed over more rows (less fertilizer in direct contact with the seed) compared to a wider 30-inch row planter.

Strip application. With this technique, P, K, or both are applied in narrow bands on approximately 30-inch centers on the soil surface, in the same direction as the primary tillage. The theory behind this technique is that, after moldboard plowing, the fertilizer will be distributed in a narrow vertical band throughout the plow zone. This system reduces the amount of soil-to-fertilizer contact as compared with a broadcast application and thus reduces the potential for nutrient fixation. Because the fertilizer is distributed through a larger soil volume than with a band application, the opportunity for root-fertilizer contact is greater.

Deep fertilizer placement. Several terms have been used to define this technique, including root-zone banding, dual placement, knife injection, and deep placement. With this system any combination of N, P, and K can be injected at a depth of 4 to 8 inches. The knife spacing varies, but generally it is 15 to 18 inches apart for close-grown crops such as wheat and 30 inches for row crops. This placement technique is often used in combination with strip-tillage operations. With this tillage system, greater early growth and increase in corn yield, compared to a no-till system, often is the result of tillage in strip-till and not the method of nutrient placement. Under low-testing soils, when surface soil conditions are dry and subsurface water content is still adequate, subsurface placement (especially for K) can be advantageous for corn in reduced tillage systems. However, the small yield increase that can be expected is not cost-effective in light of the added cost of deep placement. It is important to realize that if the application is deep, it takes a longer time for the roots to reach the fertilizer. This can be a problem in years when growing conditions limit root development. If a deep placement is chosen in low-fertility soils, applying a starter fertilizer is recommended. Another situation in which subsurface applications may be beneficial (as long as the subsurface band application does not create a channel for water and soil movement) is when the potential for surface water runoff is high.

Site-specific or variable-rate application. This application method uses several remote sensing technologies, yield monitors, global positioning systems (GPS), geographical information systems (GIS), and variable-rate technology (VRT). These technologies can improve the efficacy of fertilization and promote more environmentally sound placement of fertilizer compared to single-rate applications derived from the conventional practice of collecting a composite soil sample to represent a large area of the field. Research has shown that this technology often reduces the amount of fertilizer applied over an entire field. However, one of the drawbacks of this placement method is the expense associated with these technologies. Also, VRT can only be as accurate as the soil test information used to guide the application rate. At this point, due to the inherent high variability in soil testing over small distances and the fact that most soils where these technologies are being used have been managed to have reserved P and K levels, the technology has seldom produced significant yield increases.

Foliar fertilization. It is well known that plant leaves absorb and utilize nutrients sprayed on them. Foliar fertilization can be effective for nutrients required in small amounts by plants. Nutrients required in large amounts, such as N, P, and K, are recommended to be soil-applied rather than foliar-applied. Foliar applications can only supply very small amounts of the total nutrients needed by crops. Because it would take many applications to supply the needed amounts without burning leaves, foliar application of major nutrients is neither practical nor cost-effective.

Environmental Considerations

Phosphorus has been identified as an important pollutant to surface waters. At very low concentrations, it can increase eutrophication of lakes and streams, which leads to problems with their use for fisheries, recreation, industry, and drinking water. Although eutrophication is the natural aging process of lakes and streams, human activities can accelerate the process by increasing the concentration of nutrients flowing into water systems. Since P is the element most often limiting eutrophication in natural water bodies, controlling its input into lakes and streams is very important.

There are concerns that agricultural soils may be important contributors to eutrophication. Normally about 5% of the soil P is soluble or easily soluble (labile) and can be lost in surface water runoff; the remaining 95% is tightly bound to soil particles. When the soil particles end up in the water, chemical equilibrium reactions release some of the absorbed P into the water. Thus, erosion control and reduction of P levels in the very surface of the soil are the best ways to minimize P loss. The following practices can help minimize P loss from agricultural fields:

1. Do not maintain excessively high-P soil test levels. While soil test procedures were designed to predict where P was needed, not to predict environmental problems, the likelihood of P loss increases with high-P

test levels. Of course, environmental decisions regarding P applications should not be made solely on P soil test levels. Rather, decisions should also include such factors as distance from a significant lake or stream, infiltration rate, slope, and residue cover. One possible problem with using soil test values to predict environmental problems is in sample depth. Normally samples are collected to a 7-inch depth for predicting nutritional needs. For environmental purposes, it would often be better to collect the samples from a 1- or 2-inch depth, which is the depth that will influence P runoff. Another potential problem is variability in soil test levels within fields in relation to the dominant runoff and sediment-producing zones.

2. Maintain buffer strips (grassy waterways, vegetative filter strips, or constructed wetlands) at the point where water leaves the field.
3. Minimize soil erosion and surface water runoff by protecting soils with residue cover, conservation tillage, the use of cover crops, farming on contours and having contour buffer strips, reducing soil compaction and increasing soil-water permeability, and maintaining subsurface drainage systems, which allow excess water to move out of the field in the tiles and not on the surface. Although some of these practices may not reduce the potential for loss of dissolved P, they will reduce the potential for loss of total P.
4. Do not leave manure or P fertilizers on the soil surface. Incorporating or injecting these products not only reduces the potential for P runoff, it also reduces the potential for N volatilization and reduces odor of manure applications.
5. Match nutrient applications to crop needs. This will minimize the potential for excessive buildup of P soil tests and reallocate P sources to fields or areas where they can produce agronomic benefits.
6. Where possible, grow high-yielding, high-P-removing crops on fields that have excessively high-P soil test levels. Even when this is done, it may take several years to lower very high levels.

Time of Application

While an annual application of P and K in a corn–soybean rotation is effective, it is possible to apply enough nutrients in any one year to meet the needs of the crops to be grown in the succeeding 2 to 3 years. Biennial applications are often preferred to reduce application costs. With biennial applications, it is recommended that you apply the fertilizer required for both crops before the corn crop and make soybean a residual feeder in the rotation.

P and K fertilizers may be applied in the fall to fields that will not be fall-tilled, provided that the slope is less than 5%. Do not apply fertilizer in fall to fields that are subject to rapid runoff. When the probability of runoff loss is low, soybean stubble need not be tilled solely for the purpose of incorporating fertilizer. This statement holds true when ammoniated phosphate materials are used as well, because the potential for volatilization of N from ammoniated phosphate materials is insignificant. P and K applications are preferred in the fall because normally there is more time available than during the spring planting season, and soil conditions tend to be less conducive to compaction. One drawback of fall P application is that the small amounts of N accompanying ammoniated phosphate fertilizers are subject to nitrification and potential loss. A three-year study in Urbana showed total N recoveries at the end of May to be 17% and 45%, respectively, for fall- and spring-applied ammoniated phosphates (MAP and DAP).

For double-crop soybeans after wheat, it is suggested that P and K fertilizer required for both crops be applied before seeding wheat. This practice reduces the number of field operations at planting time and hastens soybean planting. Also, wheat can benefit by having abundant P available during early establishment.

For perennial forage crops, broadcast and incorporate all of the P and K buildup and as much of the maintenance as economically feasible before seeding. After establishment, top-dressed applications of P and K may be made at any convenient time. Usually this will be after the first harvest or in September.

Secondary Nutrients

As previously mentioned, since response to application of secondary nutrients is uncommon in Illinois, there is not a large database to correlate and calibrate soil test procedures; thus, low confidence can be placed in the suggested soil test levels offered in **Table 8.8**.

Calcium deficiencies in Illinois have not been observed for soils with pH at or above 5.5. Calcium deficiency associated with acidic soils can be corrected by adjusting soil pH with limestone.

Table 8.8. Suggested soil-test levels for secondary nutrients.

Soil type	Levels adequate for crop production (lb/A)		Rating	Sulfur (lb/A)
	Calcium	Magnesium		
Sandy	400	60–75	Very low	0–12
Silt loam	800	150–200	Low	12–22
			Response unlikely	22

Magnesium deficiency has been recognized in isolated situations in Illinois. The soils most likely to be deficient in Mg include acidic and sandy soils throughout Illinois and low CEC soils in southern Illinois. Deficiency is more likely where calcitic limestone ($CaCO_3$) rather than dolomitic limestone ($CaMg[CO_3]_2$) has been used.

The number of incidents with sulfur-deficient crops in the Midwest has increased, probably the result of increased use of S-free fertilizer; decreased use of S as a fungicide and insecticide; increased crop yields, resulting in increased requirements for all of the essential plant nutrients; and decreased atmospheric S supply. Despite the increasing frequency of S deficiency reports, crop responses to S applications in Illinois have been inconsistent. Routine application of S fertilizer is thus not recommended.

If an S soil test is performed, evaluate whether an S response is likely by also considering organic matter level, potential atmospheric S contributions, subsoil S content, and soil-water conditions just before soil samples were taken. Since soil organic matter is the primary source of S, soils low in organic matter are more likely to be deficient than soils with higher organic matter (>2.5%). Early-season S symptoms may disappear as rainfall contributes some S (especially downwind from industries emitting significant S amounts) and as root systems develop to exploit greater soil volume. Sulfur is also a very mobile nutrient. In sandy soils under excess precipitation, leaching may result in low test values of samples collected from the soil surface. Conversely, if the soil surface is dry and hot at the time of sampling, test results can overestimate the capacity of the soil to supply this nutrient during the entire growing season. For these reasons, if a soil test is unexpectedly low, use S only on a trial basis.

Micronutrients

Boron (B), chlorine (Cl), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), and zinc (Zn) are the seven essential micronutrients (also known as minor or trace elements). Although these nutrients are required only in small (micro) amounts, if any of them is deficient, it can result in severe yield reduction. Deficiencies of these nutrients are not common, making it challenging to study and to correlate and calibrate soil tests. Micronutrient tests thus have very low reliability and usefulness. Suggested levels for each test are provided in **Table 8.9**. In most cases, however, plant analysis will provide a better estimate of micronutrient needs than the soil test. **Table 8.2** shows critical plant-nutrient levels for various crops.

In general, deficiencies of most micronutrients are accentuated by one of five situations: strongly weathered soils, coarse-textured soils, high-pH soils, organic soils, and soils low in organic matter, either inherently or because erosion or land-shaping processes have removed the topsoil.

The use of micronutrient fertilizers should be limited to areas of known deficiency, and only the deficient nutrient should be applied. An exception to this guideline would be situations in which farmers already in the highest yield bracket try micronutrients experimentally in fields that are yielding less than would be expected under good management, which includes an adequate N, P, and K fertility program and a favorable pH.

Confirmed deficiencies of micronutrients in Illinois have been limited to B deficiency of alfalfa, Zn deficiency of corn, and Fe and Mn deficiencies of soybean. To identify areas before micronutrient deficiencies become important, continually observe the most sensitive crops in soil situations in which the elements are likely to be deficient (**Table 8.10**).

Boron deficiency in alfalfa results in shorter internodes and bunching of top leaves that are typically yellow-reddish. Some plants might not flower, and under severe deficiency, growing points may die. Deficiency symptoms typically appear on the second and third cuttings of alfalfa and are especially pronounced during droughty periods in some areas of Illinois. Application of B on soils with less than 2% organic matter is recommended for areas of high alfalfa production. If you suspect B deficiency, a simple test is to apply 30 pounds per acre of household borax (3.3 lb of B) to a strip. To make application easier, B can be added to the P–K fertilizer. Generally 1 to 2 pounds of B per acre can be applied yearly to sandy soil. On finer-textured soils, 3 to 4 pounds of B per acre can be applied in the first hay year to correct the deficiency for a few years. Oats are sensitive to B. If oats accompany alfalfa during the establishing year, it is better to apply B after the first year. Foliar applications of 0.1 to 0.3 pounds of B per acre are recommended for severely deficient fields. Do not apply B to alfalfa the year before corn. Both corn and soybean have

Table 8.9. Suggested soil-test levels for micronutrients.

Micronutrient and procedure	Soil-test level (lb/A)		
	Very low	Low	Adequate
Boron—hot-water soluble	0.5	1	2
Iron—DTPA	—	<4	>4
Manganese—DTPA	—	<2	>2
Manganese—H_3PO_4	—	<10	>10
Zinc—.1N HCl	—	<7	>7
Zinc—DTPA	—	<1	>1

Table 8.10. Soil situations and crops susceptible to micronutrient deficiency.

Micronutrient	Sensitive crop	Susceptible soil situations	Conditions favoring deficiency
Zinc (Zn)	Young corn	Low in organic matter, inherently or from erosion or land shaping Restricted root zone High pH (>7.3) Coarse-textured (sandy) soils Very high phosphorus Organic soils	Cool, wet
Iron (Fe)	Soybeans, grain sorghum	High pH	Cool, wet
Manganese (Mn)	Soybeans, oats	High pH Organic soils Restricted root zone	Cool, wet
Boron (B)	Alfalfa	Low organic matter Strongly weathered soils (south-central Illinois) High pH Coarse-textured (sandy) soils	Drought
Copper (Cu)	Corn, wheat	Infertile sand Organic soils	Unknown
Molybdenum (Mo)	Soybeans	Acidic, strongly weathered soils (south-central Illinois)	Unknown
Chlorine (Cl)	Unknown	Coarse-textured soils	Excessive leaching by low-Cl water

low requirements for B and can suffer toxicity if the previous alfalfa crop received heavy or repeated B applications.

Zinc deficiency in corn is characterized by interveinal light green to whitish bands from the base to the tip of new leaves. Normally the edge of the leaf, including the tip, and the midrib area stay green, but in cases of severe deficiency the new leaves can be completely white. Also, corn plants will look stunted and have shorter internodes. Applications of 5 and 10 pounds of Zn per acre are recommended for band and broadcast applications, respectively. If a chelated product is used, follow the manufacturer's directions.

Iron deficiency in soybean appears in new leaves, typically at early stages of development. The entire leaf blade turns yellow except for the veins, which remain green. The growth is often stunted. Foliar applications are more effective in restoring green color. Typically 1 to 2 pounds of Fe per acre are recommended. When using chelated products, follow the manufacturer's directions. Research in Minnesota has shown that for soybean, time of Fe application is critical to attaining a response. Apply 0.15 pounds of Fe as Fe chelate per acre to leaves within 3 to 7 days after chlorosis symptoms develop (usually in the second-trifoliate stage of growth). Waiting for soybeans to grow to the fourth- or fifth-trifoliate stage before applying Fe would result in no yield increase.

Manganese deficiency in soybean causes stunted plants with green veins in yellow or whitish newer leaves and typically occurs in late May and June if the weather turns cool and wet. To correct Mn deficiency in soybean, spray either manganese sulfate or an organic Mn formulation onto the leaves after the symptoms appear. Broadcast applications on the soil are not recommended; band applications of 5 to 8 pounds of Mn per acre can be effective. Foliar applications of 0.5 pounds of Mn per acre are recommended. For chelated products, follow the manufacturer's directions. Foliar applications of MnEDTA at rates as low as 0.15 pounds of Mn per acre in mid-June to soybean planted in early May have shown significant yield increases. Similarly, multiple applications or delaying applications to early July have been beneficial.

Nontraditional Products

Many products circulate the fertilizer market claiming to replace fertilizers and to cost less, to make nutrients in the soil more available, to supply micronutrients, or to be a natural product. Those promoting the products typically use testimonials by farmers and present data from suspect sources. The best approach that producers can take is to challenge these peddlers to produce unbiased research results in support of their claims.

Extension specialists at the University of Illinois are ready to give unbiased advice when asked about new products. An additional resource entitled *Compendium of Research Reports on Use of Non-traditional Materials for Crop Production* contains searchable data on a number of nontraditional products that have been tested by university researchers in the U.S. The publication can be accessed at extension.agron.iastate.edu/compendium.

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Managing Nitrogen

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Approximately 78% of the air above an acre of land is nitrogen (N). Unfortunately, grain crops such as corn and wheat cannot use this N because it is in N_2 form, which is very inert. This means that grain crops need to get their N from sources such as manure and fertilizer, in which the N is in forms that the plants can take up and use. Because plants have more N than any other element besides those that come from the air or water (carbon, hydrogen, and oxygen), nitrogen is the most limiting element in grain crop growth under most natural (unfarmed) systems and in many farming systems. Other than possible stress due to shortage of water, N deficiency in grain crops is also very visible. Finding ways to provide N to grain crops has been a major challenge to farmers in most parts of the world since the beginning of agriculture.

Nitrogen Rates for Corn

A bushel of corn contains about 0.8 pounds of nitrogen (N), so a 200-bushel corn crop removes about 160 pounds of N from the field. About two-thirds of the N in a corn plant ends up in the grain, so our 200-bushel crop would have about 240 pounds of N in the plants before harvest. This is 1.2 pounds N per bushel, which has been the factor that has been used to convert proven or expected yield into N rate recommendations—"1.2 is the most [we] should do." This has been the corn N rate recommendation in Illinois for more than three decades, with some minor adjustments over time. This guideline was not just made up; it resulted from early work showing how much N the plant needs relative to its yield, and it also was backed by N rate research showing that, averaged over trials, "optimum" yield (yield at the economically optimum N rate) divided by the optimum N rate came out to about 1.2 pounds of N per bushel.

At one time, the N rate recommendation was tempered by economic considerations. Thus it was suggested to lower the 1.2 pounds N/bushel to 1.1 or even 1.0 if the ratio of N price (dollars per pound) to corn price (dollars per bushel) rose from, say, 0.05 (10 cents/pound N: $2 per bushel) to 0.1 (20 cents/pound N: $2 per bushel) or higher. This makes economic sense, in that we usually try to apply an input like N at a rate where the last pound of N added produces enough extra yield to just pay for itself. Agronomically, there was incentive to apply N at the rate needed for maximum yield, plus some extra "just in case," in order to always have enough N. In fact, the development of the yield-based N recommendation provided a much-needed rationale to lower rates to more reasonable levels. Without it, N rates of 200 or more pounds per acre were used for corn not expected to produce more than 100 bushels per acre. In Illinois, the average corn yield exceeded 100 bushels per acre for the first time in 1967, and from the mid-1960s to the mid-1970s, corn yield averaged less than 100. Ammonia prices during that period averaged about $100 per ton, or about 5 cents per pound of N.

While yield-based N recommendations were appropriate and useful at the time they were developed, recent research results have shown that modern hybrids grown in Illinois soils may not need as much N as these recommendations suggest. In most studies, especially those where corn follows soybean, there is little or no relationship between yield and the N rate it takes to reach those yields (**Figure 9.1**). Reasons for this discrepancy include the fact that the soil provides varying amounts of N, and also that modern hybrids may be better both at extracting N from the soil and at using this N efficiently to produce grain. The latter is true in part because the grain protein content of newer hybrids tends to be lower than that of older hybrids, so the removal of N with the grain is lower on a per-bushel basis.

A New Approach

One way to use data from a large number of trials is to average results over the trials, producing single curves that describe average N responses (**Figure 9.2**). This approach is straightforward, and we can apply economics to such response curves to find the optimum rate. However, it can be difficult to average data over different trials done differently, and there is usually little sense of, or adjustment for, variability among response curves.

Most N response data show a curvilinear (decelerating) response, usually (depending on highest rate) leveling off at some point, with a flat curve after that. Yield decreases at high N rates occur rarely now compared to trials a few decades ago, as a result of hybrid improvement. **Figure 9.3** shows such a response from one trial. After finding a line to fit the data, we can subtract the yield at zero N fertilizer and multiply the yield added by N at each N rate times the price of corn to produce the gross return from N. Subtracting the cost of N gives the "return to N" (RTN) line, which gives the profit from N at each N rate (**Figure 9.4**). The high point of this line is the "maximum return to N" (MRTN) point, where the yield increase from adding N just paid for the N added.

Similar RTN values are calculated for each trial in the N response dataset; then these values at each N rate are averaged to produce an RTN line for the whole dataset. The MRTN is the high point on this average line over all trials, and it shows the N rate at RTN at which the maximum return to fertilizer N is reached. **Figure 9.5** shows RTN based on a dataset containing results of many trials over years and locations. Because the RTN curve tends to be rather flat on top, we think it makes sense to use a "range" of N rates instead of a single rate. We arbitrarily chose this range to be the N rates over which the RTN is within $1 per acre of its maximum, at the MRTN. In the database we have, this range of N rates is usually about 15 to 20 pounds on either side on the N rate that produces the MRTN, so the range is about 30 to 40 pounds of N wide. Ranges allow some individual choice based on personal approach to risk, environmental fragility, and other factors.

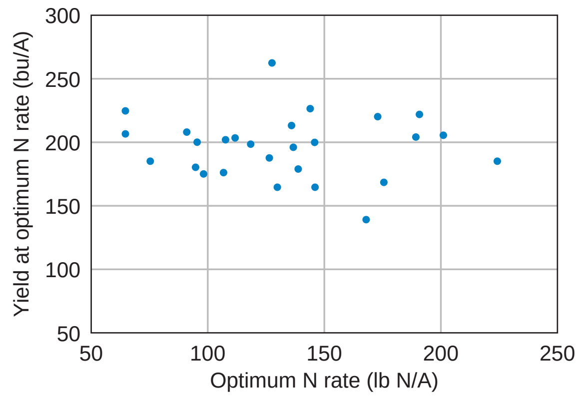

Figure 9.1. Optimum yields and optimum N rates from 27 separate N rate trials in Illinois. Trials were corn following soybean, and optimum N rates were calculated using the N price ($ per lb N) to corn price ($ per bushel) ratio of 0.1.

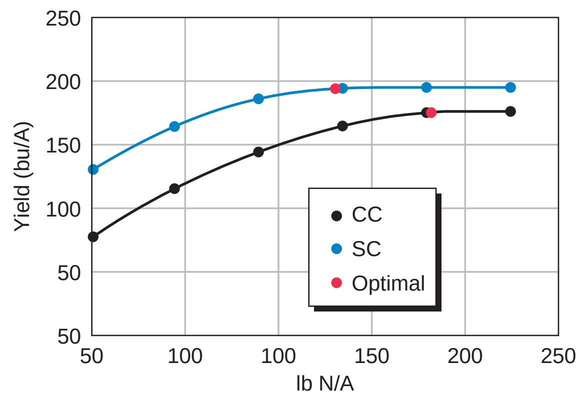

Figure 9.2. Response of corn to N rate, averaged over 27 trials with corn following corn (CC) and 27 trials with corn following soybean (SC). Optimal N rate-yield points are calculated based on the N price ($ per lb N) to corn price ($ per bushel) ratio of 0.1.

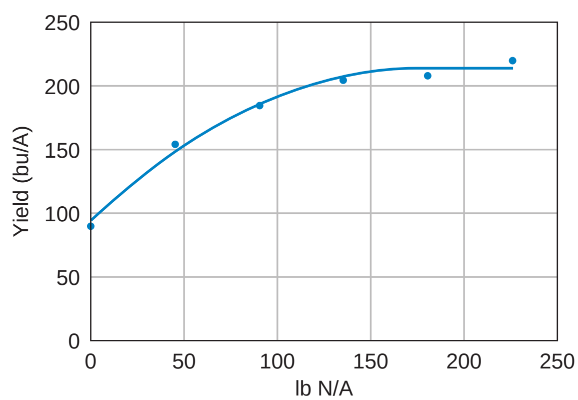

Figure 9.3. Corn yield response to N rate in a trial at Urbana where corn followed corn. The symbols are actual yields, and the line is computer-fitted as a "quadratic + plateau" line, where the curve rises then flattens out.

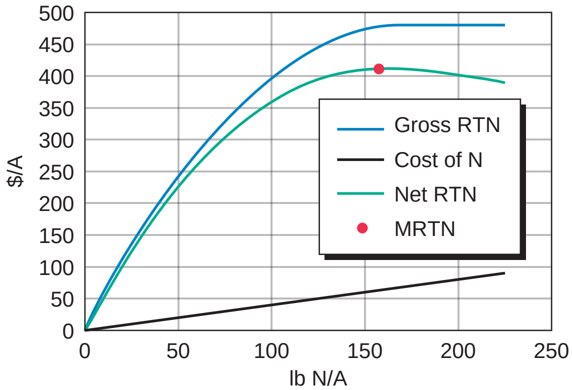

Figure 9.4. Return to N (RTN) at different N rates, using the data shown in Figure 9.3. The gross RTN is the yield increase (over the yield without N) times a corn price of $4 per bushel, and the N cost line is based on N priced at 40 cents per pound. Net RTN is the gross RTN minus the N cost. The point of maximum return to N (MRTN) is the highest point in the net RTN curve.

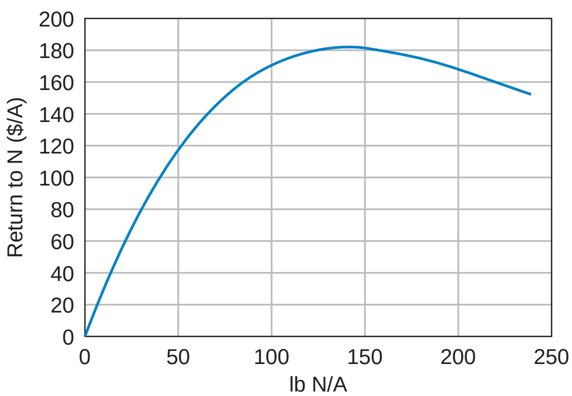

Figure 9.5. Return to N averaged over 40 trials with corn following soybean in northern Illinois.

The development of the MRTN approach was a cooperative effort among a group of scientists. Dr. John Sawyer at Iowa State University created a website where N rate guidelines can be calculated using this approach. The Illinois option on this website uses data generated from more than 400 trials in Illinois since the mid-1990s. Separate databases allow calculations to be made for northern, central, and southern Illinois, for corn following corn, and for corn following soybean. Calculations can be made for single N and corn price combinations, or different price combinations can be compared on the same graph. **Figure 9.6** shows the opening page of this website, and the output for corn following corn in northern Illinois as an example. New data are added each year, but the database in Illinois is large enough that calculated rates will not change a great deal as new data are added. The website is extension.agron.iastate.edu/soilfertility/nrate.aspx.

What Changes with the New Guidelines?

We have termed N rates calculated as described "guideline" rates, to reflect that this is a decision aid rather than a fixed recommendation. This does not mean that we don't have faith in this method—we recommend strongly that it be used, and we recommend that the yield-based N recommendation system no longer be used. We recognize that the use of a "sliding" N rate guideline and of ranges is not as comfortable for some as the single, fixed rate that could be calculated under the proven-yield (PY) system. The fact that rates can change with corn and N prices may also seem to some to be agronomically shaky, in that it might seem that there must be a "best" rate from a yield standpoint. The fact that guideline rates are not fixed also seems to allow the possibility that the crop could sometimes end up deficient in N. In truth, no reasonable N recommendation system can rule out N deficiency under some conditions. In research, we occasionally see yields respond to N rates above 250 pounds per acre. This makes it clear that it is unreasonable to use N rates high enough to guarantee that the corn crop will never be deficient.

While we know of no perfect system to set N rates under variable conditions such as those in the Corn Belt, we do think that this is the best way to use current research data to estimate N rates that are likely to provide the best return. It is clear that as corn yields continue to rise, N rates required to produce such yields are not rising at the same rate, if they are rising at all. As **Figure 9.1** shows, yields above 200 bushels can in some cases be produced with less than 100 pounds of N. From an environmental standpoint, the fact that most guideline N rates are lower than rates under the proven yield system would seem to be a positive.

We trust N rate calculations based on current N and corn prices, but if N prices drop and corn prices rise so that the ratio drops to 0.05 or less, calculated N rates could be very high. The N rate calculator has a built-in limit on this, and it will not calculate N rates with the top of the range above 240 pounds N per acre. For corn following corn in northern Illinois, this limit is reached at a ratio of about 0.03. Reaching such a ratio is unlikely; for instance, if the corn price were $8 per bushel, N would have to cost less than 25 cents per pound.

When using manure, sewage sludge, or other N sources that usually cost less per pound of N than commercial fertilizers, a conservative approach to assigning value to those products is to price the pounds of crop-available N the same as would be for a pound of N from commercial fertilizer. Usually about 50% of the total N in dry manure and 50% to 60% of the total N in liquid manure is available in the first year after application.

Corn Nitrogen Rate Calculator

Finding the Maximum Return To N and Most Profitable N Rate

A Regional (Corn Belt) Approach to Nitrogen Rate Guidelines

State: Illinois - North
Number of sites: 40
Rotation: Corn Following Soybean
Non-Responsive Sites Not Included

Nitrogen Price ($/lb): 0.40
Corn Price ($/bu): 4.00
Price Ratio: 0.10

MRTN Rate (lb N/acre):	**139**
Profitable N Rate Range (lb N/acre):	126 - 153
Net Return to N at MRTN Rate ($/acre):	$181.00
Percent of Maximum Yield at MRTN Rate:	99%
Anhydrous Ammonia (82% N) at MRTN Rate (lb product/acre):	170
Anhydrous Ammonia (82% N) Cost at MRTN Rate ($/acre):	$55.60

Most profitable N rate is at the maximum return to N (MRTN).
Profitable N rate range provides economic return within $1/acre of the MRTN.

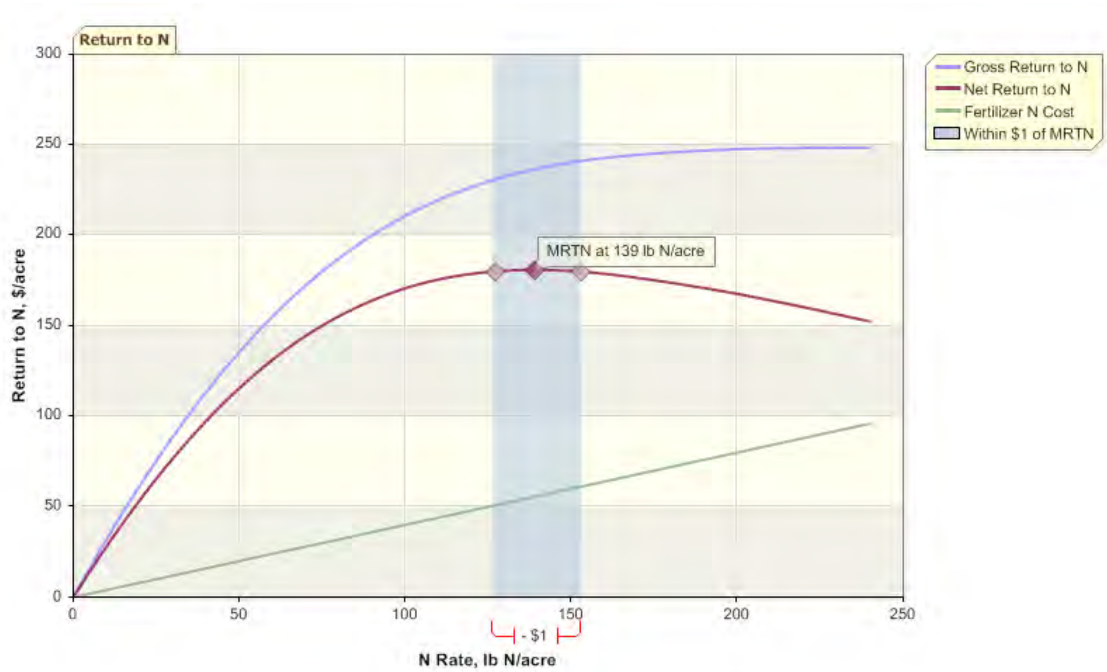

Figure 9.6. Output page from the online corn N rate calculator for corn following soybean in northern Illinois. Based on 40 different trials, 139 lb of N will maximize the return to N when the N price is 40 cents per pound and corn is $4 per bushel. The return to N is within $1 per acre of the maximum over the range from 126 to 153 lb N per acre. The profit produced by N at this rate is $181 per acre.

Guideline N rates in central Illinois are lower for corn following corn and similar for corn following soybean than under the PY method. In southern Illinois, N rates are somewhat higher than under the PY method, reflecting the fact that lower-yielding corn typically needs more N per bushel of yield than has generally been thought. In northern Illinois, N rates under these guidelines are considerably lower than under the PY method and are in line with those calculated for Iowa. We think that higher soil organic matter, more manure application in the past on many fields, and favorable weather have increased both yields and the supply of N from the soil in this part of Illinois.

One of the features of these new guidelines is that there is no longer a subtraction of a “soybean N credit.” The guideline rates for corn following soybean are calculated based only on those trials where corn followed soybean, so there is no longer any consideration of how this rate compares to the rate for corn following corn. Do not make further subtractions from the calculated rates in order to include such “credit.” In northern Illinois, corn following corn has a guideline rate about 40 pounds per acre higher than corn following soybean, so it is similar to the “N credit” previously used. In central Illinois, however, the difference is less than 10 pounds. This is not only because of different soils,

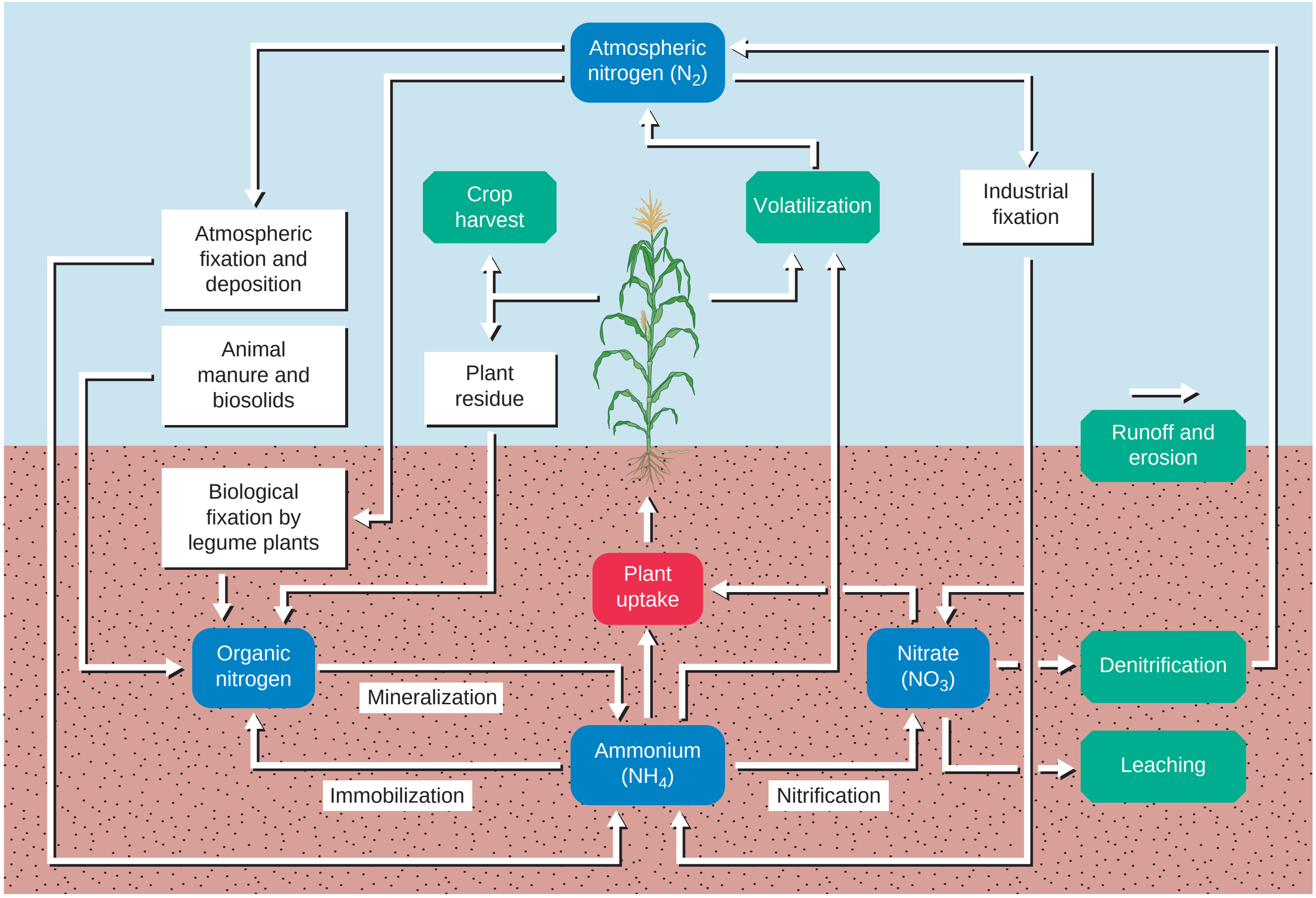

Figure 9.7. The nitrogen cycle.

but also because carryover N reduced the response to N for corn following corn in some trials following dry years. Many of the trials with corn following corn were done in different fields than those of corn following soybean, so some of this is due to chance. In any case, results for central Illinois overall indicate that corn following soybean simply needs N rates close to those needed by corn following corn. In southern Illinois, the difference is about 20 pounds.

Factors That Affect Nitrogen Availability

Soil N can undergo several transformations that influence its availability to plants. Understanding how N behaves in the soil is necessary to know how to improve its management. Key points to consider in the nitrogen cycle are the changes from inorganic to organic forms (immobilization), from organic to inorganic forms (mineralization), and from ammonium (NH_4^+) to nitrate (NO_3^-) as well as the movements and transformations of nitrate (**Figure 9.7**).

Immobilization. Inorganic N, mainly in the ammonium (NH_4^+) and nitrate (NO_3^-) forms, is taken up by plants and microorganisms to form organic compounds needed for various functions to sustain life. This process is referred to as immobilization, since it takes N "out of circulation." From a management standpoint, immobilization is important in relation to N availability and to processes such as breakdown of residues or other organic materials. The population of microbes is in equilibrium with the food (carbon) supply in the soil. When large amounts of residue are added to the soil, the microbial population increases rapidly, and the demand for N to help them grow increases as well.

Microbial growth has a carbon to nitrogen (C:N) ratio of 8:1 to 12:1, and microbes need to take in carbon and nitrogen in the ratio of about 20:1 (some C is used up in respiration) in order to grow. So when crop residue has a C:N ratio greater than 20:1 (corn stalks are 50:1 to 60:1), microbes take up some N from the soil in order to have enough N for growth. Conversely, residues rich in N, such as alfalfa and soybean (C:N less than 20:1), have more N than microbes need, so microbes will release some N to the soil as they break down such residues.

Mineralization. Mineralization is the process by which organic N is converted to NH_4^+ ions, thus becoming available for plant uptake. This takes place during the decomposition of organic matter by microorganisms. Mineralization is a relatively slow process, and N release rates depend on organic source and the environment. Mineralization of N from dead microorganisms is three to four times faster than release from other organic N sources (such as organic matter) in the soil. Those conditions that promote plant growth (warm temperatures, adequate soil pH, good water content, and proper soil aeration) also enhance mineralization.

Each percentage point of organic matter content in the top 7 inches of the soil translates to about 20,000 pounds of organic matter per acre. Approximately 5% of soil organic matter is N; many Illinois soils contain large amounts of organic matter, and consequently large amounts of N. For example, a soil with 4% organic matter contains approximately 4,000 pounds of organic N in the top 7 inches, and deep soils will have considerably more than this in their topsoil. Because it is tied up in organic compounds, most of the N in organic matter is unavailable for uptake by crops at any given time.

Through the process of mineralization, about 1% to 3% of the organic N in the topsoil is converted annually into plant-available N. This would mean that a soil with 4% organic matter might be able to provide 40 to 120 pounds of N per acre per year. This range is wide because soil and weather conditions vary so much over years. Once N is in the NH_4^+ form, it is held by soil clay and organic matter and cannot move very far until it nitrifies.

Nitrification. Nitrification is the conversion of ammonium (NH_4^+) to nitrite (NO_2^-) and then to nitrate (NO_3^-). This is a bacteria-mediated process that accelerates as soil temperatures rise between 60 and 85 °F, when soil pH is slightly acidic to slightly basic, and when there is good soil aeration. The process of nitrification does not stop completely until soil temperatures are below freezing. The transformation of nitrite to nitrate is typically fast, so NO_2^- seldom accumulates. This is fortunate, because NO_2^- is toxic to plants and animals. Since the two steps in nitrification are done by different types of bacteria, it is possible to have accumulation of NO_2^- when soil conditions are very acidic or when a large amount of organic N is being nitrified under near-saturated conditions. Under such conditions, the bacteria that transform NH_4^+ to NO_2^- are active, while the bacteria responsible to transform NO_2^- to NO_3^- are not. In field conditions this can occur when manure is injected in poorly drained soils.

While NH_4^+ cannot be lost through leaching or denitrification, NO_2^- and NO_3^- can be lost in these ways. So it is advantageous to delay nitrification until as close as possible to the time crops start to take up large amounts of N. Since NH_4^+ is transformed rapidly to NO_3^- under conditions favorable for crop growth, crops normally take up most of their N as NO_3^-. However, NH_4^+ is also important. Corn normally grows better when at least a quarter of the N supply is NH_4^+. In most fields, NH_4^+ needs are met by the normal process of mineralization, so there is generally no need to adjust fertilization practices to assure that plants have enough NH_4^+ to balance their uptake of NO_3^-.

Denitrification. Denitrification is the process by which N in the form of NO_2^- or (most commonly) NO_3^- is converted by bacteria into N_2 or N_2O gas. Both of these gases move up through the soil freely and are lost to the atmosphere, and neither can be taken up by crops. Denitrification is done by bacteria that are anaerobic, meaning that they are active when oxygen levels are low. This means that most denitrification occurs under saturated soil-water conditions. Since saturated soils are not uncommon in Illinois, denitrification is believed to be the main process by which NO_3^- and NO_2^- nitrogen are lost, except on sandy soils, where leaching is the major pathway.

The amount of denitrification depends mainly on how long the soil is saturated, the temperature of the soil and water, the pH of the soil, and the amount of energy material available to denitrifying organisms.

When water stands on the soil or the surface soil is completely saturated in late fall or early spring, N loss is likely to be small because much of the N (applied as fertilizer) is often still in the NH_4^+ rather than NO_3^- form and because the soil is cool, so denitrifying organisms are not very active. A different scenario occurs in late spring and early summer, when temperatures and microbial activity are high. The percentage of NO_3^- nitrogen in the soil (from fertilizer or nitrified from the soil supply) that can be lost through denitrification for each day the soil stays saturated varies by temperature. Nitrate losses through denitrification in Illinois are 1% to 2% when soil temperatures are less than 55 °F, 2% to 3% if soil temperatures are between 55 and 65 °F, and 4% to 5% at soil temperatures above 65 °F.

Leaching. Nitrate leaching depends on water movement, which is governed by several factors, including soil texture and structure, water status of the soil at the time of rainfall, and the amount and frequency of rainfall. An inch of water that enters a dry soil will move on average 4 to 6 inches down into a silt loam and slightly less in a clay loam. Some of the water will move farther down through preferential flow paths, such as through larger pores left by old roots or earthworms. In a loamy sand, each inch of rain that enters the soil will move down about 12 inches. By tasselling time, corn roots penetrate to depths of 5 and 6 feet in well-drained fields. So if the total rainfall at one time is more than 6 inches, little NO_3^- will be left within the rooting depth on sandy soils. Conversely, if that same amount of rain occurs in a finer-textured soil, NO_3^- will be still within the rooting depth (approximately 3 feet) as long as it does not reach tile lines and drain from the field.

As soils dry out between rainfall events, evaporation of water from the soil surface and extraction by plant roots create a suction force that moves water and dissolved nitrate from deeper in the soil to shallower depths. So if another rain event occurs a few weeks later, the water will not carry NO_3^- down from the previous point, but from shallower depths. The next rainfall event will have to replenish soil water lost since the previous event, and nitrate will not move down again until after there has been enough rain to replace this water. If the soil is already wet at the time of rainfall, water (and NO_3^-) will not move uniformly along a wetting front, but rather will flow deeply through large soil pores. All these factors, along with the fact that some rainwater might run off the surface, make it difficult to predict how deep NO_3^- has moved based solely on total rainfall.

Estimating Nitrogen Availability

Because N can become available from organic matter in different amounts, can change forms, and can be lost from the soil, testing soil to determine N fertilizer needs for Illinois field crops is not nearly as useful as is testing to determine the need to add lime, phosphorus, or potassium fertilizer. Testing soil to predict the need for N fertilizer is complicated by the fact that N availability—both the release from soil organic matter and the loss by leaching and denitrification—is regulated by unpredictable weather conditions. Under excessively wet conditions, both soil and fertilizer N may be lost by denitrification or leaching. The amount of N released from organic matter is low under dry conditions but high under ideal moisture conditions. For these reasons soil tests designed to test how much N is available and how much more fertilizer N might be needed have not been very successful under Illinois conditions. Testing to estimate how much soil N is available to the crop close to the time of rapid N uptake by the crop has, however, been reasonably successful. This is because the N present in the soil at that time has less likelihood of being leached or denitrified before the crop can take it up. Even this approach presents some challenges, as we shall see.

Total soil nitrogen test. Because 5% of soil organic matter is N, some have theorized that organic matter content of a soil could be used as an estimate of the amount of supplemental N that would be needed for a crop. As a rough guideline, many assume that 2% of the organic N will be released each year. This would amount to a release of 100 pounds N per acre on fields with 5% organic matter. This estimate tends to be very inexact because mineralization of organic matter varies significantly over time due to variations in available soil moisture and in soil temperatures as well as in crop growth rates and the ability of the crop to take up N. Soils high in organic matter usually have a higher yield potential due to their ability to provide a better environment for crop growth, and so may need to take up more N.

Illinois soil nitrogen test (ISNT, or amino sugar-N test). This test was proposed to identify fields nonresponsive to N fertilization for corn by measuring organic amino sugar-N compounds that can mineralize during the growing season. Unfortunately, data from many sites in Illinois and the Midwest showed that this test was not able to predict nonresponsive sites with sufficient accuracy to prevent incidents of yield loss. Values produced by this test usually show high correlation to soil organic matter content, and many believe that this is because the test measures a relatively constant fraction of the total soil N, rather than only a readily mineralizable fraction. Researchers have found that relatively high ISNT values do not always mean that little fertilizer N need be applied, especially when cool soils limit mineralization into early June. This suggests that caution is needed in relying on this test.

Early spring nitrate nitrogen test. This procedure has been used for several years in the drier parts of the Corn Belt (west of the Missouri River) with reasonable success. It involves collecting soil samples in 1-foot increments to a 2- to 3-foot depth in early spring for analysis of NO_3^- nitrogen. This information is then used to reduce the total amount of N to be applied by the amount found in the soil profile sampled. Results obtained by scientists in both Wisconsin and Michigan have shown this procedure to work well, but research in Iowa indicated that the procedure did not accurately predict N needs.

Since samples are collected in early spring, the procedure measures mostly N carried over from the previous crop. It thus has the greatest potential for success on corn that follows corn, especially in fields where adverse growing conditions limited yields the previous year and where dry weather has reduced loss of N from the soil. Additional work is needed to find the sampling procedure that will best characterize the field conditions, especially when N has been injected in prior years. Heavy rainfall in late spring or early summer will reduce the usefulness of this test because much of the N detected earlier in the spring may be leached or denitrified before the plant has an opportunity to take it up from the soil.

Pre-sidedress nitrate test (PSNT). Work in several states has shown this test to be useful. The PSNT is typically more accurate in high-yielding environments and in fields that have received manure or other organic fertilizers in the recent past or that have had legume crops with high N content, such as alfalfa. By sampling later in the season, this test provides a measure of the amount of N mineralized from organic N plus the amount of carryover N still present in the soil. However, if late spring temperatures are below normal, the test tends to overestimate N needs (lower soil test values), probably because of slow rates of mineralization in the soil. One of the limitations of this test is that it is useful only for fields that will receive sidedress N application. Usually a small starter rate (20 to 30 lb of N per acre) can be applied without compromising the usefulness of the test. Since N is applied at sidedress time, this brings the risks of a relatively short application window, which can be a challenge, especially in wet years, when applications may be delayed until plants are too large.

The reliability of this procedure depends heavily on ensuring that samples are collected, handled, and processed correctly. A sample to 12 inches deep is collected when corn plants are 6 to 12 inches tall (V4 to V6 development stage), or in late May to early June when planting is delayed. If the field had a history of broadcast applications, randomly collect 20 to 25 samples from an area no greater than 10 acres. If band applications of fertilizer or manure were used to fertilize the previous crops, collect at least 10 sets of three cores each between two corn rows. The first core is collected 3 inches to the right of the corn row, the second core in the middle of the two rows, and the third core 3 inches to the left of the next corn row. In all cases, place all the cores in a bucket and obtain a subsample after the cores have been thoroughly mixed. If mixing the entire sample to produce a representative subsample is too difficult, it is better to use large sample bags and keep the entire sample. Collecting a sample less than the full 12 inches or not collecting all the cores will produce unreliable results. If the samples cannot be delivered to the laboratory the same day, either freeze or air-dry the sample. If you air-dry samples, dry them as fast as possible by spreading the samples out on a paper, crushing the cores, and blowing air with a fan. Since drying can be difficult without proper facilities, freezing samples is likely the best option for most people. Make sure to tell the laboratory that you want to measure NO_3^- nitrogen. If the entire sample is sent, request that the whole sample be dried and ground before a subsample is taken.

The general consensus is that no additional N is needed if PSNT test levels are above 25 parts per million, and a full rate should be applied if NO_3^- nitrogen levels are less than 10 parts per million. When test levels fall between 10 and 25 parts per million, N rates should be adjusted proportionally.

Measuring N Status by Plant Analysis and Sensing Technologies

Plant tissue testing. Plant tissue analysis can be useful in diagnosing N deficiency. For more information on tissue N levels and how to collect samples, see Chapter 8, page 95, under the heading "Plant Analysis."

SPAD meter. The SPAD meter is a device that measures relative greenness by determining how much light passes through a leaf. It is sometimes called a green meter or chlorophyll meter. Greenness is related to N level in the leaf. By comparing chlorophyll meter readings to those in a high N-rate strip of the same hybrid, the relative N status of plants, including degree of deficiency, can be estimated at any point during the season. The ability of this test to predict N deficiency improves as the plant starts to take up considerable amounts of N. Taking readings at about the V10 growth stage (plants typically about waist-high) is timely, because differences in leaf greenness are usually apparent then and there is still enough time to apply supplemental N if needed. If N is the factor that limits corn yield, then SPAD readings taken at about the time of pollination typically show a high correlation with yield. This is shown for an Illinois trial in **Figure 9.8**.

SPAD readings should be averaged from 20 to 30 plants from each area of interest in a field. Before tassels appear, collect readings from the top leaf with a fully visible collar. The same leaf of each plant should be measured, and readings are more uniform if taken at about the same position on the leaf, about halfway between the tip and the base and as far from the edge as the instrument allows.

Relative SPAD readings can be calculated by dividing the average reading from the portion of the field in question by the average reading from the reference strip. This relative value can be used to determine the rate of N needed to bring the corn crop to full yield potential. Work from Iowa showed that if the relative SPAD reading is 0.97 (97% of the reference strip) or lower, supplemental N is needed (**Table 9.1**).

Crop color sensing technology. Remote optical sensing technologies are being developed and used to determine the N status of the crop. These might include remote sensing (usually aerial photography) or sensors mounted on applicators, with changes in crop color used to adjust N application rate in different parts of the field.

The relative greenness of a crop canopy can be measured by seeing how much light of certain wavelengths (colors) the canopy reflects. Many crop sensors measure crop reflectance in the red (650 ± 10 nm) and near infrared (770 ± 15 nm) wavelengths and then calculate a "normalized difference vegetation index" (NDVI) based on these relative

Table 9.1. Relative SPAD values collected between V10 and VT corn development stages and corresponding N fertilizer rates when 100 lb N/acre is the maximum rate to be applied.

Relative SPAD values	N to be applied (lb/A)
<0.88	100
0.88–0.92	80
0.92–0.95	60
0.95–0.97	30
>0.97	0

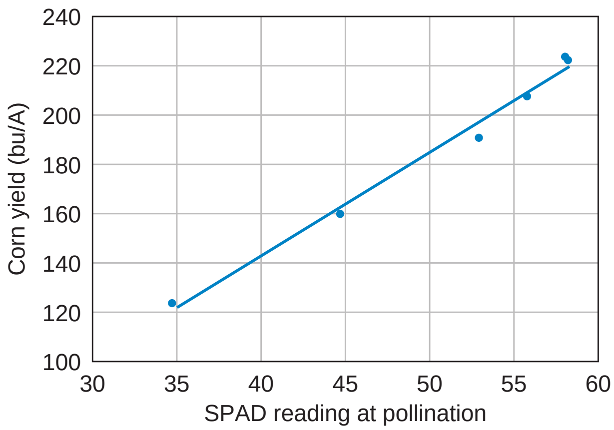

Figure 9.8. Correlation between SPAD meter readings taken on the ear leaf at pollination and final grain yield in an Illinois trial.

readings. The need for additional midseason N fertilization is assessed by comparing readings to reference strips. In some cases, such readings are made on the go by sensors mounted on the applicator, and N rates are varied based on these readings in each part of the field. Readings from an aerial photo can be used to make a map, which can then direct different N rates to different parts of the field.

These techniques are often effective on irrigated fields where additional N can be applied through the irrigation system with little application cost and without damage to the crop. They can also be useful in rainfed systems where significant N loss has occurred or when the full rate of N has not been applied. For most Illinois fields, however, it is not yet clear that N rate adjustment based on crop color is cost effective, nor is it clear how it can best be done. As with other methods, the later such color measurements can be made, the more accurately they reflect crop N status and the soil supply, so the better they predict the need for additional N.

Nitrogen Fertilization

Most of the N fertilizer materials available for use in Illinois provide N in the forms of ammonia, NH_4^+, urea, and NO_3^- or in combinations of these. For many uses on a wide variety of soils, all forms are likely to produce about the same yield—provided that they are applied correctly.

Anhydrous ammonia (NH_3). This source of N is typically among the least expensive and contains the highest percent N by weight of all forms of N (82%). Anhydrous means "without water." Anhydrous ammonia is a liquid when kept under pressure, but it turns into gas when not contained in a pressure-capable tank. The weight of this fertilizer in liquid form is 5.9 pounds per gallon.

One of the drawbacks to the use of NH_3 is the danger it poses for living organisms in the event that it escapes into the air. It requires equipment than can handle high pressure (approximately 200 pounds per square inch), and its safe transport and handling represent real challenges. Because ammonia under pressure is a mixture of liquid and vapor, it is more difficult to ensure uniform application across a tool bar; average rates can usually be attained, but distribution is affected by such things as hose length and air temperatures. These problems can be minimized by using speed-control devices, using newer manifolds that are designed to distribute ammonia more evenly, and taking time to ensure that the applicator is properly configured. Variability among application knives can be reduced by taking certain steps: make sure the manifold is leveled and the openings used are evenly distributed around the manifold; do not have a hose opening directly opposite the entry of ammonia; avoid using dual manifolds with tool bars with less than 14 knives; cut all hoses to the same length; and use the same diameter hoses, hose barbs, and knife openings in all shanks.

Although anhydrous ammonia applications kill desirable microorganisms in the soil, this should not be a concern. With normal soil moisture, ammonia moves only a few inches from the point of release out into the soil, and only within this zone—normally less than 10% of the volume of the topsoil—will microbes be killed. The effect is also temporary in that N will, in the long term, enhance microbial growth once microbes move into the application zone.

Another concern is that ammonia will adversely affect the physical and chemical properties of the soil. Research has shown that other than lowering the pH, which is a feature common to most N fertilizer sources that contain or produce ammonium (replacing hydrogen atoms with oxygen atoms, in the conversion of ammonium to nitrate, releases hydrogen, which decreases pH), anhydrous ammonia does no lasting harm to soils whatsoever.

Ammonium nitrate (NH_4NO_3). This fertilizer material is 34% N (34-0-0). Half of the N is in the NH_4^+ form and half is in the NO_3^- form. Ammonium nitrate is highly soluble in water. Because 50% of the N is present as NO_3^-, this product is more susceptible to loss from both leaching and denitrification. NH_4NO_3 thus should not be applied to sandy soils because of the likelihood of leaching, nor should it be applied far in advance of the time when the crop needs the N because of possible loss through denitrification. Ammonium nitrate is not easily volatilized, so it can be used for surface application where conditions are conducive to NH_3 volatilization. Because NH_4NO_3 has been used by individuals to produce explosives, it is no longer sold widely as a fertilizer material in the Corn Belt.

Urea ($CO[NH_2]_2$). This source is 46% N (46-0-0), and all of the N is in the urea form. As such, it is very soluble and moves freely up and down with soil water. After application in the soil, NH_2 changes to NH_3 either chemically or by the enzyme urease, and then to NH_4^+. The speed with which this conversion occurs depends largely on temperature. Conversion is slow at low temperatures but rapid at temperatures of 55 °F or higher.

If the conversion of urea to ammonium occurs on the soil surface or on the surface of crop residue or leaves, some of the resulting ammonia will be lost as a gas to the atmosphere. The potential for loss is greatest when the following conditions exist:

- Temperatures are greater than 55 °F. Loss is less likely with winter or early spring applications, but results show that the loss may be substantial if the materials remain on the surface of the soil for several days.
- Urea is left on the soil surface and not incorporated.
- Considerable crop residue remains on the soil surface.
- Application rates are greater than 100 pounds N/acre.
- The soil surface is moist but rapidly drying (under high temperatures).
- Soils have a low cation-exchange capacity.
- Soils are neutral or alkaline in reaction.

In the past, the manufacture of urea generated considerable amounts of biuret, a byproduct of urea formation that is toxic to plants. Modern manufacturing processes have reduced considerably the amount of biuret produced, and the concern about toxicity from it has subsided.

Ammonium sulfate ($[NH_4]_2SO_4$). This source is 21% N (21-0-0-24[S]) and supplies all N in the NH_4^+ form. This theoretically gives it a slight advantage over products that supply a portion of their N in the NO_3^- form, because the NH_4^+ form is not susceptible to leaching or denitrification. However, this advantage is usually short-lived because all NH_4^+-based materials quickly convert to NO_3^- once soil temperatures are favorable for activity of soil organisms (above 50 °F).

In contrast to urea, there is little risk of loss of the NH_4^+ contained in $(NH_4)_2SO_4$ through volatilization. As a result, it is an excellent material for surface application on no-till fields with a lot of crop residue on the soil surface. As with any other NH_4^+-based material, there is a risk associated with surface application in years when there is inadequate precipitation to allow for adequate root activity in the fertilizer zone. This can result in what is known as "positional unavailability," in which adequate N may be present but roots cannot reach it, usually due to dry soils that restrict roots and keep N from moving down to the roots.

Ammonium sulfate is an excellent material for use on soils that may be deficient in both N and sulfur. However, applying it at a rate sufficient to meet the N need will cause overapplication of S. That is not of great concern because sulfur is mobile and moves out of the profile quickly. Fortunately, there is no known environmental threat associated with sulfate sulfur in water supplies.

Most $(NH_4)_2SO_4$ available is a byproduct of the steel, textile, and lysine industries and is marketed as either a dry granulated material, a slurry, or a solution.

Ammonium sulfate is more acidifying—that is, causes greater drops in pH—than any other N source. In general, 5 pounds of lime are needed to neutralize 1 pound of N from ammonium sulfate, compared to 2 pounds of lime per pound of N from ammonia or urea. The extra acidity is of little concern as long as the soil is monitored for pH every 4 years and pH is corrected with lime as needed.

In areas where fall application is acceptable, $(NH_4)_2SO_4$ could be applied in late fall (after temperatures have fallen below 50 °F) or in winter on frozen ground where the slope is less than 5%.

Nitrogen solutions. The most common nitrogen solutions are NH_4NO_3 solutions that also contain urea. Urea-containing solutions (commonly called "UAN" for urea-ammonium nitrate) have 28% to 32% N. These materials have 50% urea, 25% ammonium, and 25% nitrate. The weight of solution per gallon is 10.70 and 11.05 pounds for the 28% and 32% solutions, respectively, meaning that one gallon of 28% has 3 pounds N and one gallon of 32% has 3.5 pounds N. Another common source is NH_4NO_3 solutions containing ammonia, which can have up to 41% N. The constituents of all these compounds will undergo the same reactions as described for the constituents applied alone. Urea-containing solutions can be dribbled or sprayed on the soil surface or injected to prevent urea volatilization. Ammonia-containing solutions, including aqua ammonia (ammonia dissolved in water, with an analysis of 21-0-0), have slight vapor pressure and must be injected 1 to 2 inches deep to prevent ammonia volatilization.

Ammoniated phosphate. Mono-ammonium phosphate (MAP; typically 11% N, for example, 11-51-0) and di-ammonium phosphate (DAP; 18% N, 18-46-0) are used mostly as phosphorus fertilizers (See Chapter 8, page 106, "MAP vs. DAP"). These sources have an acidifying potential similar to $(NH_4)_2SO_4$. Under warm soil conditions, the NH_4^+ from both products transforms quickly to NO_3^- and is subject to leaching or denitrification. Other less common sources available are liquid and dry ammonium polyphosphate (10% and 15% N, respectively). Like MAP and DAP, these are primarily considered P sources, not N sources.

Organic-N fertilizers. Manure, poultry litter, and other organic-N fertilizers can supply not only N but also phosphorus, potassium, and other nutrients. These products are excellent nutrient sources, and they often supply nutrients at lower cost than inorganic fertilizers. They should be incorporated to avoid N loss by volatilization or runoff. Most of the N is in uric acid and NH_4^+ forms that can rapidly transform to NO_3^-. Applications should be done as far as possible from environmentally sensitive areas, such as on steep slopes and near bodies of water.

Before application, these fertilizers should be analyzed for nutrient content. Many of these sources, if applied at rates needed to meet the N needs of the crop, will result in an overapplication of phosphorus, which can lead to environmental problems. For this reason, application should be based on meeting phosphorus requirements rather than the N requirements of the crop, with additional N applied using inorganic fertilizers. The soil phosphorus level and nutrient contents of these organic-N fertilizer sources must be known in order to determine the appropriate application rate.

Nitrogen Fertilizer Amendments

The critical need to supply adequate but not excessive N to crops, along with high N fertilizer prices, has resulted in the development of various products designed to make the use of N fertilizers more efficient. Most such products are designed to affect biological reactions in order to prevent changes in N form that can lead to N loss. For example, we described how microbial activity can affect N transformations and loss, and some of these amendments are designed to decrease microbial growth and activity.

Nitrification inhibitors. As **Figure 9.7** shows, once NH_4^+ is nitrified to nitrate (NO_3^-), N is susceptible to loss by denitrification or leaching. Nitrification inhibitors such as dicyandiamide (DCD) or nitrapyrin (known by its trade name N-Serve) can retard this conversion, reducing loss potential. When properly applied, inhibitors can significantly affect crop yields. In one experiment, 42% of the applied ammonia remained in the NH_4^+ form through the early part of the growing season when the inhibitor was used, in contrast with only 4% when the inhibitor was not used. However, the benefit from using an inhibitor varies with soil condition, time of year, type of soil, geographic location, rate of N application, and prevailing weather conditions between N application and crop uptake. Yield increases of 10 to 30 bushels per acre are possible by using an inhibitor in years with excessive rainfall, but there is often no advantage when soil conditions are not conducive to leaching or denitrification.

Nitrification inhibitors are most often used with fall applications to help protect against N loss. In general, poorly or imperfectly drained soils that easily become water saturated and coarse-textured (sandy) soils with high potential for leaching probably benefit the most from nitrification inhibitors. Moderately well-drained soils that undergo frequent periods of 3 or more days of flooding in the spring also benefit. Although they are not commonly done, when springs are very wet and on nearly all types of soil from which N losses frequently occur, especially on sandy and poorly drained soils, spring preplant applications may benefit from the use of an inhibitor. Application of inhibitors is generally not recommended for sidedress applications. Soils typically do not stay saturated with water very long during the growing season after sidedress application, and only a few weeks elapse between sidedressing and rapid plant uptake, so there is little benefit to preventing conversion to nitrate. The longer the period between N application and absorption by the crop, the greater the probability that nitrification inhibitors will contribute to higher yields. However, the length of time that fall-applied inhibitors remain effective in the soil also depends partly on soil temperature. On a Drummer silty clay loam soil, an inhibitor application when soil temperature is 55 °F can keep close to 50% of the applied ammonia in NH_4^+ form for about 5 months. When soil temperature is 70 °F, the soil may retain the same amount for only 2 months.

Time of application and geographic location must be considered along with soil type when determining whether to use a nitrification inhibitor. Using inhibitors can significantly improve the efficiency of fall-applied N on the loam, silt loam, and silty clay loam soils of central and northern Illinois in years when the soil is very wet in the spring. At the same time, inhibitors do not adequately reduce the rate of nitrification in the low-organic-matter soils of southern Illinois when N is applied in the fall for the following year's corn. The lower organic matter content and the warmer temperatures of southern Illinois soils, both in late fall and early spring, cause the inhibitor to degrade too rapidly. Furthermore, applying an inhibitor on sandy soils in the fall does not adequately reduce N loss because the potential for leaching is too high. Fall applications of N with inhibitors thus are not recommended for sandy soils or for soils low in organic-matter content, especially south of Illinois Route 16.

Nitrification inhibitors should be viewed as management tools to reduce N loss. Nitrification inhibitors are most likely to increase yields when N is applied at or below the optimal rate. When N is applied at a rate greater than that required for optimal yields, benefits from an inhibitor are unlikely, even when moisture in the soil is excessive. Finally, it is not safe to assume that the use of a nitrification inhibitor will make it possible to reduce N rates below the MRTN rate, because those rates were developed from fields where no significant amount of N was lost.

Urease inhibitors. The chemical compound N-(n-butyl) thiophosphoric triamide, commonly referred to as NBPT and sold under the trade name AgrotaiN, has been shown to inhibit the urease enzyme that converts urea to ammonia. This material can be added to UAN solutions or to urea and will reduce the potential for volatilization of such products when they are surface-applied. Experimental results collected around the Corn Belt over the last several years have shown an average increase of 4.3 bushels per acre when applied with urea and 1.6 bushels per acre when applied with UAN solutions. Where nonvolatile N treatments resulted in a higher yield than urea without the amendment, thus indicating high loss potential for urea, addition of the urease inhibitor increased yield by 6.6 bushels per acre for urea and by 2.7 bushels per acre for UAN solutions. In a year characterized by a long dry period in the spring, NBPT with urea resulted in yield increases as high as 20 bushels per acre compared to urea alone. These results clearly showed the importance of proper urea management techniques in years when it stays dry after surface application of urea.

Urease inhibitors have the greatest potential for benefit when urea-containing materials are surface-applied without incorporation at 50 °F or higher. Since the amount of urease is substantially greater in crop residue than in the soil, the potential benefit of the inhibitor is even greater if there is a large amount of residue remaining on the soil surface. In situations where the urea-containing materials can be incorporated within 2 days after application, either with tillage or with adequate rainfall (at least 1/2 in.), the potential for benefit from a urease inhibitor is very low.

Coatings and ureaform. Urea is available in the form of products designed to provide physical or chemical protection against volatilization loss that can follow transformation to NH_4^+ soon after application. Physical barriers can include polymer coatings and sulfur coatings. Chemical barriers can include the use of formaldehyde or other materials that inhibit the chemical breakdown of urea. The rate of N release from such products is dictated mostly by temperature and soil-water conditions. These products can be beneficial in years where substantial rainfall early in the spring may cause significant leaching or denitrification. On the other hand, if the season is dry, N may not be released in time to supply the crop's needs.

Time of Nitrogen Application

Fall applications. Because of concerns over environmental degradation and reductions in economic return on N brought on by higher fertilizer prices, fall applications should be done only in soils and regions with low N-loss potential. Fall N applications should not be done in soils that are sandy, organic, or very poorly drained or that have excessive drainage, or where soils rarely freeze or temperatures decline very slowly from 50 °F to freezing. Nitrogen, other than that included incidentally with the phosphorus application, should not be fall-applied for corn on any soil south of a line that approximates Illinois Route 16, or the terminal moraine of the last glacier. Soil maps may be used to determine where within this boundary area fall N can be safely applied. Most of the incidental N in phosphorus fertilizers should not be expected to be available the next spring. However, the amount of N in a typical P application is small, and so its loss would rarely translate into a significant yield loss. When applied properly, fall N on wheat is acceptable (see the discussion on page 129 on wheat, oats, and barley).

Fall N applications are often preferred because they are more economical to farmers and the fertilizer industry. Fall applications often lower the cost of fertilization by reducing transportation and storage expenses and by requiring less storage and application equipment. They also provide logistical advantages, such as saving time in the spring to allow for early planting, better distribution of labor and equipment, and generally better soil conditions in the fall to protect soils from compaction during fertilizer application.

In places where fall application is environmentally acceptable, farmers should apply N in forms that do not contain nitrate. The preferred source for fall application is anhydrous ammonia, because it nitrifies more slowly than other forms. Manure and poultry litter can also be applied in the fall as long as they are incorporated in the soil and the guidelines are followed on soil temperature and soil conditions as described for fall application of inorganic N fertilizers. Urea-containing fertilizers, even when incorporated, are not as effective as fall-applied anhydrous ammonia or spring-applied urea.

Fall N applications should be done when daily maximum bare soil temperature at 4 inches is below 50 °F. On average, this temperature is reached after the first day of November in northern and central Illinois. However, this average date is not a satisfactory guide because of the great variability present from year to year. Current soil temperatures for different regions of Illinois are available at www.isws.illinois.edu/warm/soiltemp.asp. While these temperatures may be useful in most cases, soil temperature can vary due to many factors, including soil color, drainage, and amount of crop residue on the surface. For this reason the best method to determine soil temperature is direct measurement in the field to be fertilized. It is important to note that while the rate of nitrification is significantly reduced below the recommended 50 °F soil temperature, microbial activity continues until temperatures are below 32 °F. The 50 °F temperature for fall application is a realistic guideline for farmers. Applying N earlier risks too much loss (**Figure 9.9**). Waiting until later risks wet or frozen fields, which would prevent application and fall tillage.

In Illinois, most of the N applied in late fall or very early spring is converted to NO_3^- by corn-planting time because of nitrification during the long periods when soil temperatures are between freezing and the mid-40s. In consideration of the date at which NO_3^- is formed and the conditions that prevail thereafter, the difference in susceptibility to denitrification and leaching loss between late fall and early spring applications of NH_4^+ sources is probably small. Both are, however, more susceptible to loss than is N applied at planting time or as a sidedress application.

Large amounts of residue generated from corn or other crops can create challenges for planting and field operations in the spring. There is also concern that the high ratio of carbon to nitrogen in the residue means a high potential for tying up N and making it unavailable for the following crop when it needs it. A common question has been whether application of N, such as UAN, on the residue would help with the breakdown of corn stalks. Research has shown no benefit in fall application of N to increase microbial decomposition of corn residue or to improve N availability for the next crop. Typically, low temperature or dry residue, and not N availability, is the main limiting factor for microbial decomposition of residue in the fall.

Winter applications. Based on observations, the risk of N loss through volatilization associated with winter application of urea for corn on frozen soils is too great to consider the practice unless one is assured of at least half an inch of precipitation occurring within 4 to 5 days after application. Yield losses as high as 30 to 40 bushels per acre have been observed when urea is surface-applied on frozen soils during the winter months. On the other hand, in most years, application of urea on frozen soils has been an effective practice for wheat production. This difference is likely due to better protection under the wheat canopy and to the fact that wheat takes up its N earlier than corn. If manure applications cannot be accomplished in the late fall, wait until the spring to do the application. Surface application of manure on frozen soils not only can result in substantial N loss, it could be an environmental hazard.

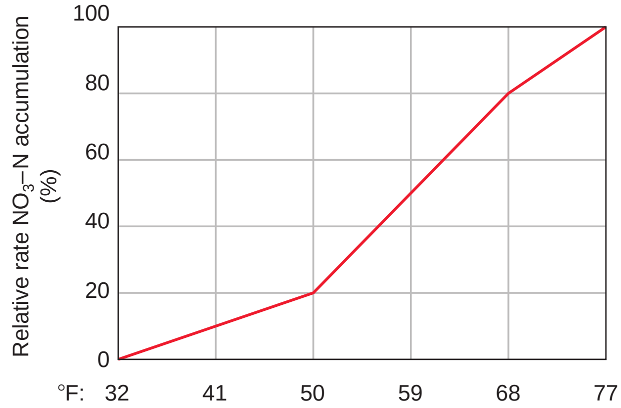

Figure 9.9. Influence of soil temperature on the relative rate of NO_3 accumulation in soils.

Spring (preplant) applications. Relative to fall applications, applying N in the spring reduces the time for N to be nitrified (and potentially lost) before crop uptake. Since this application is done before planting, it normally prevents damage to plants and eases the incorporation of urea fertilizers. Spring applications also have some drawbacks. Soils in the spring tend to be wet, and additional wheel traffic to apply N can result in soil compaction. Planting the crop in a timely fashion is important to maximizing yield potential. Since planting date is so important, it is advisable not to delay planting to apply N. It is better to plant on time and apply N later. If anhydrous ammonia is used after planting, it needs to be kept away from the seed rows to prevent seedling injury.

Sidedress applications. Sidedressing can help minimize N losses because N is applied close to the time of crop uptake. This application time can further increase N efficiency by allowing farmers to determine whether a full rate is needed or whether the rate can be reduced due to lower expected yields caused by poor growing season conditions and/or lower-than-expected corn stands. In some cases there might even be a decision to replace corn with a different crop, in which case N application might be avoided. Finally, this application time allows flexibility in the choice of N source.

While anhydrous ammonia and N solutions are preferred for sidedress applications, any common N fertilizer source can be used if proper care is taken. Potential drawbacks of sidedressing include not being able to apply N on time due to prolonged wet periods, root damage resulting from subsurface applications done after roots have grown out into row middles, the need for sufficient rain to move surface-applied N into the root zone, and the need for high-clearance equipment if the application is delayed until the crop is too tall.

Many fields in east-central Illinois, and to a lesser extent in other areas, have low spots where surface water may collect at some time during the spring or early summer. The flat, claypan soils of south-central Illinois may also be saturated, though not flooded, during that time. Sidedressing would avoid the risk of spring loss through denitrification on these soils but would not affect midseason loss. Unfortunately, these are the soils on which sidedressing is difficult in wet years.

Sidedressing can be done any time between planting and tasseling. No corn yield reduction should be expected due to delayed N application, if application can be done before the 5th-leaf stage, or if there is enough N in the soil from starter or broadcast fertilizer to keep plants from becoming deficient before application can be done. Most soils in Illinois can provide sufficient N to satisfy the demands of young corn plants. Beginning at about V7 or V8 (8 leaf collars visible), N uptake is rapid until after pollination. So if supplemental N cannot be applied before the 5th-leaf stage, it is critical to apply it as soon as possible, especially if plants start to show deficiency symptoms. Application up to the time of tasseling will increase yields in most cases, unless the soils dry out and applied N does not reach the roots. While it is possible to increase yield by applying N after tasselling, this has only been observed in severely N-deficient fields when N was applied within two weeks after tasseling and when sufficient precipitation moved the applied N to the root zone. We would not expect such fields to yield as much as those with N applied early enough to prevent deficiency.

Methods of Nitrogen Application

Subsurface applications. Nitrogen materials that contain free ammonia (NH_3), such as anhydrous ammonia and low-pressure solutions, must be injected into the soil to avoid loss of ammonia in gaseous form. When released into the soil, ammonia quickly reacts with water to form NH_4^+. In this positively charged form, the ion is not susceptible to leaching or gaseous loss because it is temporarily attached to the negative charges on clay and organic matter. Some of the ammonia reacts with organic matter to become a part of the soil humus.

On silt loams or finer-textured soils, ammonia moves about 4 inches from the point of injection. On more coarsely textured soils, such as sandy loams, ammonia may move 5 to 6 inches from the point of injection. If the depth of application is shallower than the distance of movement, some ammonia may move to the soil surface and escape as a gas over several days' time. On coarse-textured (sandy) soils, anhydrous ammonia should be placed 8 to 10 inches deep, whereas on silt loam soils, the depth of application should be 6 to 8 inches. Except for sands or soils with very coarse texture, the soil can hold large amounts of ammonia, so there should not be concern about the capacity of the soil to hold ammonia when agronomic rates are applied at the appropriate soil depths.

Because anhydrous ammonia moves out into the soil until it is all dissolved in soil water, it is lost more easily from shallow placement than is ammonia in a low-pressure solution, which is already dissolved when applied. Nevertheless, low-pressure solutions contain some free ammonia and thus need to be placed into the soil at a depth of 2 to 4 inches. Some ammonia will escape to the atmosphere whenever there is a direct opening from the point of injection to the soil surface, so it is important to apply into soil conditions that allow good closure of the applicator knife track. It is common to see white puffs during application (water droplets, formed as ammonia lowers the temperature of the air surrounding the applicator knife) and to smell ammonia after application. The human nose is extremely sensitive to ammonia; a faint smell indicates too little loss to be of concern. If the soils dry out after application and the smell continues or grows stronger, then N loss is occurring.

Combining shallow tillage (field cultivation, disking, etc.) with ammonia application is possible in fine-textured soils as long as the soil has adequate moisture and ammonia is applied behind the tillage operation at least 4 inches below the soil surface. If deeper tillage is needed after the application, it is important to wait at least 5 to 8 days to allow sufficient time for the ammonia to react with soil water and form NH_4^+. This reaction is typically very fast, but its speed depends on soil conditions. The best and easiest way to test whether it is safe to till is by seeing if there is an ammonia smell immediately after tillage. If there is, then the transformation to NH_4^+ is not completed and tillage should be delayed. Free ammonia is harmful to living tissues, and application of fertilizers containing or forming free ammonia should be separated from seeds and seedlings by time or space. Most problems of plant injury occur when soils are wet at the time of application, the application slot does not close properly, and the ammonia moves only a very short distance from the release point and is thus at high concentration in the soil. If the soil dries quickly and cracks along the knife track, ammonia can move up to damage seeds or seedlings. This can also happen when applications are done in dry soils, thus allowing ammonia to move to the surface before it reacts with water, or when shallow applications allow ammonia to reach the surface soil.

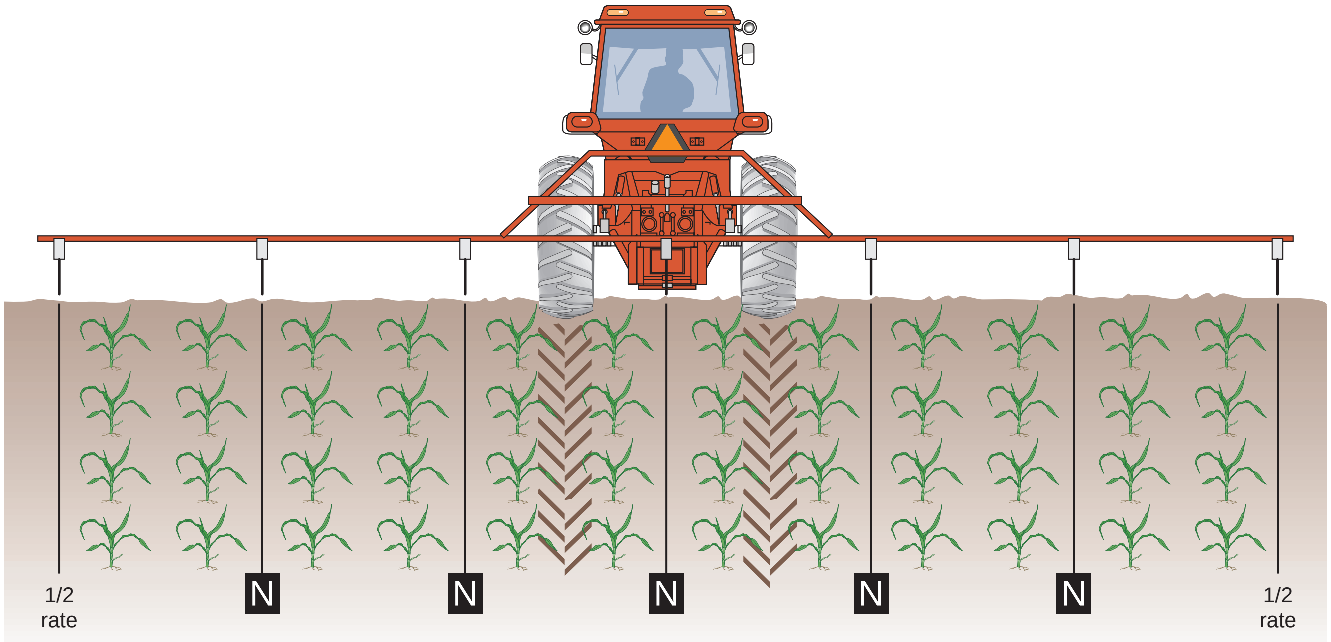

Figure 9.10. Schematic of every-other-row sidedress nitrogen injection. The outside two injectors are set at half-rate because the injector runs between those two rows twice.

If planting is done about a week after application or when there is some rainfall after application, most ammonia should have been converted to NH_4^+ and plant damage would not be expected. But in extreme cases, there has been damage even after fall-applied ammonia. This has happened when application was in late fall on wet soils where serious compaction occurred along the side walls of the knife track, followed by dry winter and spring weather. When the surface soils dried in the spring, the soil cracked along the knife track and allowed the ammonia to escape into the seed zone.

Research has shown that a relatively small portion of corn root system can take up all the nutrients the crop needs, including N. Because every-other-row injection supplies N on one side of each row (**Figure 9.10**), N injected between every other row results in yields similar to those from injection between all rows, irrespective of tillage system, soil type, or nitrogen rate. Use of wider injection spacing at sidedressing allows for reduced power requirement for a given applicator width or use of a wider applicator with the same power requirement. From a practical standpoint, the lower power requirement frequently means a smaller tractor and smaller tire, making it easier to maneuver between rows and causing less compaction next to the row.

With this system, positions can be adjusted to avoid placing an injector in the wheel track, where N losses can be greatest. Since roots will reach the center of the row before rapid N uptake starts and applying N close to the row can damage roots, take care to keep injection midway between the rows. If it is necessary to match application to the planter width with the usual even number of rows, the outside two injectors must be adjusted to half-rate application, as the injector will go between those rows twice if one avoids having knives in the wheel track. This can be done by splitting the output of one port in the manifold with a T and connecting hoses to the two outer knives. To avoid problems of back-pressure that might be created when applying at relatively high speeds, use a double-tube knife, with two hoses in each knife; the outside knives would require only one hose to give the half-rate application.

The use of autosteer to plant and to apply sidedress ammonia in alternate rows will increase application efficiency by allowing all knives to apply the full rate rather than using half-rates on the outside knives. This means applying without regard to planter pass, and it will work only if planting was done with good accuracy, both in terms of driving straight and of maintaining uniform guess row width.

Although urea–ammonium nitrate (UAN) solutions do not have free ammonia and can be applied on the soil surface, many studies have shown that injecting UAN below the surface to avoid contact with crop residue is a technique superior to broadcast and surface-dribble applications. If UAN is applied as sidedress, it is recommended that it be applied 4 inches from the soil surface (especially in dry years) to ensure that the roots of corn will reach this N.

Urea is commonly broadcast on the soil surface and then incorporated with tillage. In recent years there has been some interest in subsurface banding of urea. Our data show that subsurface banding is at least as effective as broadcast and incorporated placement. When doing subsurface banding it is important to avoid applying urea under the corn row, as this can result in substantial lower yield. This is likely the result of urea hydrolysis, which produces ammonia and inhibits root growth in the fertilizer band.

Corn responds very well to starter fertilizers under most conditions. The response is often greatest in soils with low fertility or when cool and wet early-season conditions slow crop growth. Although N typically provides the greatest benefit, starter fertilizers are often a mixture of several nutrients. For more information on starter fertilizers, see Chapter 8, p. 108, under "Starter or Row Fertilization."

Surface applications. Because of the high level of urease activity in crop residue in no-till fields, surface application of UAN solutions can result in significantly lower no-till corn yield than surface application of NH_4NO_3 or injection of UAN or anhydrous ammonia. Addition of a urease inhibitor can increase yield compared to broadcast urea, but yields are likely not going to be as high as those obtained with injected UAN or ammonia.

Dribble application of UAN solutions in concentrated bands on 30-inch spacings on the soil surface is also more efficient in reducing the potential for N loss compared with an unincorporated broadcast application. Such dribble applications are not superior to an injected or incorporated application of UAN solution, and they can result in some loss of N and unavailability of N to the roots if the weather stays dry after application.

If weather conditions do not allow sidedress with regular field equipment, it is possible to do a delayed application up to tasselling by using high-clearance sprayers with drop nozzles. If this method is used, it is important to keep the fertilizer off the plants—especially the green, active leaves above the third or fourth leaf below the ear leaf—in order to avoid leaf burning that can reduce yield. Many drop nozzles release only a few feet below the boom; an extra length of tubing to lower the release point should help minimize leaf burning.

In fields that have not received N applications or where there is insufficient N supply, aerial application of dry N fertilizers can increase yield. This practice should not be considered a replacement for normal N application, but rather an emergency treatment in situations where corn is too tall for normal application equipment. To avoid severe leaf burning, do not apply more than 125 pounds N per acre of urea or NH_4NO_3. Urea is often used for foliar applications because it produces low salt damage compared to other sources. Aerially applying N solutions on growing corn is not recommended, as extensive leaf damage likely results if the rate is greater than 10 pounds N per acre.

Nitrogen Rates for Crops Other Than Corn

Soybean

Soybean and other legume crops can access much of their N needs through a symbiotic relationship with bacteria that have the ability to transform N_2 from the air into forms that these plants can use. Legume crops also remove significant amounts of N from the soil if soils have plant-available forms, and N fixation requires the plant to expend energy. Research, however, has not shown consistent yield increases from N fertilization, including foliar fertilization, when legume crops are well nodulated. In fact, applying N fertilizer to legumes reduces nodulation and activity of existing nodules and thus reduces N fixation. This makes little economic sense, since N fixation provides N at relatively no cost. So rather than apply N fertilizer to legume crops, ensure proper nodulation by inoculating seed with the appropriate bacteria if the crop has not been grown in the field for 5 years or more. Also, maintain soil pH at optimum levels for crop production. If desired pH levels cannot be maintained, be certain that molybdenum availability is adequate.

On average, corn removes 0.8 pounds N per bushel of grain and soybean removes approximately 3 pounds N per bushel (amount can vary depending on protein content). Based on a corn yield of 180 bushels per acre and a soybean yield of 50 bushels per acre, the total N removed per acre by soybean (150 pounds) is greater than that removed by corn (144 pounds). When properly nodulated, symbiotic fixation of N accounts for 63% of the N removed in harvested soybean grain. Thus, the net N removed from the soil by soybean (56 lb/A) is less than that removed by corn (144 lb/A). Even though there is a large net N removal from soil by soybean, research at the University of Illinois has generally indicated no soybean yield increase from either residual N in the soil or N fertilizer applied for the soybean crop.

A four-location study showed no soybean yield increase from residual N in the soil even when rates as high as 320 pounds of N per acre were applied to the previous corn crop. Similarly, studies where N was applied to the soybean crop have not shown consistent yield increase. In some trials a tendency for higher yields has been observed, but the yield increase was not enough to pay for the additional N.

Studies in Illinois and elsewhere have shown very consistently that starter fertilizers do not enhance soybean yields compared to a broadcast application. Very few reports, all from other states, have shown benefit from the use of N in

Table 9.2. Recommended spring nitrogen application rates for wheat.

Soil situation	Organic matter	Amt of N that 1 bushel of wheat will "buy"			
		Very high (>13 lb)	High (9–13 lb)	Medium (5–9 lb)	Low (<5 lb)
		lb N/A			
Low in capacity to supply nitrogen: inherently low in organic matter (forested soils)	<2%	150	120–150	90–120	60–90
Medium in capacity to supply nitrogen: moderately dark-colored soils	2–4%	100–120	80–100	60–80	40–60
High in capacity to supply nitrogen: deep, dark-colored soils	>4%	70–90	50–70	30–50	30

Rates assume no more than 30 lb of fall-applied N and spring application at greenup.

a starter for soybean. In all cases, the advantage occurred when low temperatures slowed normal nodulation and N fixation early in the season. Because soybean is sensitive to salt, fertilizers should not be applied with the seed. Studies have shown as much as 50% stand loss when as little as 3 pounds of N per acre was applied with the seed.

Wheat, Oats, and Barley

The rate of nitrogen to apply on wheat, oats, and barley depends on soil type, crop and variety to be grown, future cropping intentions, and, in the case of wheat, time of spring application. Light-colored soils (low in organic matter) require the highest rate of nitrogen application because they have a low capacity to supply nitrogen. Deep, dark-colored soils require lower rates of nitrogen application for maximum yields. Estimates of organic-matter content for soils of Illinois may be obtained from soil surveys or from soil tests that include organic matter.

The amount of N needed for good fall growth of wheat is modest, since the total uptake in roots and tops before cold weather is not likely to exceed 30 to 40 pounds per acre. Twenty to 30 pounds of N in the fall is recommended; it can be supplied in the form of di-ammonium phosphate (DAP), which should also supply the maintenance levels of phosphorus needed.

Recent studies with wheat nitrogen management allow the incorporation of economics into the nitrogen rate decision process, similar to the approach taken for corn. The cost of fertilizer N and the expected wheat grain price are incorporated into the spring wheat nitrogen recommendations in **Table 9.2**. One needs only to calculate the amount of N equivalent in value to one bushel of wheat. For example, a bushel of wheat at $6 per bushel would "buy" 10 pounds of N if N costs 60 cents per pound. Use the column in the table that corresponds to this value, and determine the suggested N rate based on estimated soil organic matter.

Spring nitrogen recommendations in **Table 9.2** are based on applying no more than 30 pounds of N in the fall and on making the spring application at early green-up (Feekes growth stage 3 or 4). On soils low in organic matter in southern Illinois, research has shown that N rates can be decreased by 10% when one of the following applies: spring application is delayed to late tillering (Feekes growth stage 5.0-6.0); spring N applications are split, with one at early green-up and one at late tillering or early jointing; or a nitrification inhibitor or a slow- or controlled-release nitrogen source is used. On soils with higher organic matter, spring application timing has had little impact. Research has also shown that a spring-split N application, with one-third early and two-thirds at late tillering to jointing, can increase yields by about 10% compared to a single spring application at green-up, especially when conditions favor N loss. Delaying all of the N application to late tillering or early jointing usually produces the same yield as splitting N applications in the spring.

Nearly all modern varieties of wheat have been selected for improved standability, so concern about lodging under high N rates has decreased considerably. But it is still recommended that no more than 150 pounds of spring N be applied to wheat grown on soils with low organic matter soils and no more than 90 pounds to wheat grown on soils with high organic matter. Varieties of oats, though substantially improved with regard to standability, will still lodge occasionally, and N should be used carefully. Barley varieties, especially spring barley, are prone to lodging, so rates of nitrogen application shown in **Table 9.3** should not be exceeded.

Nitrogen recommendations are based on equipment delivering a uniform application of nitrogen across the spread path. If there is not uniform application, significant lodging can occur at the higher rates of N application, along with significant yield losses.

For wheat grown after corn in rotation, there can be a significant amount of residual soil N following the corn crop, depending on rate of N application, corn yield, and the amount of rainfall during the summer. The breakdown of corn residue may tie up some of this N, but depending on whether the residue is tilled into the soil and on the amount of soil moisture in the fall, this might take place mostly in the spring after soils warm up, which is often after wheat has taken up most of its N. Though it is not often done, it is possible to test soils for nitrate after corn harvest and to use this to adjust N rates for wheat, especially if the weather has been dry enough to reduce corn yields substantially. If little residual N is available for wheat seeding after corn, then using 25 to 30 pounds per acre of fall N is important to provide enough N for fall growth. If significant amounts of carryover N are found or suspected, it might be helpful to test residual N just prior to spring N application, with rates adjusted accordingly.

Some wheat and oats in Illinois serve as companion crops for legume or legume–grass seedings. On those fields, it is best to apply N fertilizer at rates 20% to 25% below the optimal rate to limit vegetative growth of the small grain and thus produce less competition for the young forage seedlings. Seeding rates for small grains should also be somewhat lower if they are used as companion seedings.

The introduction of nitrification inhibitors and slow- or controlled-release nitrogen (such as polymer-coated urea) combined with improved application equipment provides two additional options for applying nitrogen to wheat. In northern and central Illinois, research has shown that when the entire amount of nitrogen needed is applied in the fall with a nitrification inhibitor, the resulting yield is equivalent to that obtained when a small portion of the total need was applied in fall and the remainder in early spring. This has been much less successful in southern Illinois. Producers who are frequently delayed in applying nitrogen in the spring because of wet soils may wish to consider fall application (or early green-up applications in southern Illinois) with a nitrification inhibitor or a slow- or controlled-release nitrogen source. For fields that are not usually wet in the spring, either system of application will provide equivalent yield.

Most available forms of N fertilizer will work for spring application to the wheat crop, but care needs to be taken to minimize loss potential. Cool or cold soils at the time of application help slow the transformations that make N more susceptible to loss, but the weather can also turn warm quickly, and the potential for loss increases if that happens. Heavy rainfall on sloping soils, especially when they are still frozen, can cause runoff of N. Fertilizer materials containing urea (UAN, dry urea) can experience loss following breakdown by urease, though this is rare given the low soil temperatures typical at the time of application. Nitrate can leach at any time and can undergo denitrification if soils warm up and stay wet. Using UAN can also cause some damage to plants, though this is relatively rare on small plants when the weather is cool or when it rains soon after application. Uniformity of application can also be affected by the equipment used to apply different forms.

Table 9.3. Recommended total N application rates for oats and barley.

Soil situation	Organic matter	lb N/A
Low in capacity to supply nitrogen: inherently low in organic matter (forested soils)	<2%	80–90
Medium in capacity to supply nitrogen: moderately dark-colored soils	2–4%	60–80
High in capacity to supply nitrogen: deep, dark-colored soils	>4%	40–60

When oats and barley are used as a companion seeding for forage legume, rates can be reduced.

There is no risk-free way to apply N to wheat in the late winter and early spring, but be aware of potential for loss and try to apply in a way that minimizes loss.

Grass Hay

The species grown, period of use, and yield goal determine optimal N fertilization for grass hay (**Table 9.4**). The lower rate of application is recommended on fields where production is limited by inadequate stands or moisture.

Kentucky bluegrass is shallow-rooted and susceptible to drought. Consequently, the most efficient use of N by bluegrass is from an early-spring application, with September application a second choice. September fertilization stimulates both fall and early-spring growth.

Orchardgrass, smooth bromegrass, tall fescue, and reed canarygrass are more drought-tolerant than bluegrass and can use higher rates of N more effectively. Because more uniform production is obtained by splitting high rates of N, two or more applications are suggested.

If extra spring growth can be utilized, make the first N application in March in southern Illinois, early April in central Illinois, and mid-April in northern Illinois. If spring growth is adequate without extra N, the first application may be delayed until after the first harvest to distribute production more uniformly throughout the summer. Total production likely will be less, however, if N is applied after first harvest rather than in early spring. Usually the second application of N is made after the first harvest; to stimulate fall growth, however, this application may be deferred until August or early September.

Legume–grass mixtures should not receive N if legumes make up at least 30% of the mixture. Because the main objective is to maintain the legume, the emphasis should be on applying phosphorus and potassium rather than N. See **Table 8.6** in Chapter 8 for phosphorus and potassium maintenance required.

After the legume has declined to less than 30% of the mixture, the objective of fertilizing is to increase the yield

Table 9.4. Nitrogen fertilization of grass hay.

Species	Time of application of N (lb/A)			
	Early spring	After first harvest	After second harvest	Early Sept
Kentucky bluegrass	60–80			See text
Orchardgrass	75–125	75–125		
Smooth bromegrass	75–125	75–125		50*
Reed canary grass	75–125	75–125		50*
Tall fescue for winter use		100–125	100–125	50*

*Optional if extra fall growth is needed.

of grass. The suggested rate is about 50 pounds N per acre when legumes make up 20% to 30% of the mixture.

Pasture

The productivity of the grazing animals, the plant species present, and the management level and goals for the pasture must be evaluated to determine N fertilization for pasture. If legumes comprise 30% or more of the sward, do not apply N fertilizer because an adequate amount will be contributed through fixation. If the legume portion is less than 30%, grass will probably respond to N fertilizer. If applying 100 pounds N per acre, apply the first 50 pounds in early to mid-June when the spring flush of grass growth is over; apply the second 50 pounds in late July to early August. Because early-season growth is generally excessive, an early-spring application is not suggested unless the first harvest can be efficiently grazed or will be harvested as hay or silage. Nitrogen application early in the season can make grazing management of the spring flush more difficult.

Source of N is important for summer application. Use a dry N source such as NH_4NO_3, $(NH_4)_2SO_4$, or urea. Do not apply liquid UAN solutions to actively growing pasture.

Nitrogen Rate Adjustments

Once a rate of N has been determined, it is important to consider agronomic factors that influence N availability and N use by the crop to further adjust the planned rate. These factors include past cropping history and the use of manure (**Table 9.5**), as well as the date of planting.

Previous Crop

Corn following another crop typically yields better than corn following corn, although there is some evidence that the continuous corn "yield penalty" might be decreasing, in part because of improvement of hybrids, including the incorporation of traits that provide rootworm control. Still, most trials show somewhat higher yields when corn follows a legume, such as soybean or alfalfa. This may be due partly to the residual N provided by the legume.

Since the N rate calculator already accounts for the effect of soybean on corn, there is no need to adjust the rate when corn follows soybean. For corn following a good alfalfa stand, it is not unusual to have sufficient N available from the alfalfa crop to supply a large portion of the N needs of corn. Often, when the alfalfa stand is destroyed and manure is applied, it is possible to grow the following corn crop without additional N. To assess the amount of N available in the spring, use the preplant or pre-sidedress soil nitrate test described earlier.

The contribution of legumes to the N supply for a following wheat crop will be less than the contribution to corn because the release N from legume residue will not be as rapid in early spring, when N needs of small grain are greatest, as in late spring and early summer, when N needs of corn are greatest (**Table 9.5**).

Idled Acres and Carryover Nitrogen

Depending on the crop grown, the N credit from idled acres may be positive or negative. Plowing-under a good stand of a legume that had good growth will result in a contribution of 60 to 80 pounds N per acre. If either stand or growth of the legume was poor or if corn is no-tilled into a good legume stand, thus delaying availability to the corn crop, the legume N contribution could be reduced to 40 to 60 pounds N per acre. Because most of the net N gained from first-year legumes is in the herbage, fall grazing will reduce the contribution to 30 to 50 pounds N per acre.

In years where a full rate of N was applied but yields were lower than expected, it is possible to have unused N carried over to the following year. The amount of carryover N will depend on weather conditions. Under unusually wet conditions, denitrification and leaching can reduce the amount of carryover N. But if the weather remains dry through the fall and winter, it could be very useful to take a soil test in March or April and analyze it to determine how much nitrate might be already present.

Manure

Nutrient content of manure varies with source and method of handling (**Table 9.6**). The availability of the total N content also varies by method of application. When manure is incorporated during or immediately after application, about 50% of the total N in dry manure and 50% to 60% of the total N in liquid manure will be available for the crop that is grown during the year following manure application.

Table 9.5. Reductions in nitrogen rates resulting from agronomic factors.

Crop to be grown	After soybean	1st year after alfalfa or clover: 5 plants/sq ft	1st year after alfalfa or clover: 2–4 plants/sq ft	1st year after alfalfa or clover: <2 plants/sq ft	2nd year after alfalfa or clover: 5 plants/sq ft	2nd year after alfalfa or clover: <5 plants/sq ft	Manure
	Nitrogen reduction (lb/A)						
Corn	N/A	100	50	0	30	0	5*
Wheat	10	30	10	0	0	0	5*

*Nitrogen contribution in pounds per ton of manure. See Table 9.6 for adjustments for liquid manure.

Table 9.6. Average composition of manure.

Manure type	Nutrients: Nitrogen	P_2O_5	K_2O
Solid handling systems: no bedding; nutrients in lb/ton			
Dairy cattle	9	3	6
Beef cattle	11	7	10
Swine	11	8	5
Chicken	33	48	34
Liquid handling systems: nutrients in lb/1,000 gal			
Dairy cattle—liquid pit	31	15	9
Dairy cattle—lagoon	4	3	4
Beef cattle—liquid pit	29	18	26
Beef cattle—lagoon	4	3	4
Swine—liquid pit	36	25	22
Swine—lagoon	5	3	4
Poultry—liquid pit	60	45	30

Time of Planting

If planting is delayed, it may be possible to adjust sidedress N rates to reflect both lower corn yield potential and also the fact that late-planted corn takes up its N sooner after planting, so there is less chance of N loss. This needs to be done cautiously, since heavy rainfall and warm soils can create high N-loss conditions even after late planting. Late-planted corn that is planted into wet soil conditions can also struggle to take up N due to restricted roots, especially if it turns dry after planting. But if corn is planted a month or more after the optimum planting date—that is, after mid- to late May—and soils are warm and average rainfall is expected, it might be more profitable to reduce sidedress N rates by 20 to 40 pounds per acre. A pre-sidedress N soil test might help with this decision, especially if some N was applied before planting and if conditions have been favorable for mineralization before planting.

10

Soil Management and Tillage

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Soil is one of our most precious natural resources. Proper soil management is a key to sustainable agricultural production. Soil management involves six essential practices: proper amount and type of tillage, maintenance of soil organic matter, maintenance of a proper nutrient supply for plants, avoidance of soil contamination, maintenance of the correct soil acidity, and control of soil loss (erosion). In Illinois, the greatest concern for soil degradation is erosion caused by water. All of these practices depend on soil type, soil texture, and slope as well as on the crops that are grown.

The potential for erosion of a specific soil type largely depends on the severity of the slope, the crops grown, and the number and types of tillage operations. Several techniques are available to reduce soil erosion, including residue management, crop rotation, contour tillage, grass waterways, terraces, and conservation structures. The techniques adopted must ensure the long-term productivity of the land, be environmentally sound, and, of course, be profitable. Conservation tillage and crop residue management are recognized as cost-effective ways to reduce soil erosion and maintain productivity.

Conservation Compliance

A dramatic step taken to encourage the adoption of techniques to control soil erosion was the passage of the 1985 Food Security Act. Provisions of this act require farmers producing agricultural commodities on *highly erodible land* (HEL) to fully implement an approved conservation plan to remain eligible for certain farm program benefits. This program, known as "conservation compliance," was amended in subsequent versions of the Farm Bill. Conservation systems must meet specifications or guidelines of the *Natural Resources Conservation Service Field Office Technical Guide* and must be approved by the local conservation district. Most conservation compliance systems include use of mulch-till or no-till. The goal of conservation compliance is to reduce soil erosion to levels that will maintain the long-term productivity of the land. Even though conservation compliance pertains only to HEL fields, many farmers are adopting conservation tillage systems not only to reduce soil erosion but also to reduce labor and equipment costs.

Federal conservation provisions focus on reducing soil erosion, both to maintain soil productivity and to limit the amount of sediment that enters streams and rivers. Concerns about water quality are likely to continue to be an issue in legislation. Conservation practices such as conservation tillage, terraces, strip cropping, contour tillage, grass waterways, and filter strips all help reduce water runoff and soil erosion and thus help preserve water quality.

As indicated earlier, the tillage system selected to produce a crop has a significant effect on soil erosion, water quality, and profitability. Profitability, of course, is determined from crop yield (net income) and costs. But it is useful to include considerations of long-term effects on soil loss and productivity, not simply on yields in the short term. Selecting a tillage system is thus an important management decision. Before the factors are discussed in detail, several tillage systems will be defined.

Nationwide there has been a slight recent increase in the amount of no-till acreage that coincides with rapid adoption of glyphosate-tolerant soybeans (**Table 10.1**). In Illinois, the percentage of glyphosate-tolerant soybean has risen to more than 90% within 12 years of the introduction of this trait, and the percentage of no-till soybean now exceeds 50%. By comparison, no-till corn production accounts for less than 17% of Illinois corn acreage.

Conservation Tillage

The objective of conservation tillage is to provide a means of profitable crop production while minimizing soil erosion due to wind and/or water. The emphasis is on soil conservation, but conserving soil moisture, energy, labor, and even equipment provides additional benefits. To be considered conservation tillage, the system must provide conditions that resist erosion by wind, rain, and flowing water. Such resistance is achieved either by protecting the soil surface with crop residues or growing plants or by maintaining sufficient surface roughness or soil permeability to increase water filtration and thus reduce soil erosion.

Conservation tillage is often defined as any crop production system that provides either a residue cover of at least 30% after planting to reduce soil erosion due to water or at least 1,000 pounds per acre of flat, small-grain residues (or the equivalent) on the soil surface during the critical erosion period to reduce soil erosion due to wind.

The term *conservation tillage* represents a broad spectrum of tillage systems. However, maintaining an effective amount of plant residue on the soil surface is the crucial issue, which is why the Natural Resources Conservation Service (NRCS) has replaced conservation tillage with the term *crop residue management*. This term refers to a philosophy of year-round management of residue to maintain the level of cover needed for adequate control of erosion. Adequate erosion control often requires more than 30% residue cover after planting. Other conservation practices or structures may also be required. Some of the conservation tillage systems are described here.

Table 10.1. Trends in tillage types in the United States from 1992 through 2007.

	% of all planted U.S. acres			
Year	**No-till**	**Mulch-till**	**Reduced-till**	**Conventional tillage**
1992	9.9	20.2	25.9	42.7
1996	14.8	19.8	25.8	38.5
2000	17.5	18.0	26.2	42.7
2004	22.6	17.4	21.5	37.7
2007*	23.7	17.2	21.4	36.8

Percentages are of all planted acres. Data from the Conservation Tillage Information Center.

*Data from 2004 supplemented by additional sampling.

No-Till

With no-till, the soil is left undisturbed from harvest to seeding and from seeding to harvest. The only "tillage" is the soil disturbance in a narrow band created by a row cleaner, coulter, seed furrow opener, or other device attached to the planter or drill. Many no-till planters are now equipped with row cleaners to clear row areas of residue. No-till planters and drills must be able to cut residue and penetrate undisturbed soil. In practice, a tillage system that leaves more than 70% of the surface covered by crop residue is considered to be a no-till system.

Strip-Till

Strictly speaking, a no-till system allows no operations that disturb the soil other than planting or drilling. On some soils, including poorly drained ones, the no-till system is sometimes modified by the use of a strip tillage operation, typically in the fall, to aid soil drying and warming in the spring. This system is called strip-till. It is considered a category of no-till, as long as it leaves the necessary amount of surface residue after planting.

Strip-till is sometimes done along with the fall application of anhydrous ammonia, dry fertilizer, or both. This usually involves using a mole knife, which is designed to shatter and lift soil as it places fertilizer. A closing apparatus, usually disk blades run parallel to the row, pulls soil into the row. In some cases a rolling cage is used to firm the strip and break up clods. This process creates a small, elevated strip called a berm.

One benefit of strip-till, compared to no-till, is accelerated soil warming that results from removing residue and disturbing the soil in the berm. Planting takes place as close as possible to the center of the berm, which has usually "melted down" by spring to be little higher than the soil between the rows. The width of the strip-till implement is usually matched to the planter width, and the use of RTK-directed autosteer greatly assists the strip-till and planting processes. Maintenance of interrow residue helps to provide the benefits of a no-till system, while the uncovered soil near the seed row reduces the negative effects of cold, wet soils often found in no-till. The advantages of strip-till over no-till are thus most likely to be seen in cold, wet springs.

Disadvantages of strip-till include difficulty in getting the process completed in a wet fall, and washing out of the soil in the berm by heavy rainfall in the spring. Failure to complete strip-tilling in the fall raises the question of whether or not to strip-till in the spring. In many cases, soils are too wet to do effective soil shattering and tillage in the spring until near planting time. When this happens, the amount of soil warming in strips will be limited, and it may be better to use row cleaners to improve seed placement and to plant instead of forming strips first. Placement of fertilizer with the strip-till knife is generally safe for dry fertilizer, but ammonia needs to be placed quite deep beneath the row in order to prevent damage to the seedlings, and even then ammonia can move up if the soil dries after planting.

Ridge-Till

Ridge-till is also known as ridge-plant or till-plant. With ridge-till, the soil is left undisturbed from harvest to planting except for possible fertilizer application. Crops are planted and grown on ridges formed in the previous growing season. Typically, ridges are built and reformed annually during row cultivation. A planter equipped with sweeps, disk row cleaners, coulters, or horizontal disks is used in most ridge-till systems. These row-cleaning attachments remove 0.5 to 2 inches of soil, surface residue, and weed seeds from the row area. Ideally, this process leaves a residue-free strip of moist soil on top of the ridges into which the seed is planted. Special heavy-duty row cultivators are used to reform the ridges. Corn and grain sorghum stalks are sometimes shredded before planting. The use of ridge-till has decreased considerably in the past decade, and it is currently practiced on small acreage. Reasons for its decline include the inconvenience related to driving across ridges during harvest, the difficulty in forming and maintaining ridges, especially on slopes, and the requirements for specialized equipment and row cultivation during the season.

Mulch-Till

Mulch-till includes any conservation tillage system other than no-till and ridge-till. Deep tillage might be performed with a subsoiler or chisel plow; tillage before planting might include one or more passes with a disk harrow, field cultivator, or combination tool. Herbicides and row cultivation control weeds. The tillage tools must be equipped, adjusted, and operated to ensure that adequate residue cover remains for erosion control, and the number of operations must also be limited. At least 30% of the soil surface must be covered with plant residue after planting.

Conventional Tillage

Conventional tillage is the sequence of operations traditionally or most commonly used in a given geographic area to produce a given crop. The operations used vary considerably for different crops and in different regions. In the past, conventional tillage in Illinois included moldboard plowing, usually in the fall. Spring operations included one or more passes with a disk harrow or field cultivator before planting. More recently, conventional tillage has changed to include the use of a chisel plow instead of a moldboard plow, and newer combination tools are replacing chisel plows. These implements leave more residue than traditional moldboard plows, but often not enough to qualify as conservation tillage.

The soil surface following conventional tillage as practiced in the past was essentially free of plant residue. This was helpful with older planting equipment that had limited ability to plant into residue. It also buried weed seed and disease-bearing crop and weed residue, thereby helping to reduce problems with weeds and plant diseases before the advent of modern chemical control.

The term *clean tillage* is used for any system that leaves the soil surface more or less free of residue. A soil surface essentially free of residues can also be achieved with other implements, especially following a crop such as soybean that produces fragile, easy-to-cover residue. Removing all residue from the soil surface and disturbing the soil surface greatly increase the potential for soil erosion. The potential for water erosion is less in flat fields, but the potential for wind erosion is high. Improved planters, seed quality, and herbicides have largely eliminated the need to practice clean tillage.

Effects of Tillage on Soil Erosion

The primary advantages of conservation tillage systems, particularly no-till, are less soil erosion due to water on sloping soils and conservation of soil water for later crop use. Residue absorbs the impact of raindrops, thereby reducing the amount of soil dislodged. It also intercepts water as it moves down the slope, which allows soil particles to settle. Although wind erosion in Illinois is not as great a problem as water erosion, the residue left on the surface by conservation tillage systems slows the wind near the soil surface, thereby reducing the movement of soil particles into the air.

A bare, tillage-disturbed (or smooth) soil surface is extremely susceptible to erosion. Many Illinois soils have subsurface layers that are not favorable for root growth and development. Soil erosion slowly but continually removes the topsoil that is most favorable for root development, resulting in gradually decreasing soil productivity. Even on soils without root-restricting subsurface layers, erosion removes nutrients that must be replaced with additional fertilizers to maintain yields.

An additional problem related to soil erosion is sedimentation. Sediment and other materials (such as pesticides and nutrients) from eroding fields increase water pollution, reduce storage capacities of lakes and reservoirs, and decrease the effectiveness of surface drainage systems.

Surface residues effectively reduce soil erosion. A residue cover of 20% to 30% after planting reduces soil erosion by approximately 50% compared to a bare field. A residue cover of 70% after planting reduces soil erosion more than 90% compared to a bare field. On long, steep slopes, even conservation tillage may not adequately control soil erosion. Other practices may be required on such fields, such as contouring, grass waterways, terraces, or structures. For technical assistance in developing erosion control systems, consult your district conservationist or the NRCS.

Residue Cover

The percentage of the soil surface covered with residue after planting is affected by both the previous crop grown and the tillage system used. In general, the higher the crop yield, the more residue the crop produces. More important, however, is the type of residue a crop produces. Plant characteristics such as composition and sizes of leaves and stems, density of the residues, and relative quantities produced are all factors in the effectiveness of soil protection.

Often there is a desire to predict the amount of residue that will remain on the soil surface using a particular tillage system. This estimate is important for compliance with conservation measures. The prediction requires knowing the amount of residue cover remaining after each field operation included in the tillage system. Typical percentages of the residue cover remaining after various field operations are given in **Table 10.2**.

A corn crop that yields more than 120 bushels per acre will usually provide a residue cover of 95% after harvest. Grain sorghum, most small grains, and lower-yielding corn will generally provide a cover of 70% to 80%. In all cases, the residue must be uniformly spread behind the combine to most effectively prevent erosion. For a given tillage system, a rough approximation of the residue cover remaining after planting can be obtained by multiplying the initial percentage of residue cover by the values in **Table 10.2** for each operation. To leave

Table 10.2. Residue cover remaining on the soil surface after weathering or specific field operations.

	% of residue remaining	
	Nonfragile	**Fragile**
Climatic effects		
Overwinter weathering following summer harvest[a]	70–90	65–90
Overwinter weathering following fall harvest[a]	80–100[b]	75–100[b]
Field operations		
Moldboard plow	0–10	0–5
V ripper/subsoiler	60–80[b]	40–60[b]
Disk-subsoiler	30–50	10–20
Chisel plow with straight spike points	35–75[b]	30–60[b]
Chisel plow with twisted points or shovels	25–65[b]	10–30[b]
Coulter-chisel plow with straight spike points	35–70[b]	25–40[b]
Coulter-chisel plow with twisted points or shovels	25–60[b]	5–30[b]
Offset disk harrow—heavy plowing > 10-in. spacing	25–50	10–25
Tandem disk harrow		
Primary cutting > 9-in. spacing	30–60	20–40
Finishing 7- to 9-in. spacing	40–70	25–40
Light disking after harvest	70–80	40–50
Field cultivator as primary tillage operation		
Sweeps 12 to 20 in.	60–80	55–75
Sweeps or shovels 6 to 12 in.	35–75	50–70
Field cultivator as secondary tillage operation		
Sweeps 12 to 20 in.	80–90	60–75
Sweeps or shovels 6 to 12 in.	70–80	50–60
Combination finishing tool with disks, shanks, and leveling attachments	50–70	30–50
Combination finishing tool with spring teeth and rolling baskets	70–90	50–70
Anhydrous ammonia applicator	75–85	45–70
Conventional drill	80–100	60–80
No-till drill	55–80	40–80
Conventional planter	85–95	75–85
No-till planter with ripple coulters	75–90	70–85
No-till planter with fluted coulters	65–85	55–80
Ridge-till planter	40–60	20–40

From *Estimates of Residue Cover Remaining After Single Operation of Selected Tillage Machines,* developed jointly by the Soil Conservation Service, USDA, and Equipment Manufacturers Institute. First edition, February 1992.

[a]With long periods of snow cover and frozen conditions, weathering may reduce residue levels only slightly, while in warmer climates, weathering losses may reduce residue levels significantly.

[b]Value adjusted based on University of Nebraska research and field observations.

30% or more residue cover following corn, only one or two tillage operations can be performed. To leave 30% cover following soybeans essentially requires that a no-tillage system be used. Even strip-till or fall application of ammonia might reduce residue cover to less than 30% in soybean stubble.

Crop Production with Conservation Tillage

Crop response to various tillage systems is variable in both farmers' fields and experimental plots. The variability is often difficult to explain because so many factors that directly affect crops are influenced by tillage. Crop germination, emergence, and growth are largely regulated by soil temperature, aeration, and moisture content, by nutrient availability to roots, and by mechanical impedance to root growth. All of these factors are affected by tillage.

Soil Temperature

Crop residue on the soil surface insulates the soil from the sun's energy. In most of Illinois, soil temperatures in the spring are usually less than ideal for plant growth, and an insulating cover of residue both deflects warming sunlight and prevents warm air from warming the soil. Later in the season, soil temperatures are often warmer than ideal, and ways to cool the soil would be helpful.

Minimum daily temperatures of the soil surface usually occur between 6 a.m. and 8 a.m., and in spring they are often the same or slightly higher with residue cover than without. Maximum daily temperatures of the soil surface occur between 3 p.m. and 5 p.m., and with clean tillage they are 3 to 6 °F warmer than those with residue cover. During the summer, a complete crop canopy restricts the influence of crop residue on soil temperature, and soil surface temperatures are about the same with and without surface residue.

During May and early June, the reduced soil temperatures caused by a surface mulch influence early plant growth. In northern regions of the state, average daily soil temperatures are often close to the temperature required for corn growth, and the reduced temperatures caused by surface residues result in slow plant growth. In southern regions of the state, average daily temperatures are usually well above the temperature required for corn growth, and the reduced temperatures caused by surface residues have less effect on early corn growth.

The amount of residue influences soil temperature. Residues from corn, wheat, and grass sod maintain cooler soil than residue from soybeans and other crops that produce less residue or residue that decomposes rapidly.

Whether the lower soil temperature and subsequent slower early growth result in lower yields depends largely on weather conditions during the summer. Research shows that lower yields with reduced tillage systems occur most often on poorly drained soils and on most soils in northern Illinois in years not affected by drought. In these situations, soil temperature, corn growth, and yield potential often improve when residues are removed from the row area. However, on well-drained soils in southern Illinois, reduced soil temperature caused by in-row residues may increase crop growth and yield.

An example of daily fluctuation of soil temperature in the row (about 2 in. deep) from three different tillage systems is shown in **Figure 10.1**. Night temperatures are similar for all treatments, but soil that is tilled and mostly free of residue heats more quickly and to higher temperatures during the day. Strip-till closely resembles chisel-plowed (conventionally tilled) soil in the way it heats during the day.

Moisture

A soil surface reside cover of 30% or more decreases the amount of water evaporated from the soil surface and increases water infiltration rates, leading to more water stored in the soil. More stored water is usually advantageous in dry summer periods, but it may be disadvantageous at planting time and during early growth, especially on soils with poor internal drainage.

In most years in Illinois, the crop needs more water than rainfall supplies after the crop canopy closes. Soil moisture saved through reduced tillage systems may be important in years with below-normal rainfall. In the northern half of Illinois, excessive soil moisture in the spring months often reduces crop growth because it slows soil warming and may delay planting. However, on soils where drought stress often occurs during summer months, additional stored moisture leads to higher yields.

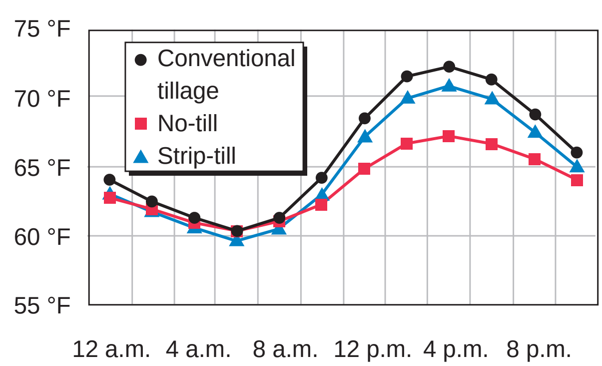

Figure 10.1. Soil temperatures across the day (averaged over several weeks after planting) in no-till, strip-till, and conventional tillage systems.

Organic Matter

Soil organic matter tends to stabilize at a certain level for a specific tillage system used in fields with a particular soil texture. Moldboard plowing buries essentially all residues and increases oxidation of organic matter. With conservation tillage systems, especially no-till and ridge-till, residue is left on the soil surface where decomposition is slow, which then causes organic matter in the upper few inches to increase after several years. Crop roots decompose more slowly than aboveground residue, and so tend to contribute relatively more to soil organic matter than does aboveground residue.

Both the amount and distribution of organic matter change with the tillage system. Compared to moldboard plowing, organic matter with no-till gradually increases near the soil surface and is maintained or increased slightly below a depth of 4 inches. With mulch tillage systems, organic matter will typically approach a level between those in conventional tillage and no-till systems.

Soil Density and Compaction

The loss of air-filled pore volume in soils caused by mechanical compression results in an increase in soil density, referred to as soil compaction. Excessive compaction restricts plant root growth, impedes drainage, reduces soil aeration, increases injury potential of some herbicides, and reduces uptake of potassium and nitrogen. Untilled soil usually has a greater density than freshly tilled soil. However, after soil is loosened by tillage, density increases over time as a result of wetting and drying, wheel traffic, and secondary tillage operations. By harvest time soil density is often about equal to that of untilled soil. Wheel traffic of heavy equipment such as tractors, combines, and grain carts may cause plant rooting to be limited or redirected with any tillage system.

In an experiment at the University of Illinois, corn and soybeans were grown with and without wheel traffic compaction on tilled soil before planting (**Table 10.3**). Heavy wheel traffic on the entire soil surface significantly decreased corn yields when rainfall was adequate or excessive. In years with excessive rainfall, ponding of water occurred on plots with the entire surface compacted, and corn yields were reduced significantly. On other plots, wheel traffic was applied to every other row of the plot area before planting—which may be more typical of field conditions. On these plots, yields were not significantly affected compared to yields from no-extra-compaction plots.

Problems such as compacted layers or "tillage pans," excessive traffic areas, ruts from wheel traffic, and livestock trails are troublesome with no-till. Compacted layers from previous field operations can limit rooting. Natural soil processes such as freezing and thawing, wetting and drying, and the channeling of earthworms and roots eventually act to reduce the effects of compacted zones under no-till, but these processes are slow, and they may not be effective for deep compaction. The use of a chisel plow or subsoiler before beginning no-till should speed the process if compaction is not reintroduced by subsequent traffic and excessive secondary tillage. Benefits from subsoiling can generally be expected only when it disrupts or loosens a drainage- or root-restricting layer. The disruption allows excess water to drain and plant roots to explore a greater volume of soil.

Table 10.3. Effects of wheel traffic compaction on soybean and corn yields at Urbana.

	11-yr avg yields (bu/A)	
Compaction treatment	**Soybeans**	**Corn**
No extra compaction	40.3	163
Half-surface compaction	40.0	160
Entire surface compacted	38.8	150*

*Soil compaction caused water to pond after heavy rain in some years.

There have been considerable expenditures in recent years aimed at breaking through compacted soil layers using a tillage procedure usually called *deep ripping*. A large, heavy tractor pulls an implement with 5 or 7 heavy standards, usually on 30-inch spacing, equipped with one of several types of points. These are typically run at depths of 12 to 16 inches, or at a depth below the depth of the compacted layer. Research at the University of Illinois showed that such deep tillage operations, done annually or every two or four years on fields with only minor compaction, had little effect on corn or soybean yield. On fields where very heavy equipment is operated, deep ripping may well improve rates of water infiltration and may improve yields. Such ripping should usually be done only in parts of the field that have a compaction problem, and it should be done when soils are dry enough to shatter; if done when soils are somewhat wet, compaction from driving the heavy equipment across the field may well negate the benefits of breaking up the compacted zone. Rather surprisingly, deep ripping, if done carefully using "minimum residue disturbance" shanks and points that do not disturb the soil surface much, can be done in "no-till" fields.

Some soils, including those found in parts of southern Illinois, have a natural hardpan or claypan at a depth of 12 to 18 inches. Generally, the layers below the pan are also compacted and poorly drained. In such cases, chiseling or subsoiling is ineffective because it is impossible to break through to a better-drained layer.

Soil surface compaction and non-uniformity from wheel or livestock traffic can cause uneven seed placement and poor stands in no-till. To the extent possible, no-till fields should be kept smooth. Where the soil surface is not smooth, shallow tillage may be needed to obtain uniform seed placement.

Stand Establishment

Uniform planting depth, good contact between the seed and moist soil, and enough loose soil to cover the seed are necessary to consistently produce uniform stands. Planting shallower than normal in the cool, moist soil common to many conservation tillage seedbeds may partially offset the disadvantage of lower soil temperatures. However, if dry, windy weather follows planting, germination may be poor, and shallow-planted seedlings may be stressed for moisture. A normal planting depth is thus suggested for all tillage systems.

For most conservation tillage systems, planters and drills are equipped with coulters in front of each seed furrow opener to cut the surface residues and penetrate the soil. Row cleaners can also be mounted in front of each seed opener. Generally, coulters should be operated at seeding depth. Row cleaners should be set to move the residue from the row area and to move as little soil as possible. Extra weight is sometimes needed on planters and drills for no-till so that the soil-engaging components function properly and sufficient weight is ensured on the drive wheels. Heavy-duty, down-pressure springs may also be necessary on each planter unit to penetrate firm, undisturbed soil.

Two major challenges in no-till are stand establishment and development of the nodal root system. These are more likely to be problems when soils are somewhat wet at planting. Wet soils at the time of planting, especially when planting no-till, usually result in what is commonly called sidewall compaction. Better described as sidewall smearing, this results from the sealing of the soil where it makes contact with the opener disks. This surface hardens as it dries and can become a serious barrier to penetration of roots, especially nodal roots of corn. This lack of nodal root penetration into the bulk soil can result in “rootless” corn, which can cause corn plants to fall over or desiccate. Failure of roots to penetrate into the bulk soil will often cause corn roots to grow up and down the row, or down through the bottom of the planting furrow (forming what some call “tomahawk” roots) rather than diagonally out into the soil.

Fertilizer Considerations in Reduced Tillage

Since soils are cooler, wetter, and less well aerated with no-till, the ability of crops to utilize nutrients may be altered, and adjustments in fertilizer management may be important.

Stratification of relatively immobile nutrients, such as phosphorus and potassium, with high concentrations near the soil surface and decreasing concentrations with depth has been routinely observed where no-till and other conservation tillage systems have been used for at least 3 to 4 years. This stratification results from both the addition of fertilizer to the soil surface and from the “cycling” of nutrients, in which roots take up nutrients from well below the soil surface; some of these nutrients are then deposited on the soil surface in the form of crop residue.

When soil moisture is adequate, nutrient stratification has not been found to decrease nutrient availability because root activity in the fertile zone near the soil surface is sufficient to supply plant needs. The residue enhances root activity near the soil surface by reducing evaporation of water, which helps keep the surface soil moist and cool. If the surface dries out and the shallow roots become inactive, nutrient uptake could be reduced, especially if the lower portions of the old plow layer are low in nutrients.

Details on soil fertility are covered in Chapter 8. The key points on fertility management for no-till are as follows:

- Liming to neutralize soil acidity is important, especially with surface applications of nitrogen fertilizer. Lime rates may need to be adjusted and applications more frequent with no-till, with care taken not to raise surface pH levels much above 7.2 or 7.3. Where possible, lime should be incorporated as needed before establishing a no-till system.
- Any phosphorus and potassium deficiencies should be corrected prior to switching to no-till because surface applications move into the soil very slowly.
- After several years of no-till, it may be desirable to take samples for nutrient analysis from near the soil surface (0 to 3 inches deep) and from lower portions of the old tillage zone (3 to 7 inches deep). If depletion of nutrients or accumulation of acidity (pH less than 5.3 or so) in the lower portion occurs and crops show nutrient deficiency, moldboard or chisel plowing can correct the stratification problem. If there has been stratification but no deficiency symptoms appear, then such tillage may not be necessary.
- Starter fertilizer appears to be more important with no-till, especially for continuous corn. More information on the use of starter for no-till is provided in Chapter 8.
- Nitrogen management is very important to success with no-till planting of corn. Anhydrous ammonia applied in the spring before planting can severely injure or kill seedlings if corn is planted directly above it. Anhydrous

ammonia can safely be applied in the fall or in the spring before planting, if application is made between rows to be planted. If rain is not received within 3 days after application, there is a potential for loss of a portion of the nitrogen surface applied on no-till in the form of urea or urea–ammonium nitrate solutions. To minimize this loss potential, apply these products 1 to 2 days before a rain, or use a urease inhibitor.

Weed Control

Controlling weeds is essential for profitable production with any tillage system. With less tillage, weed control becomes more dependent on herbicides. However, effective herbicides are available for controlling most weeds in conservation tillage systems. Herbicide selection and application rate, accuracy, and timing become more important. Application accuracy is especially important with drilled or narrow-row soybeans because row cultivation is impractical.

Perennial weeds such as milkweed and hemp dogbane may be a problem with no-till systems. Small-seeded, surface-germinating weeds, such as grasses, waterhemp, and nightshade, may also increase with reduced tillage systems. Some large-seeded broadleaf weeds, such as velvetleaf, cocklebur, and jimsonweed, are often less of a problem with no-till. With glyphosate now used on most fields of soybean where reduced tillage is practiced, some of these weed shifts have begun to change. Glyphosate-tolerant weeds are starting to appear, and we can expect this to alter weed management strategies.

Soil-applied herbicides may not give optimal performance under tillage systems that leave large amounts of crop residue and clods on the soil surface if the herbicides adsorb onto the crop residue.

Herbicide incorporation is impossible in no-till systems. Residual or postemergence herbicides are effective, and mechanical cultivation is usually not done.

Heavy-duty cultivators are available to cultivate with high amounts of surface residues and hard soil, but these are not widely used. High amounts of crop residues interfere with most attempts at mechanical weed control, leading to dependence on chemical control.

Crop Yields

Tillage research is conducted at University of Illinois Agricultural Research and Demonstration Centers (see the map on the inside front cover) to evaluate crop yield responses to different tillage systems under a wide variety of soil and climatic conditions. Crop yields vary due more to weather conditions during the growing season than to the tillage system used. Corn and soybean yields are generally higher when the crops are rotated compared to either crop grown continuously. It is important with any tillage system that plant stands be adequate, weeds be controlled, soil compaction not be excessive, and adequate nutrients be available.

Data from recent Illinois studies show that, on average, tillage tends to increase yields slightly (**Table 10.4**). This was true at Monmouth for corn and soybean grown continuously or in rotation with each other or with wheat. At Perry, no-till produced yields as high as those with tillage for continuous corn, for corn rotated with soybean, and for soybean and wheat, but not for corn in the 3-year rotations. So responses to tillage are somewhat affected by crop and rotation and by soil and weather. Most yield differences favor tillage over no-till, but because no-till typically has lower cost, profitability may not be much different. No-till also reduces soil loss. On the negative side, getting good seed placement and good stands for a crop like wheat is more challenging with no-till, and there has been a tendency for soils under no-till to show more signs of increasing bulk density (more compaction.)

On well-drained to moderately well-drained, medium-textured soils, expected yields with all tillage systems are quite similar for rotated corn and soybeans, though there may be some exceptions. In previous research, yields of continuous corn were often found to be lower as tillage was reduced. There is less evidence for this in more recent

Table 10.4. Yields of corn, soybean, and wheat in a crop rotation and tillage study at two locations in western Illinois.

Crop and rotation	Monmouth (bu/A)		Perry (bu/A)	
	Tilled	No-till	Tilled	No-till
Corn				
Continuous corn	202	193	180	180
Soybean–corn	210	207	186	189
Soybean–wheat–corn	220	214	197	188
Wheat–soybean–corn	221	219	200	193
Soybean				
Continuous soybean	69	68	45	44
Corn–soybean	72	70	46	46
Wheat–corn–soybean	75	72	46	45
Corn–wheat–soybean	76	72	43	40
Wheat				
Corn–soybean–wheat	92	87	77	73
Soybean–corn–wheat	89	83	78	74

The study was established by the late 1990s, and these data are from three years, 2006–2008.

research, as shown in **Table 10.4**. The soils in that study are Clarksdale silt loam at Perry and Muscatune silt loam at Monmouth, both of which are moderately well drained and medium textured. On very well-drained, sandy soils, conservation tillage systems that retain surface residues reduce wind erosion and conserve moisture, typically producing high yields. Soils such as Cisne silt loams, which are very slowly permeable and poorly drained, have a clay pan that usually restricts root development regardless of tillage system. On such soils, yields are frequently higher with less tillage. This is partly due to the fact that they are mostly in southern Illinois, where soil temperature is less of an issue, and because surface residue helps to retain soil water, which is more often limiting in such soils.

The SOILS Project, an initiative funded by the Illinois Department of Agriculture, used demonstration sites across the state to compare mulch-till, strip-till, and no-till systems. In three years of the demonstrations (2000–2002), corn grain yields increased slightly as the amount of tillage increased, and there was a substantial difference in the retention of crop residue after planting (**Table 10.5**). In the first two years of this work, it was relatively warm and dry near the time of planting, and there was little difference among treatments. The third year was not as warm at planting, and the treatments with less tillage, especially no-till, did not do as well in some of the northern locations. Much of this was a result of stand reductions with no-till. As we have seen in other studies, cooler soils at planting due to less tillage often mean a slower start to the crop, and in some cases lower stands and lower yields. These are the major drawbacks to no-till systems. Strip-till usually produces a better seedbed and so seldom results in stand problems, as long as the planting conditions are uniform. As shown in **Figure 10.1**, soil temperatures with strip-till are closer to those in tilled soils than in no-till.

Table 10.5. Corn yields and residue cover under different tillage systems.

Tillage system	Corn yield (bu/A)	Residue after planting (%)
Mulch-till	164	19
Strip-till	161	52
No-till	158	63

Data, from 2000–2002, are averaged over 30 on-farm sites.

Adaptability of No-Till to Specific Soils

Soil, climate, and crop rotation influence the success of no-till. In addition, success is influenced by pest control, fertility practices, and management experience of the farm operator. The decision to adopt no-till may be based on net return, potential for reduced soil erosion, or eligibility for government programs. Yield potential of crops grown with no-till is an important consideration.

Several states have classified soils into tillage management groups for corn and soybean production. Soil types are grouped according to unique soil properties and their influence on crop yield with no-till planting. Soil characteristics include drainage, texture, organic matter, and slope. A summary of the classification as might be applied to Illinois follows:

- *Equal yield*. In central and northern Illinois, when crops are rotated and when no-till is used on naturally well-drained soils or on slopes greater than 6%, no-till should provide yield potential equal to that of other systems for corn, soybeans, and wheat.
- *Equal or higher yield*. In southern Illinois, with crop rotation, well-drained soil, slope greater than 6%, or very low organic matter soil, no-till will often produce higher yields than other tillage systems, especially in years when there are dry periods during the season.
- *Higher yield*. In southern Illinois, on light (very low organic matter), somewhat poorly drained, and poorly drained silt loams (that are nearly level to gently sloping and overlie very slowly permeable fragipan-like soil layers that restrict plant rooting and water movement), no-till yield potential should be higher than with other tillage systems.
- *Lower yield*. On dark, poorly drained silty clay loams to clay soils with 0% to 2% slope, lower yields are typically expected with no-till compared to other tillage systems.

Machinery and Labor Costs

Machinery-related costs include the expenses for owning and operating machinery and the labor to operate it. Many factors must be taken into account to estimate these costs for a farm and for various tillage systems.

Machinery costs include depreciation, interest, insurance, housing, repairs, fuel, and lubrication, as well as costs of labor to operate equipment. Programs are available to determine the optimal machinery set for various tillage systems and farm sizes. For the latest information on machinery costs, see the website www.farmdoc.illinois.edu/manage/machinery.

Total costs for machinery and labor per acre decrease as the amount of tillage is reduced and as farm size increases. For reduced tillage, fewer implements and field operations are used, and the necessary power units are sometimes smaller for a given farm size. If a reduced tillage system is used on only part of the land farmed, implements and tractors will need to be available for other portions, so savings may be smaller than indicated.

With reduced tillage systems, labor costs are less because some fall or spring tillage operations are less intensive or are eliminated. The labor saved in this way has value only if it reduces the cost of hired labor or if the saved labor time is directed into other productive activities, such as raising livestock, working off-farm, or farming more land.

While equipment and labor costs are typically lower when less tillage is done, whether it pays to convert to systems with less tillage depends on several factors. The type of soil and the location often influence the effect of tillage changes on yield. No-till systems, while they tend to lower costs and in some cases increase yields, often require more attention to soil conditions, and they may be more difficult to impose in fields with a wide range of soil types. No-till fields tend to have cooler and wetter soils than tilled fields, and while the common advice to "wait a few days extra" before starting to plant no-till fields is sound, it can also mean planting delays that reduce yields in some years. Strip-till might reduce this need to wait and so may be a solution for some producers in some fields. At the same time, few changes in tillage are "free"—most bring new challenges, and few solve all problems.

In general, while almost any tillage system can be made to "work" on almost any field, factors like soil variability, especially in conjunction with factors like a rapidly expanding farm operation, may mean that the drawbacks to no-till are greater than the benefits. No matter what tillage system is used, however, it is essential that everything possible be done to maintain soil productivity, by working to keep soil in the field and to manage the soil properly.

Using a drill or narrow-row planter for soybeans is an option for most tillage systems. However, owning a drill for soybeans and a planter for corn often increases the machinery inventory and costs for a corn–soybean farm. This is part of the reason why many producers have moved to split-row planters, using 30-inch rows for corn and 15-inch rows, formed by splitter units, for soybean. This allows the use of the wider planter for both crops and of row units for soybean seed placement, which often improves stands. The effects on machinery cost for the farm depend on farm size and the cost of planting equipment.

An extra cost for additional or more expensive pesticides may be associated with some conservation tillage systems. For example, a burndown herbicide may be needed with no-till and ridge tillage systems. These increases are usually more than offset by reduced machinery and labor costs with conservation tillage.

Costs for corn and soybean seeds are usually the same for different tillage systems. However, when soybeans are drilled or planted in narrow rows, the seeding rate is usually increased by 10% to 20% compared to planting in rows 15 or 30 inches apart.

In most cases the amounts of fertilizers and lime do not change with different tillage systems. However, the forms and application techniques may vary depending on the tillage system. For example, surface-applied urea works well if the field is tilled after application, but it does not work well in no-till, when the weather may stay dry after application and N losses may be high. Any differences in such costs should be considered when considering a change in tillage system. As another example, starter fertilizer for corn is often recommended with conservation tillage, especially with the no-till system, and planter attachments to apply starter fertilizer in a separate band represent an additional cost, both in equipment and in the time needed to supply the fertilizer at planting.

11

Water Management

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A superior water-management program seeks to provide an optimal balance of water and air in the soil, which allows full expression of genetic potential in plants. The differences among poor, average, and record crop yields generally can be attributed to the amount and timing of the soil's water supply.

Improving water management is an important way to increase crop yields. By minimizing crop-water stress, the producer obtains more benefits from improved cultural practices and realizes the full yield of the cultivars now available. Crops are particularly sensitive to water stress when they are undergoing reproductive growth.

To produce maximum yields, the soil must be able to provide water as it is needed by the crop. But the soil seldom has just the right amount of water for maximum crop production; a deficiency or a surplus usually exists. A good water-management program seeks to avoid both extremes through a variety of measures. These measures include draining waterlogged soils, making more effective use of the water-holding capacity of soils so that crops will grow during periods of insufficient rainfall, increasing the soil's ability to absorb moisture and conduct it down through the soil profile, reducing water loss from the soil surface, and irrigating soils with low water-holding capacity.

In Illinois, the most frequent water-management need is improved drainage. Close to 10 million acres of land have tile drainage, and another several million acres have some form of surface drainage system. Initial efforts in the 1800s to artificially drain Illinois farmland made our soils among the most productive in the world. Excessive water in the soil limits the amount of oxygen available to plants and thus retards growth. This problem occurs where the water table is high or where water ponds on the soil surface. Removing excess water from the root zone is an important first step toward a good water-management program. A drainage system should be able to remove water from the soil surface and lower the water table to about 12 inches beneath the soil surface in 24 hours and to 21 inches in 48 hours. In most Illinois soils, this is equivalent to removing 3/8 inch of water from the soil profile in 24 hours.

The Benefits of Drainage

A well-planned drainage system provides a number of benefits: better soil aeration, more timely field operations, less flooding in low areas, higher soil temperatures, less surface runoff, better soil structure, better incorporation of herbicides, better root development, higher yields, and improved crop quality.

Soil aeration. Good drainage ensures that roots receive enough oxygen to develop properly. When the soil becomes waterlogged, aeration is impeded and the amount of oxygen available is decreased. Oxygen deficiency reduces root respiration and often the total volume of roots developed. It also impedes the transport of water and nutrients through the roots. The roots of most nonaquatic plants are injured by oxygen deficiency, and prolonged deficiency may result in the death of some cells, entire roots, or, in extreme cases, the whole plant. Proper soil aeration also will prevent rapid losses of nitrogen to the atmosphere through denitrification.

Timeliness. Because a good drainage system increases the number of days available for planting and harvesting, it can enable you to make more timely field operations. Drainage can reduce planting delays and the risk that good crops will be drowned or left standing in fields that are too wet for harvest. Good drainage may also reduce the need for additional equipment that is sometimes necessary to speed up planting when fields stay wet for long periods.

Soil temperature. Drainage can increase soil surface temperatures during the early months of the growing season by 6 to 12 °F. Warmer temperatures assist germination and increase plant growth.

Surface runoff. By enabling the soil to absorb and store rainfall more effectively, drainage reduces runoff from the soil surface and thus reduces soil erosion.

Soil structure. Good drainage is essential in maintaining the structure of the soil. Without adequate drainage the soil remains saturated, precluding the normal wetting and drying cycle and the corresponding shrinking and swelling of the soil. The structure of saturated soil will suffer additional damage if tillage or harvesting operations are performed on it.

Herbicide incorporation. Good drainage can help avoid costly delays in applying herbicide, particularly postemergence herbicide. Because some herbicides must be applied during the short time that weeds are still relatively small, an adequate drainage system may be necessary for timely application. Drainage may also help relieve the cool, wet-stress conditions that increase crop injury by some herbicides.

Root development. Good drainage enables plants to send roots deeper into the soil so that they can extract moisture and nutrients from a larger volume of soil. Plants with deep roots are better able to withstand drought.

Crop yield and quality. All of the benefits previously mentioned contribute to greater yields of higher-quality crops. The exact amounts of the yield and quality increases depend on the type of soil, the amount of rainfall, the fertility of the soil, crop-management practices, and the level of drainage before and after improvements are made. Of the few studies that have been conducted to determine the benefits of drainage, the most extensive in Illinois was initiated at the Agronomy Research Center at Brownstown. This study evaluated drainage and irrigation treatments with Cisne and Hoyleton silt loams.

Drainage Methods

A drainage system may consist of surface drainage, subsurface drainage, or some combination of both. The kind of system you need depends in part on the ability of the soil to transmit water. The selection of a drainage system ultimately should be based on economics. Surface drainage, for example, would be most appropriate where soils are impermeable and would require too many subsurface drains to be economically feasible. Soils of this type are common in southern Illinois.

Surface Drainage

A surface drainage system is most appropriate on flat land with slow infiltration and low permeability and on soils with restrictive layers close to the surface. This type of system removes excess water from the soil surface through improved natural channels, human-made ditches, and shaping of the land surface. A properly planned system eliminates ponding, prevents prolonged saturation, and accelerates the flow of water to an outlet without permitting siltation or soil erosion.

A surface drainage system consists of a farm main, field laterals, and field drains. The farm main is the outlet serving the entire farm. Where soil erosion is a problem, a surface drain or waterway covered with vegetation may serve as the farm main. Field laterals are the principal ditches that drain adjacent fields or areas on the farm. The laterals receive water from field drains, or sometimes from the surface of the field, and carry it to the farm main. Field drains are shallow, graded channels (with relatively flat side slopes) that collect water within a field.

A surface drainage system sometimes includes diversions and interceptor drains. Diversions, usually located at the bases of hills, are channels constructed across the slope of the land to intercept surface runoff and prevent it from overflowing bottomlands. These channels simplify and reduce the cost of drainage for bottomlands.

Interceptor drains collect subsurface flow before it resurfaces. These channels may also collect and remove surface water. They are used on long slopes that have grades of 1% or more and on shallow, permeable soils overlying relatively impermeable subsoils. The locations and depths of these drains are determined from soil borings and the topography of the land.

The principal types of surface drainage configurations are the random and parallel systems (**Figure 11.1**). The random system consists of meandering field drains that connect the low spots in a field and provide an outlet for excess water. This system is adapted to slowly permeable soils with depressions too large to be eliminated by smoothing or shaping the land.

The parallel system is suitable for flat, poorly drained soils with many shallow depressions. In a field that is cultivated up and down a slope, parallel ditches can be arranged to break the field into shorter lengths. The excess water thus erodes less soil because it flows over a smaller part of the field before reaching a ditch. The side slopes of the parallel ditches should be flat enough to permit farm equipment to cross them. The spacing of the parallel ditches will vary according to the slope of the land.

For either the random or parallel systems to be fully effective, minor depressions and irregularities in the soil surface must be eliminated through land grading or smoothing.

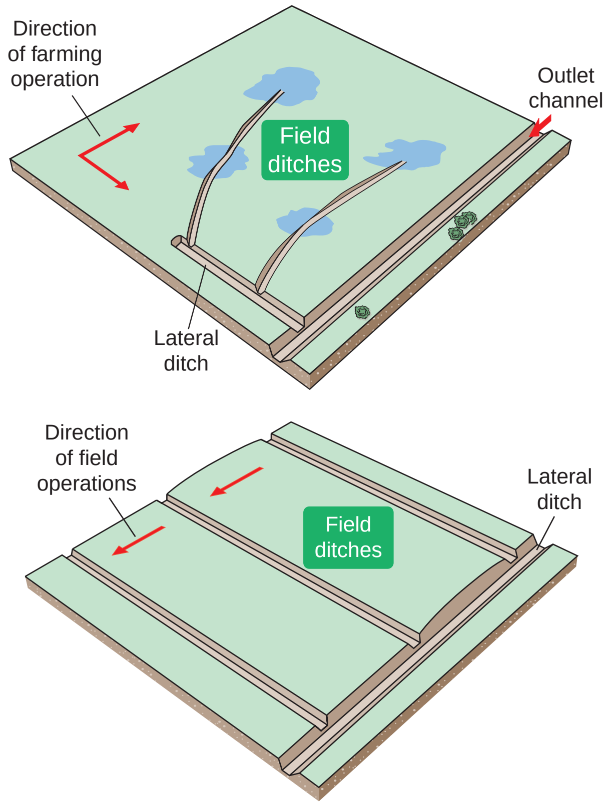

Figure 11.1. Types of surface drainage systems: random ditches (top); parallel ditches (bottom).

Bedding is another surface drainage method that is used occasionally. The land is plowed to form a series of low, narrow ridges that are separated by parallel, dead furrows. The ridges are oriented in the direction of the steepest slope in the field. Bedding is adapted to the same conditions as the parallel system, but it may interfere with farm operations and does not drain the land as completely. It is not generally suited for land that is planted in row crops because the rows adjacent to the dead furrows will not drain satisfactorily. Bedding is acceptable for hay and pasture crops, although it will cause some crop loss in and adjacent to the dead furrows.

Subsurface Drainage

Many of the deep, poorly drained soils of central and northern Illinois respond favorably to subsurface drainage. A subsurface drainage system is used in soils permeable enough that the drains do not have to be placed too closely together. If the spacing is too narrow, the system will not be economical. By the same token, the soil must be productive enough to justify the investment. Because a subsurface drainage system functions only as well as the outlet, a suitable one must be available or constructed. The topography of the fields also must be considered because the installation equipment has depth limitations,

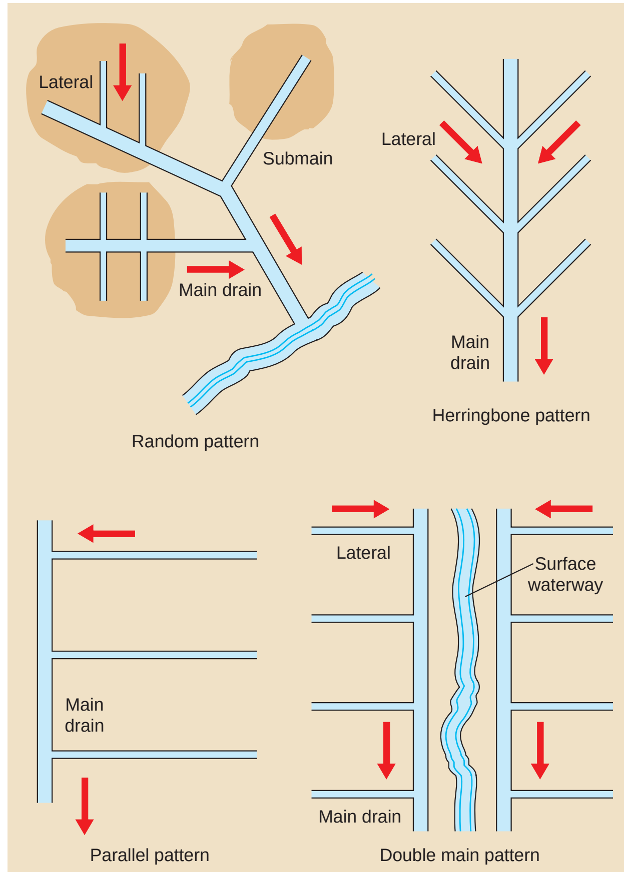

Figure 11.2. Types of subsurface drainage systems. The arrows indicate the direction of water flow.

and a minimum amount of soil cover is required over the drains.

Subsurface systems are made up of an outlet or main, sometimes a submain, and field laterals. The drains are placed underground, although the outlet is often a surface drainage ditch. Subsurface drainage conduits are constructed of clay, concrete, or plastic.

There are four types of subsurface systems: random, herringbone, parallel, and double-main (**Figure 11.2**). A single system or some combination of systems may be chosen according to the topography of the land.

For rolling land, a random system is recommended. The main drain is usually placed in a depression. If the wet areas are large, the submains and lateral drains for each area may be placed in a gridiron or herringbone pattern to achieve the required drainage.

With the herringbone system, the main or submain is often placed in a narrow depression or on the major slope of the land. The lateral drains are angled upstream on either side of the main. This system sometimes is combined with others to drain small or irregular areas. Because two laterals intersect the main at the same point, however, more drainage than necessary may occur at that intersection. The herringbone system may also cost more because it requires more junctions. Nevertheless, it can provide the extra drainage needed for the heavier soils found in narrow depressions.

The parallel system is similar to the herringbone system, except that the laterals enter the main from only one side. This system is used on flat, regularly shaped fields and on uniform soil. Variations are often used with other patterns.

The double-main system is a modification of the parallel and herringbone systems. It is used where a depression, frequently a natural watercourse, divides the field in which drains are to be installed. Sometimes the depression may be wet due to seepage from higher ground. A main placed on either side of the depression intercepts the seepage water and provides an outlet for the laterals. If only one main were placed in the center of a deep and unusually wide depression, the grade of each lateral would have to be changed at some point before it reaches the main. A double-main system avoids this situation and keeps the grade lines of the laterals uniform.

The advantage of a subsurface drainage system is that it usually drains soil to a greater depth than surface drainage. Subsurface drains placed 36 to 48 inches deep and 80 to 100 feet apart are suitable for crop production on many medium-textured soils in Illinois. When properly installed, these drains require little maintenance, and because they are underground they do not obstruct field operations.

More specific information about surface and subsurface drainage systems can be obtained from the *Illinois Drainage Guide (Online)* at www.wq.uiuc.edu/dg. This website addresses the planning, design, installation, and maintenance of drainage systems for a wide variety of soil, topographic, and climatic conditions.

Deciding to Drain

For the producer, the decision to install or improve a drainage system is a practical one, based on principles of good economics and good husbandry. If the benefits outweigh the associated costs, then drainage makes good sense. However, the cost–benefit analysis is not always clear-cut. The associated expenses include material costs, installation costs, and maintenance costs. There may also be other expenses, such as increased hauling costs associated with the increased yield that comes from drainage. Even more difficult to grasp and to quantify are the hidden costs associated with water quality degradation.

Many tools have been developed to help determine the practicability of drainage. The *Illinois Drainage Guide (Online)*, for example, includes an economic analysis calculator (click the link at left for "Economic Considerations," then "Economic Analysis") that can be used to determine the profitability of a drainage system. It provides many measures of profitability, but they are all consistent with each other and are but a reflection of user preference. The measures of profitability used in the guide are listed here:

- The **net present value (NPV)** is the present value of the expected future cash flows minus the initial cost. A positive NPV value is indicative of a profitable system.
- The **profitability index (PI),** also known as the benefit–cost ratio, is the ratio of the net present value to the initial capital investment. If the NPV is positive, then the PI is greater than 1.0, indicating that the benefits of a system outweigh the costs.
- The **internal rate of return (IRR)** is the rate at which the future cash flow, discounted back to the present, equals its price. It can be viewed as the interest rate that results in an NPV of 0 or a PI of 1. If the IRR exceeds the interest rate at which capital can be obtained, then the system is profitable.
- The **discounted payback time (DPT)** is the length of time it takes to recover the cost of an initial investment, with regard to the time value of money. For this measure, the value of future income is discounted by the cost of obtaining capital, that is, the interest rate charged on a loan.
- The **undiscounted payback time (UPT)** is the length of time it takes to recover the cost of an initial investment, without regard to the time value of money. In effect, the UPT is the same as evaluating the DPT under the assumption that the cost of capital, the interest rate, is 0.

Drain spacing plays an important role in determining the cost of a subsurface drainage system. A typical drainage system in the Midwest is designed with a drainage coefficient of 3/8 inch, meaning it is designed to remove 3/8 inch of water in 24 hours, when the water table is initially at the soil surface. This drainage coefficient can be achieved with different combinations of depth and spacing. In Drummer Silty clay loam, for example, a 3/8-inch drainage coefficient can be achieved by installing drains 60 feet apart at a depth of 2.5 feet, or by installing drains 100 feet apart at a depth of 5 feet. The system with the more closely spaced laterals would be more expensive. In general, for a given depth, yield will increase with decreased drain spacing up to a point, beyond which it is insensitive to decreases in spacing. In fact, computer simulations indicate that in some soils in some locations, it is possible to place drains so close together that yield is adversely affected. Field experiments are being conducted to determine if these simulations are reflected in reality. The objective is to determine the spacing that maximizes profitability.

Drainage Strategy

Once the decision has been made to incorporate drainage into a farm management plan, a good strategy is to start with fields or sections of fields that will benefit most from drainage. The proceeds from this exercise can then be applied to areas with lesser benefit until the desired coverage is achieved. It is important to remember that there may be situations in which the yield increase does not justify drainage, and the best option is not to install a drainage system in that field or section of a field. Under most conditions, drainage makes economic sense on most hydric soils. However, if the mains are too costly, if the outlets are distant and inaccessible, or if the soil is such that iron ochre or sedimentation would reduce the life of a drainage system to an uneconomic level, it is best not to install a drainage system.

Drainage Installation

The price of drain installation is dependent on many factors, including the equipment used in installation, the size of the job, the time of year when the system will be installed, the contractor's pricing structure, and the level of competition in the county or region. These factors make it worthwhile to obtain quotes from two or more drainage contractors. Different contractors have different pricing structures and business strategies.

The choice of a drainage contractor can significantly affect the profitability of a drainage system. Improper backfilling or grade reversals during installation can dramatically reduce the system's life, though problems may not show up in the first few years. So it is best to select a contractor with a good reputation who will provide a performance guarantee. Take care to select someone who emphasizes quality rather than speed of installation. While it is possible to move through the field relatively quickly with modern drainage equipment, problems such as excessive tile stretch and grade reversals can be minimized by reducing the speed of travel to recommended levels.

Some producers choose to install their own drainage systems. If that is your preference, getting some training on installation techniques is recommended. Such training is often offered by state extension services, trade associations, and equipment manufacturers. It is also strongly recommended that lasers be used in all drain installations. Because of the small slopes at which drains are typically installed, there is not much room for error, so using a properly calibrated laser system is essential.

Conservation Drainage

All across the Midwest, research is being conducted on management practices that improve drain outflow water quality without adversely affecting crop yield. Conservation drainage, as these practices are collectively termed, is the optimization of drainage systems for production, environmental, and water supply benefits. In light of the importance of drainage to agriculture in the region, conservation drainage practices (CDPs) should reduce nutrient transport from drained land without adversely affecting drainage performance or crop production. In Illinois, cost-share funds are available for one such practice, drainage water management.

In drainage water management, often referred to as controlled drainage, a control structure is placed at the outlet of a tile system to control the outlet level. This practice can be used to raise the water level after harvest, thereby reducing nitrate loading from tile effluent, or to retain water in the soil during the growing season. The normal mode of operation in Illinois is to set the water table control height to within 6 inches of the soil surface on November 1 and to lower the control height to the level of the tile on March 15. Thus, water is held back in the field during the fallow period. In experiments in Illinois, reductions were measured of up to 45% for nitrate and 80% for phosphate.

The water control structure in a drainage water management system effectively functions as an in-line weir, allowing the drainage outlet elevation to be artificially set at levels ranging from the soil surface to the bottom of the drains, as shown in **Figure 11.3.**

Types of structures in common usage are shown in **Figure 11.4.** The water table level is controlled with these structures by adding or removing "stop logs" or by using float mechanisms to regulate the opening and closing of a flow valve. There are many variations in the shapes and sizes of structures. Flashboard structures may be either manually operated or automated to adjust the outlet elevation on fixed dates or in response to rainfall patterns.

Drainage water management practices can target agronomic goals, environmental (water quality) goals, or both. The drainage outlet elevation can be set at or close to the soil surface between growing seasons to recharge the water table, temporarily retaining soil water containing nitrate in the soil profile, where it may be subject to attenuating and nitrate transforming processes, depending on soil

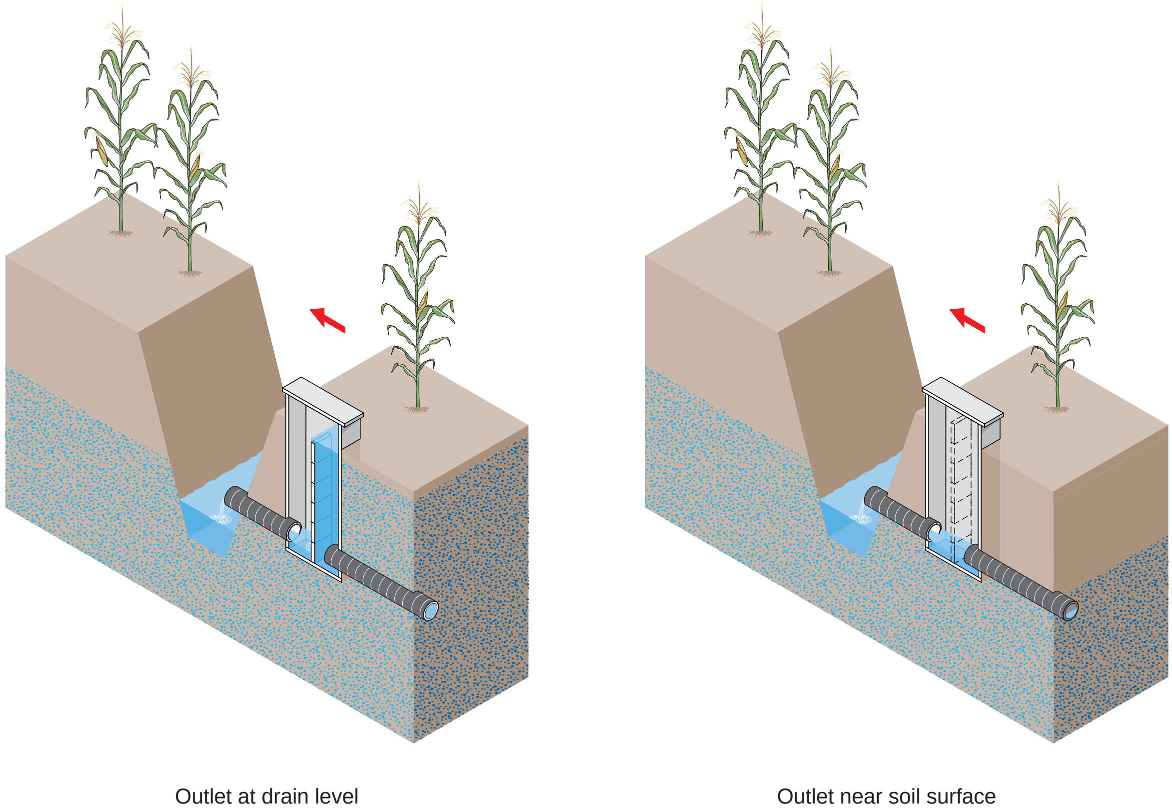

Figure 11.3. Using control structures to manipulate drain outlet levels.

temperature and microbiological activity. In addition, it is possible to raise the outlet elevation after planting to help increase water availability to then-shallow plant roots, and to raise or lower it throughout the growing season in response to precipitation conditions. In some soils, water may even be added during very dry periods to reduce crop loss from drought; this related practice is termed subirrigation. However, the drain spacing for subirrigation may be half to a third of the recommended value for drainage to maintain a water table at a proper depth to reduce deficit crop stress without increasing excess water stress.

In the 2004 crop year, Illinois farmers reported yield increases of 5 to 10 bushels an acre for corn and 3 to 6 bushels an acre for soybean due to the implementation of drainage water management. However, these are only anecdotal reports; research on the yield benefits of this practice is in the early stages, and any benefits may vary by soil and climate. The practice can also be used to benefit wildlife by creating ponded conditions in some fields during the fallow period, providing temporary aquatic habitats for migrating birds.

More information on drainage water management can be found in the regional bulletin *Drainage Water Management for the Midwest,* available online at www.ces.purdue.edu/extmedia/WQ/WQ-44.pdf. In addition, the *Illinois Drainage Guide (Online)* at www.wq.uiuc.edu/dg includes a template for creating a drainage water management plan in the format required by the Illinois NRCS cost-sharing program (click “Related Information” in the left-hand navigation column to go to the relevant portion of the guide).

Benefits of Irrigation

During an average year, most regions of Illinois receive ample rainfall for growing crops, but, as shown in **Figure 11.5,** rain does not occur when crops need it the most. From May to early September, growing crops demand more water than is provided by precipitation. For adequate plant growth to continue during this period, the required water must be supplied by stores in the soil or by irrigation. During the growing season, crops on deep, fine-textured soils may draw upon moisture stored in the soil if the normal amount of rainfall is received throughout the year. But if rainfall is seriously deficient or if the soil has little capacity for holding water, crop yield may be reduced. Yield reductions are likely to be most severe on sandy soils or soils with claypans. Claypan soils restrict root growth, and both types of soils often cannot provide adequate water during the growing season.

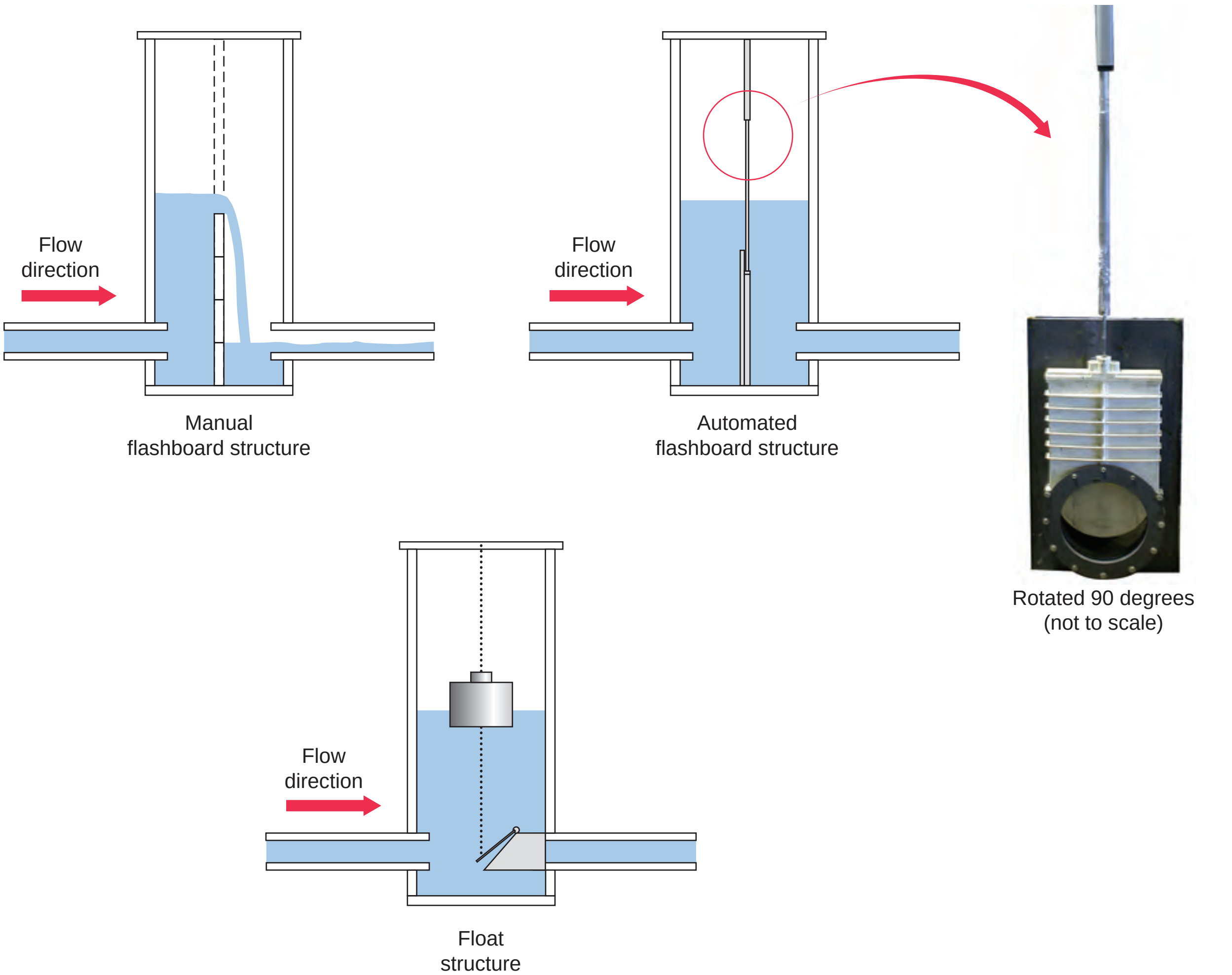

Figure 11.4. Types of water table control structures.

To prevent crop-water stress during the growing season, more and more producers are using irrigation. It may be appropriate where water stress can substantially reduce crop yields and where a supply of usable water is available at reasonable cost. Irrigation is still most widely used in the arid and semiarid parts of the United States, but it can be beneficial in more humid states, including Illinois. Almost yearly, Illinois corn and soybean yields are limited by drought to some degree, even though the total annual precipitation exceeds the water lost through evaporation and transpiration.

With current cultural practices, a good crop of corn or soybeans in Illinois needs at least 20 inches of water. All sections of the state average at least 15 inches of rain from May through August. Satisfactory yields thus require at least 5 inches of stored subsoil water in a normal year.

Crops growing on deep soil with high water-holding capacity, that is, fine-textured soil with high organic matter content, may do quite well if precipitation is not appreciably below normal and if the soil is filled with water at the beginning of the season.

Sandy soils and soils with subsoil layers that restrict water movement and root growth cannot store as much as 5 inches of available water. Crops planted on these soils suffer from inadequate water every year. Most of the other soils in the state can hold more than 5 inches of available water in the crop-rooting zone. Crops on these soils may suffer from water deficiency when subsoil water is not fully recharged by about May 1 or when summer precipitation is appreciably below normal or poorly distributed throughout the season.

Water stress delays the emergence of corn silks and shortens the period of pollen shedding, thus reducing the time of overlap between the two processes. The result is incomplete kernel formation, which can have disastrous effects on corn yields.

Corn yields may be reduced by as much as 40% when visible wilting occurs on four consecutive days at the time

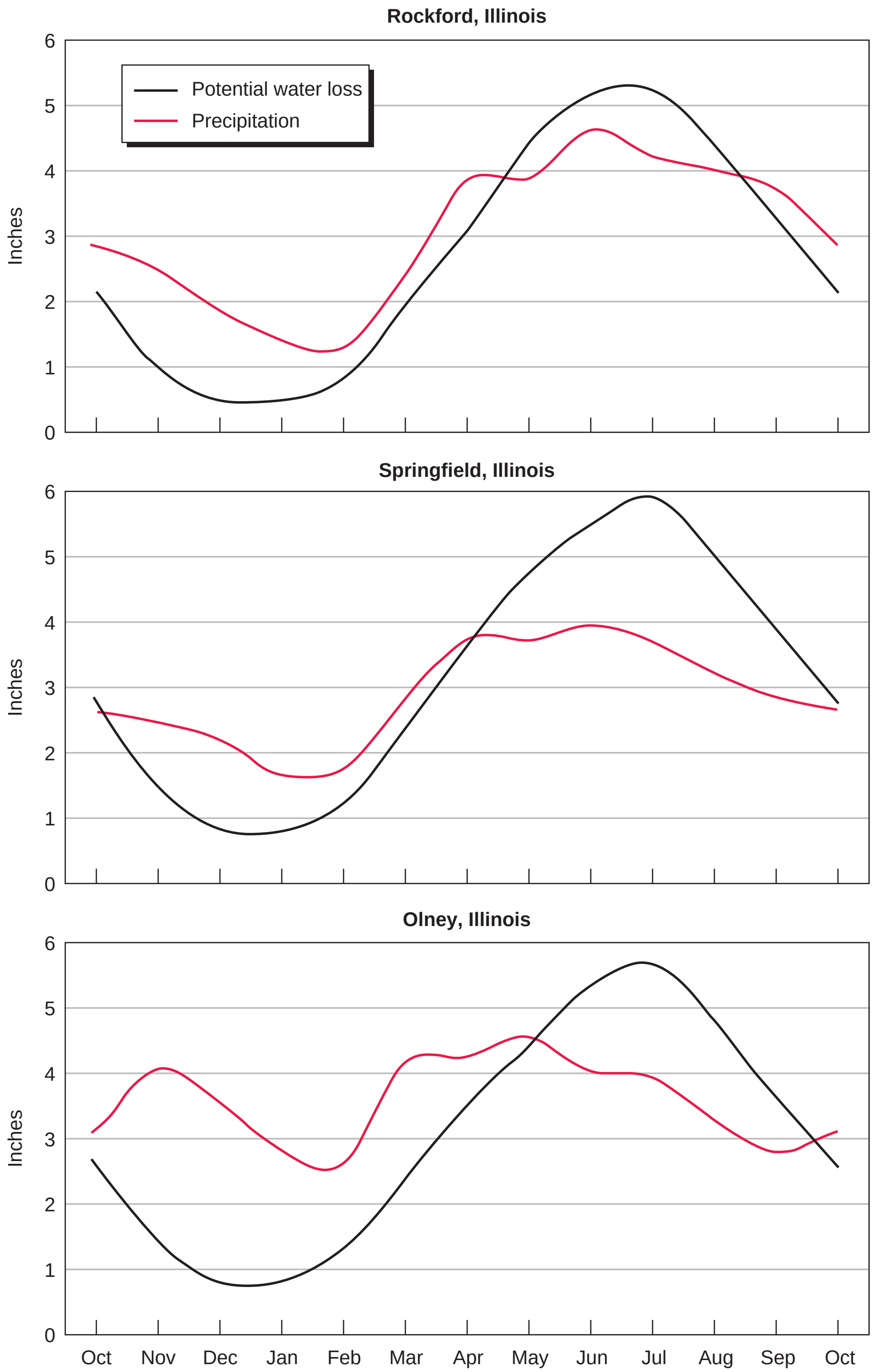

Figure 11.5. Average monthly precipitation and potential moisture loss from a growing crop in three regions of Illinois.

of silk emergence. Studies have also shown that severe drought during the pod-filling stage causes similar yield reductions in soybeans.

Increasing numbers of farmers are installing irrigation systems to prevent the detrimental effects of water deficiency. Some years of below-normal summer rainfall and other years of erratic rainfall distribution throughout the season have contributed to the increase. As other yield-limiting factors are eliminated, adequate water becomes increasingly important to ensure top yields.

Most of the development of irrigation systems has occurred on sandy soils or other soils with correspondingly low levels of available water. Some installations have been made on deeper, fine-textured soils, and other farmers are considering irrigation of such soils.

Deciding to Irrigate

The need for an adequate water source cannot be overemphasized when one is considering irrigation. If a producer is convinced that an irrigation system will be profitable, an adequate source of water is necessary. In many parts of Illinois, such sources do not currently exist. Fortunately, underground water resources are generally good in the sandy areas where irrigation is most likely to be needed. A relatively shallow well in some of these areas may provide enough water to irrigate a quarter section of land. In some areas of the state, particularly the northern third, deeper wells may provide a relatively adequate source of irrigation water.

Some farmers pump their irrigation water from streams, a relatively good and economical source if the stream does not dry up in a droughty year. Impounding surface water on an individual farm is also possible in some areas of the state, but this water source is practical only for small acreages. However, an appreciable loss may occur both from evaporation and from seepage into the substrata. Generally, 2 acre-inches of water should be stored for each acre-inch actually applied to the land.

A 1-inch application on 1 acre (1 acre-inch) requires 27,000 gallons of water. A flow of 450 gallons per minute provides 1 acre-inch per hour. So a 130-acre center-pivot system with a flow of 900 gallons per minute can apply 1 inch of water over the entire field in 65 hours of operation. Because some of the water is lost to evaporation and some may be lost from deep percolation or runoff, the net amount added is less than 1 inch.

The Illinois State Water Survey and the Illinois State Geological Survey (both located in Champaign) can provide information about the availability of irrigation water. Submit a legal description of the site planned for development of a well and request information regarding its suitability for irrigation-well development. Once you decide to drill a well, the Water Use Act of 1983 requires you to notify the local Soil and Water Conservation District office if the well is planned for an expected or potential withdrawal rate of 100,000 gallons or more per day. There are no permit requirements or regulatory provisions.

An amendment passed in 1987 allows Soil and Water Conservation Districts to limit the withdrawals from large wells if domestic wells meeting state standards are affected by localized drawdown. The legislation currently affects Kankakee, Iroquois, Tazewell, and McLean counties.

The riparian doctrine, which governs the use of surface waters, states that you are entitled to a reasonable use of the water that flows over or adjacent to your land as long as you do not interfere with someone else's right to use the water. No problem results as long as water is available for everyone. But when the amount of water becomes limited, legal determinations become necessary regarding whether someone's water use interferes with someone else's rights. It may be important to establish a legal record to verify the date on which the irrigation water use began.

Assuming that it will be profitable to irrigate and that an assured supply of water is available, how do you find out what type of equipment is available and what is best for your situation? University representatives have discussed this question in various meetings around the state, although they cannot design a system for each individual farm. Your local University of Illinois Extension advisor can provide a list of dealers located in and serving Illinois. This list includes the kinds of equipment each dealer sells, but it will not supply information about the characteristics of those systems.

If you contact a number of dealers to discuss your individual needs in relation to the type of equipment they sell, you will be in a better position to determine what equipment to purchase.

Subsurface Irrigation

Subirrigation can offer the advantages of good drainage and irrigation using the same system. During wet periods, the system provides drainage to remove excess water. For irrigation, water is forced back into the drains and then into the soil.

This method is most suitable for land where the slope is less than 2%, with either a relatively high water table or an impermeable layer at 3 to 10 feet below the surface. The impermeable layer ensures that applied water will remain where needed and that a minimum quantity of water will be sufficient to raise the water table.

The free water table should be maintained at 20 to 30 inches below the surface. This level is controlled and maintained at the head control stands, and water is pumped accordingly. In the event of a heavy rainfall, pumps must be turned off quickly and the drains opened. As a general rule, to irrigate during the growing season requires a minimum of 5 gallons per minute per acre.

The soil should be permeable enough to allow rapid water movement so that plants are well supplied in peak consumption periods. Tile spacing is a major factor in the cost of the total system and is perhaps the most important single variable in its design and effectiveness. Where subirrigation is suitable, the optimal system will have closer drain spacings than a traditional drainage system.

Fertigation

The method of irrigation most common in Illinois, the overhead sprinkler, is the one best adapted to applying fertilizer along with water. Fertigation permits nutrients to be applied to the crop as they are needed. Several applications can be made during the growing season with little or no additional application cost. Nitrogen can be applied in periods when the crop has a heavy demand for both nitrogen and water. Corn uses nitrogen and water most rapidly during the 3 weeks before tasseling. About 60% of the nitrogen needs of corn must be met by silking time. Generally, nearly all the nitrogen for the crop should be applied by the time it is pollinating, even though some uptake occurs after this time. Fertilization through irrigation can be a convenient and timely method of supplying part of the plant's nutrient needs.

In Illinois, fertigation appears to be best adapted to sandy areas where irrigation is likely to be needed even in the wettest years. On finer-textured soils with high water-holding capacity, nitrogen might be needed even though water is adequate. Neither irrigating just to supply nitrogen nor allowing the crop to suffer for lack of nitrogen is an attractive alternative. Even on sandy soils, only part of the nitrogen should be applied with irrigation water; preplant and sidedress applications should provide the rest of it.

Other problems associated solely with fertigation include possible lack of uniformity in application, loss of ammonium nitrogen by volatilization in sprinkling, loss of nitrogen and resultant groundwater contamination by leaching if overirrigation occurs, corrosion of equipment, and incompatibility and low solubility of some fertilizer materials.

Irrigation Scheduling

Experienced irrigators have developed their own procedures for scheduling applications, whereas beginners may have to determine timing and rates of application before feeling prepared to do so. Irrigators generally follow one of two basic scheduling methods, each with many variations.

The first method involves measuring soil water and plant stress by taking soil samples at various depths with a soil probe, auger, or shovel and then measuring or estimating the amount of water available to the plant roots; inserting instruments such as tensiometers or electrical resistance blocks into the soil to desired depths and then taking readings at intervals; or measuring or observing some plant characteristics and then relating them to water stress.

Although in theory the crop can utilize 100% of the water that is available, the last portion of that water is not actually as available as the first portion that the crop takes from the soil. Much like with a sponge that is half wrung-out, the water remaining in the soil following 50% depletion is more difficult to remove than the first half.

The 50% depletion figure is often used to schedule irrigation. For example, if a soil holds 3 inches of plant-available water in the root zone, we could allow 1-1/2 inches to be used by the crop before replenishing the soil's water with irrigation.

Management Requirements

Irrigation will provide maximum benefit only when it is integrated into a high-level management program. Good seed or plant starts of proper genetic origin planted at the proper time and at an appropriate population, accompanied by optimal fertilization, good pest control, and other recommended cultural practices, are necessary to ensure the highest benefit from irrigation.

Farmers who invest in irrigation may be disappointed if they do not manage to irrigate properly. Systems are so often overextended that they cannot maintain adequate soil moisture when the crop requires it. For example, a system may be designed to apply 2 inches of water to 100 acres once a week. In two or more successive weeks, soil moisture may be limited, with potential evapotranspiration equaling 2 inches per week. If the system is used on one 100-acre field one week and another field the next week, neither field may receive much benefit. This is especially true if water stress comes at a critical time, such as during pollination of corn or soybean seed development. Inadequate production of marketable products may result.

12

Weed Management

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Numerous plant species are considered weeds in agronomic cropping systems. Weeds have many attributes undesirable to crop producers, not the least being the ability to reduce crop yields through competition for resources such as sunlight, water, nutrients, and space. Weeds also may harbor insects and provide a host for certain plant pathogens. Some weed species, such as wild garlic and eastern black nightshade, can reduce the quality of the harvested crop. Eliminating or reducing the deleterious effects of weeds on agronomic crops is the ultimate goal of weed management. Integrated weed management includes all practices that enhance a crop's competitive ability and decrease weeds' ability to reduce yield.

Successful weed management requires identifying relevant species and understanding their biological characteristics so that management can be tailored to the weeds present in individual fields. Accurate identification is critical: identification of seedling weeds is necessary for selecting an appropriate postemergence herbicide, while identifying mature weeds often indicates which species will populate a particular field the following season. Most weed species in Illinois agronomic cropping systems are either broadleaves or grasses. Broadleaf species are generally easier to differentiate than grasses, especially at early growth stages. Many excellent identification references are available, including the several listed here; one or more should be part of every weed management practitioner's library.

- *Weeds of the North Central States* (B772). Available from the University of Illinois (www.pubsplus.illinois.edu).
- *Weeds of the Great Plains* (ISBN-10: 0939870002; ISBN-13: 978-0939870004). Available from the Nebraska Department of Agriculture, 402-471-2394.
- *Weeds of the Northeast* (ISBN-10: 0801483344; ISBN-13: 978-0801483349). Available from Cornell University Press.

Most weeds of agronomic cropping systems are herbaceous, but a few species that can become established in reduced-tillage fields are woody (such as maple trees). Weeds can be categorized according to their life cycle, or how long they live: *annual*, *biennial*, and *perennial* (**Table 12.1**). Knowledge of life cycles is important to reducing the potential for weeds to produce viable seed or vegetative structures that aid in weed dispersal (**Table 12.2**).

Annual plants complete their life cycle (from seed to seed) in one year; they are sometimes further divided into winter annuals and summer annuals. Summer annual weeds emerge in the spring, grow in spring and summer, then flower and produce seed during late summer or early fall (**Figure 12.1**). These species are the most common weeds that grow in agronomic crops. Summer annual weeds can be controlled by various soil-applied herbicides before they emerge; they are easiest to control with postemergence herbicides when they are small (about 4 inches or less). In general, most weeds become progressively harder to control with herbicides as they become larger.

Winter annual weeds emerge during late summer or fall, overwinter in a vegetative state, then flower and produce seed the following spring (**Figure 12.2**). They are common in fields where no tillage is done after harvest and in fall-seeded small grains and forages. Controlling winter annual weeds with herbicides may be accomplished during late fall or early spring. It is best to control all existing weed vegetation (including winter and summer annuals) before planting corn or soybean in the spring or before fall-seeding small grains or forages.

Biennial plants complete their life cycle over two years. Biennials emerge in the spring or summer, overwinter

Table 12.1. Examples of weed species by life cycle.

Annuals			Perennials	
Winter	**Summer**	**Biennials**	**Simple**	**Spreading**
butterweed common chickweed downy brome field pennycress henbit horseweed little barley prickly lettuce purple deadnettle shepherd's-purse yellow rocket	barnyardgrass burcucumber common cocklebur common lambsquarters common ragweed crabgrass giant foxtail giant ragweed green foxtail jimsonweed kochia shattercane smartweed smooth pigweed tall morningglory velvetleaf waterhemp yellow foxtail	bull thistle common burdock musk thistle poison hemlock teasel wild carrot	common milkweed curly dock dandelion field bindweed hedge bindweed honeyvine milkweed horsenettle pokeweed smooth groundcherry	Canada thistle hemp dogbane Jerusalem artichoke johnsongrass perennial sowthistle quackgrass swamp smartweed trumpetcreeper wirestem muhly yellow nutsedge

Table 12.2. Characteristics of weed life cycles.

Weed type	Duration of life cycle	Overwintering state	Method of reproduction
Annual	1 yr	Seed	Seed
Biennial	2 yr	Rosette	Seed
Perennial	>2 yr	Seed, vegetative propagule	Seed, vegetative propagules

in a vegetative stage (often referred to as a rosette), then resume growth the following spring (**Figure 12.3**). Elongation of the flowering stalk (bolting) and seed production can vary by species; it occurs during the spring, summer, or fall of the second year. Biennial weeds are often best controlled with postemergence herbicides during the rosette stage of growth. Their susceptibility to herbicides generally decreases rapidly after the onset of bolting.

Perennial species live longer than two years—theoretically, indefinitely (**Figure 12.4**). Some species reproduce almost exclusively by seed and are referred to as simple perennials. Other species can reproduce by both seed and various types of vegetative propagules (creeping roots, rhizomes, tubers, etc.). These types of perennials are referred to as creeping, or spreading, perennials.

Perennial weed species often become established in no-till production fields and can cause great frustration with respect to how best to control or eradicate them. Without the option of mechanical weed control (i.e., tillage), perennial weed species are generally best controlled with postemergence translocated herbicides. Which translocated herbicide is used, as well as when the application is made, can impact the success achieved.

Perennial weed species are frequently difficult to control because they store food reserves in their root systems or underground storage structures. Controlling only what is above ground is usually not sufficient for satisfactory, long-term control; what is underground must be controlled as well. Translocated herbicides (those that can move into the roots) are usually the most effective chemical option to control perennial weeds, but when they are applied is very important. In the spring, perennials rely on stored food reserves to initiate new growth, so most of the food at this time of year is moving upward from the roots to support new vegetative development. Because of this upward movement, it's often difficult to get sufficient herbicide into the root when applications are made in early spring.

Better control of perennial broadleaf species can be achieved when postemergence translocated herbicides are applied about the time the plants begin to flower. Another good time to treat perennial weed species is early to mid-fall. As day length shortens and temperatures fall, perennial plant species begin to move food back into their roots, and more translocated herbicide moves to the root as well.

Figure 12.5 depicts a generalized representation of postemergence herbicide effectiveness on annual, biennial, and perennial weeds as influenced by stage of weed growth at application.

Scout agronomic production fields for weeds several times each season. In no-till fields, determine which winter annual or early-emerging summer annual species are present prior to any herbicide application so that herbicide selection and application rates can be optimized for the species present before planting.

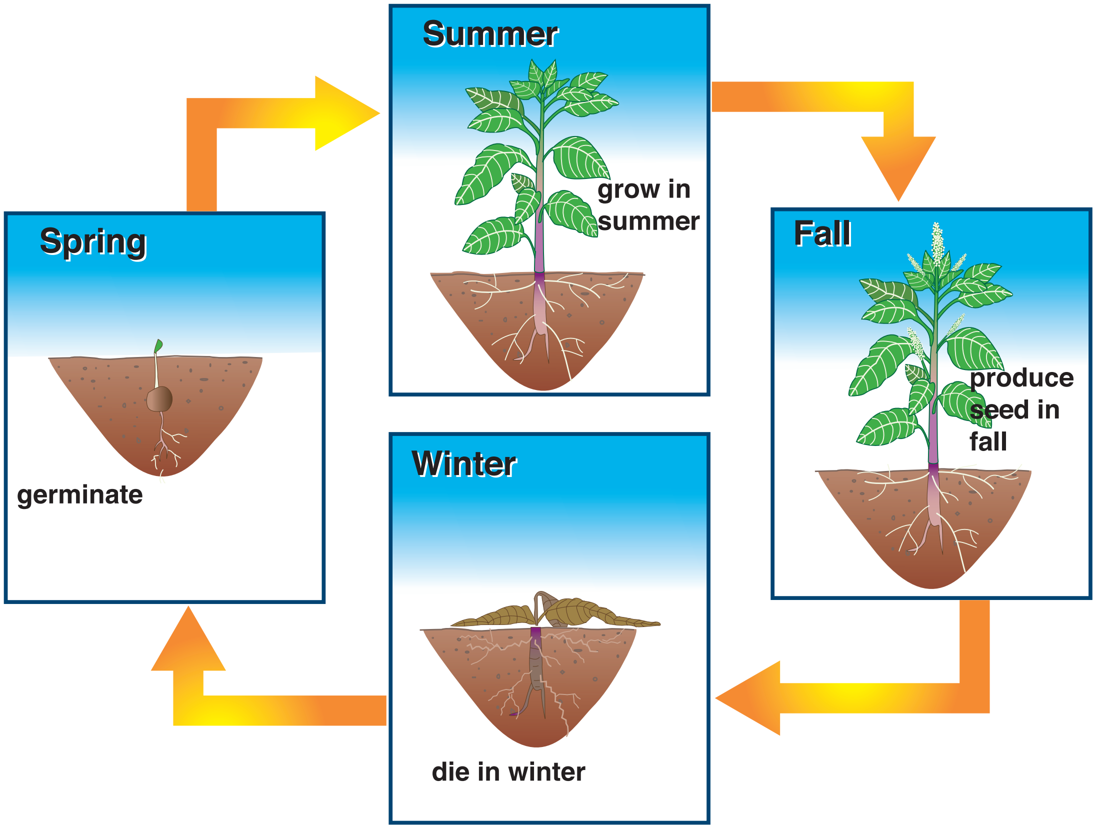

Figure 12.1. Summer annual weed life cycle.

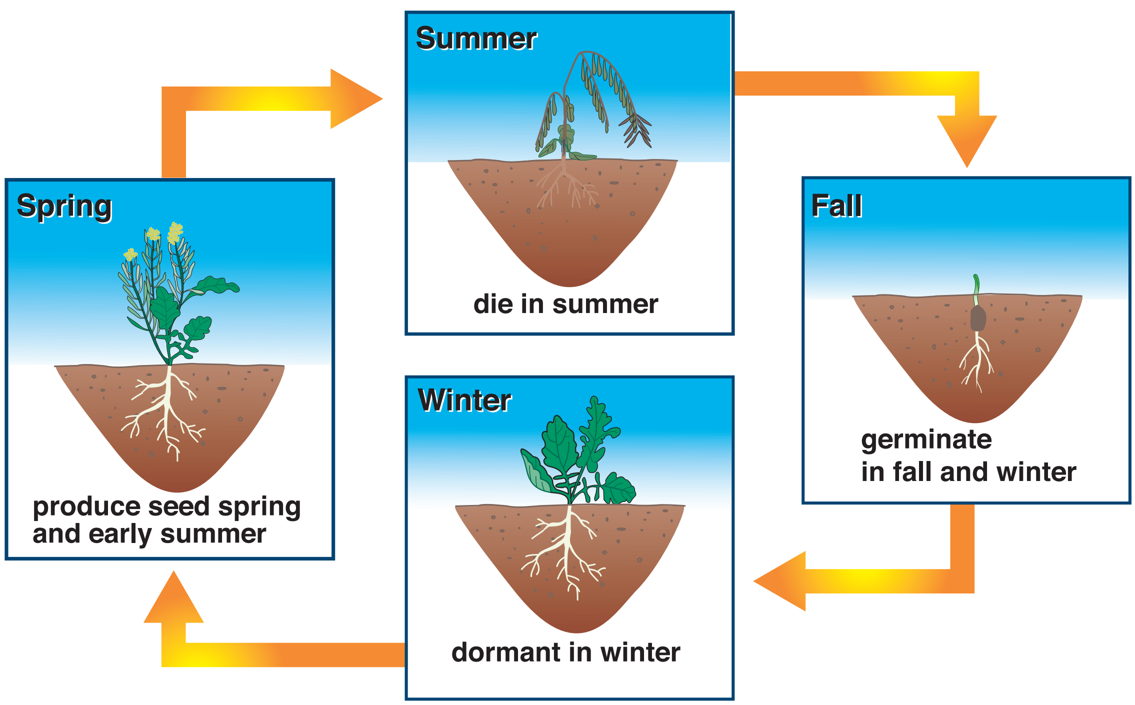

Figure 12.2. Winter annual weed life cycle.

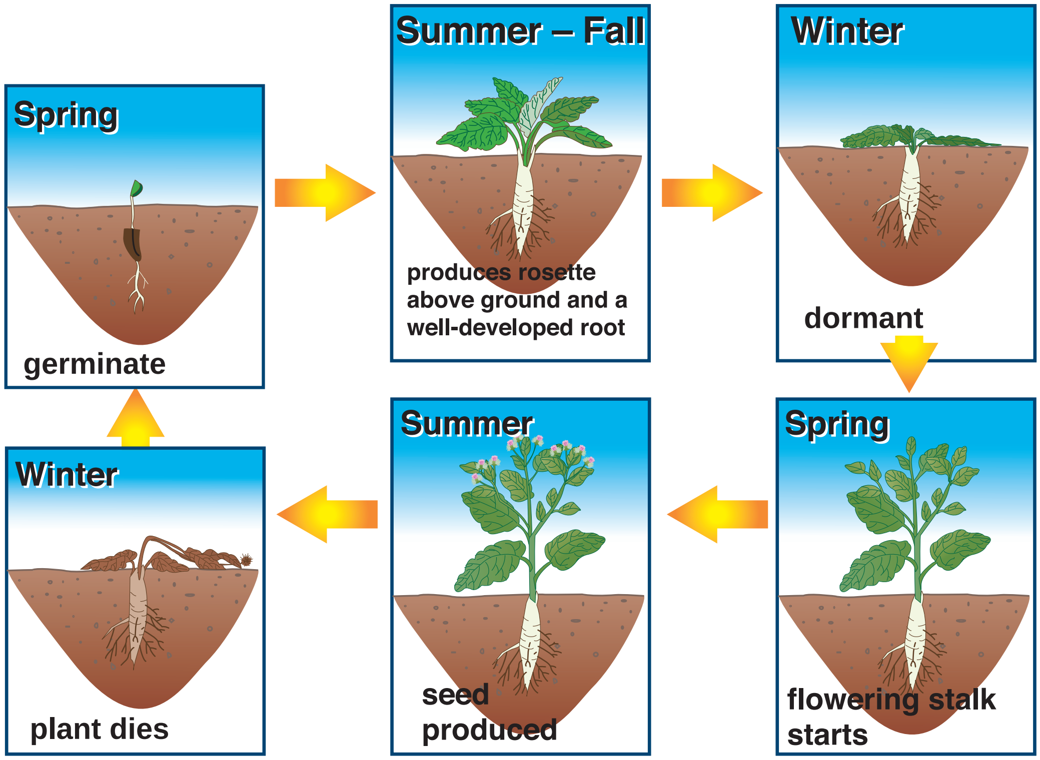

Figure 12.3. Biennial weed life cycle.

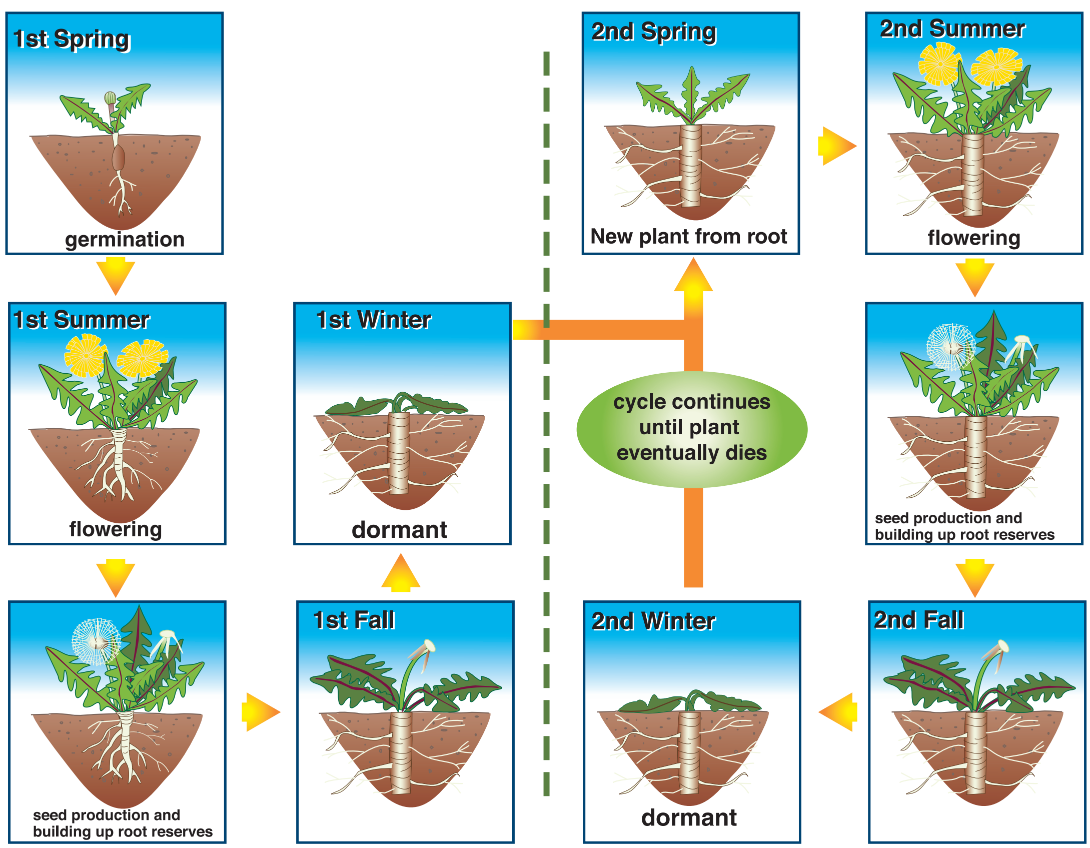

Figure 12.4. Perennial weed life cycle.

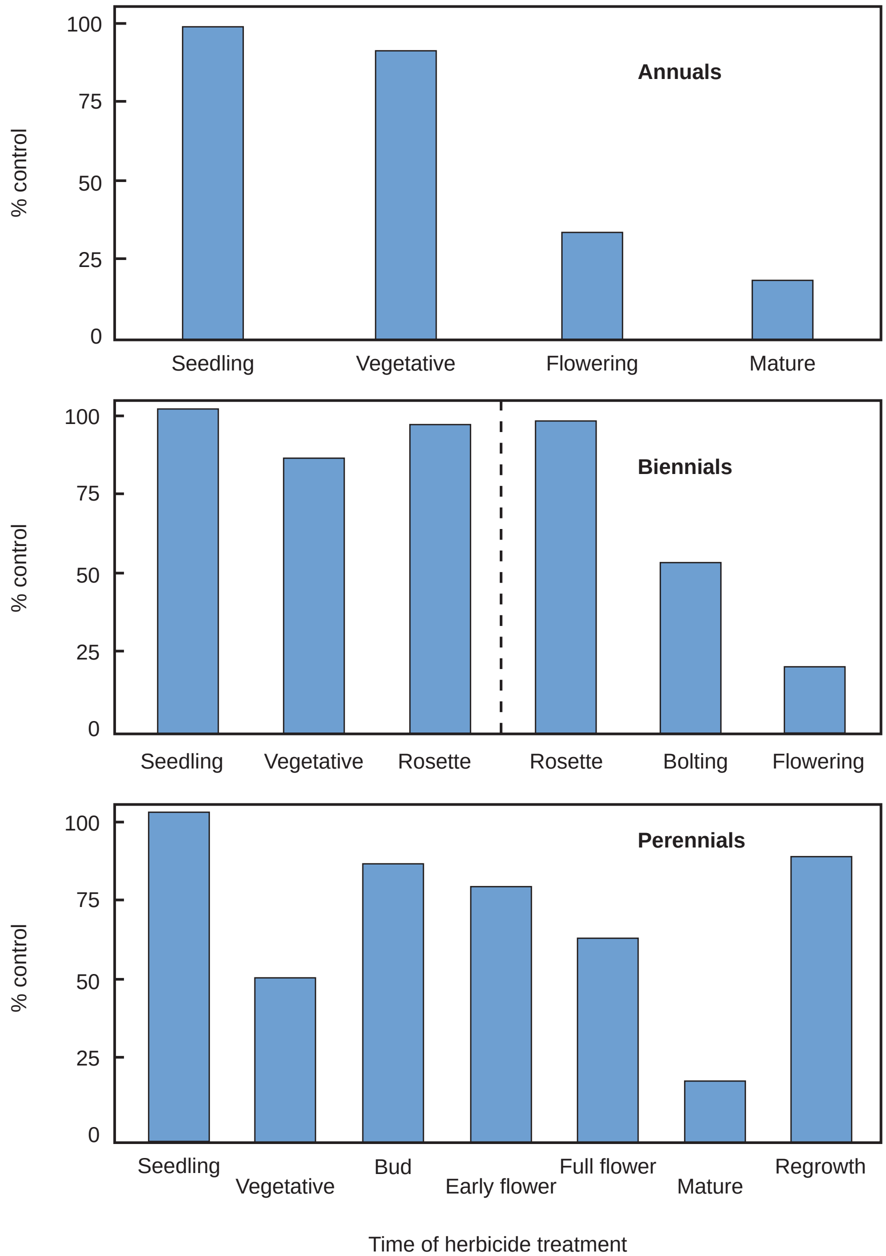

Figure 12.5. Postemergence herbicide effectiveness on annual, biennial, and perennial weeds as influenced by stage of weed growth at the time of application.

Knowing when weed species begin to emerge can vastly improve your management program if you practice timely scouting and subsequent control tactics. Weed emergence can, and often does, vary somewhat from year to year. Weeds such as smartweed and kochia emerge during early spring, while morningglory species can emerge during mid-summer (see **Figure 12.6** for emergence sequences for weed species common in corn and soybean). Some species, such as velvetleaf, tend to have a relatively short period of emergence, whereas others, such as waterhemp, tend to emerge over a relatively long part of the growing season.

Weed Interference*

Weed management strategies attempt to limit the deleterious effects weeds have when growing with crop plants. Most common is competition with the crop for available growth factors (light, water, etc.). Whatever quantities weeds use are unavailable for use by the crop. If weeds can use a sufficient amount of some growth factor, crop yield can be, and often is, adversely impacted.

Currently the most common method of managing weeds is herbicides. Many options are available, each with distinct advantages and disadvantages. There are also several methods by which herbicides can be applied. Whatever the herbicide or method of application, the goal is to prevent weeds from contributing to crop yield loss by reducing the amount of competition exerted by the weeds.

The concept of competition between weeds and crops has received a great deal of recent attention from farmers and herbicide manufacturers alike. A particular point of interest focuses on when competition (from weeds) should be removed so that yields (of corn and soybean primarily) are not adversely impacted. Soil-applied residual herbicides can be used to eliminate any early-season weed competition, but some farmers would rather use only postemergence herbicides to control weeds. Is one method better than another at reducing weed interference? What research is needed to determine how and when competition reduces crop yield? How should results of such research be interpreted?

Those involved in managing weeds have long recognized their harmful effects on crop growth and productivity through competing for light, moisture, nutrients, and space

**Some text in the "Weed Interference" section has been modified from L.M. Wax, 1998, "Factors to Consider When Interpreting Crop-Weed Competition Studies,"* Proceedings of the Illinois Agricultural Pesticides Conference.

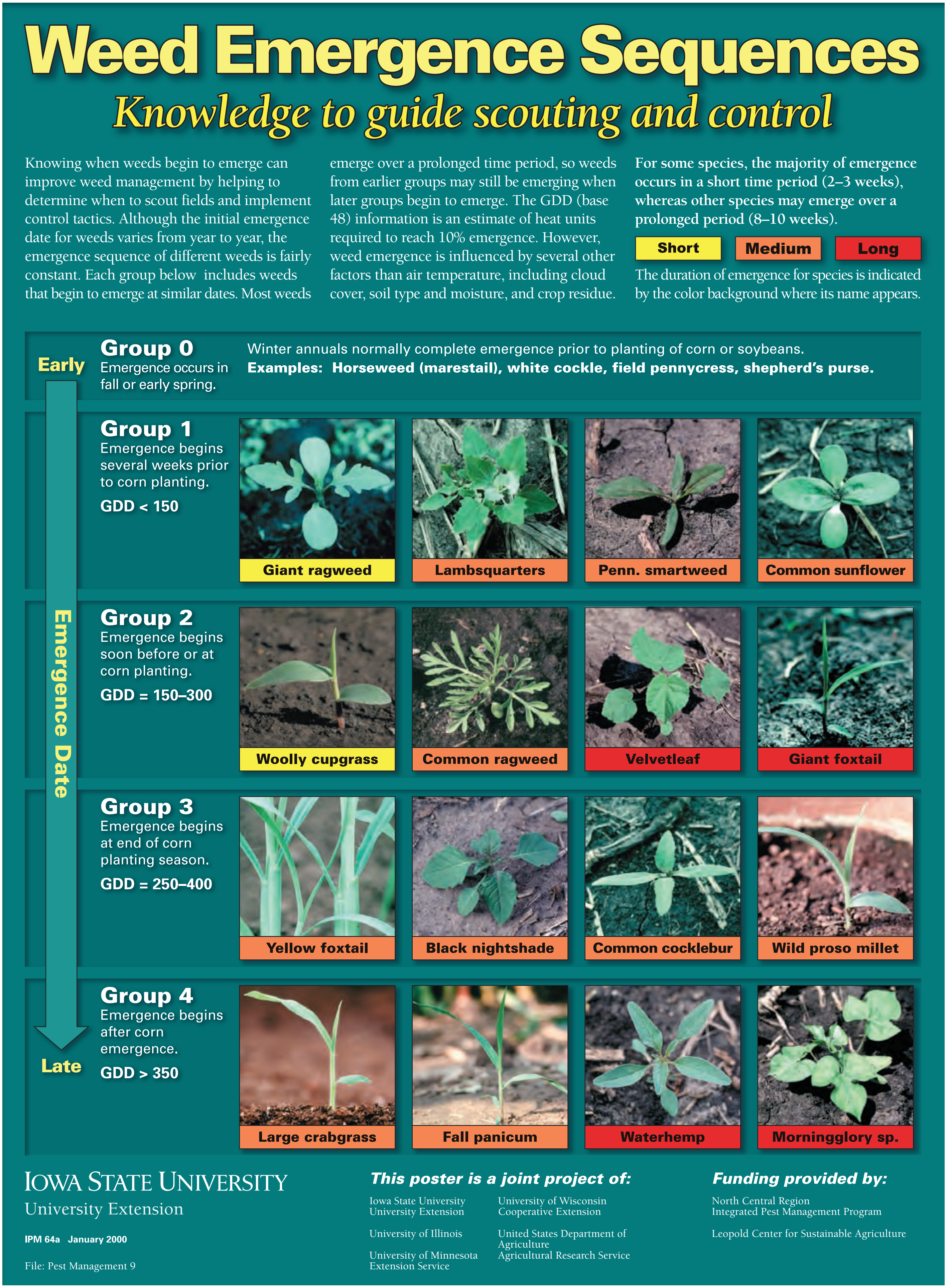

Figure 12.6. Emergence sequences for weed species common in midwestern corn and soybean.

as well as hampering harvest operations, reducing quality of the harvested crop, and producing propagules that lead to future problems. Numerous experiments over the years have compared weed species and density in various crops and assessed the importance of the *duration of competition* and the *time of weed removal*. From those studies, some general guidelines evolved regarding the relative competitiveness of weeds with various crops, the weed-free time needed following crop emergence, and the appropriate time of weed removal with postemergence treatments to preclude loss of crop quantity and quality. However, as tillage, planting, and weed management practices have changed over the years, the once-accurate guidelines regarding crop–weed competition should be revisited, and in some instances modified, as new findings are reported. The following text reviews crop–weed competition research, both past and present, and offers guidelines for interpreting related data.

Cropping and Cultural Practices

Crops vary greatly in their ability to compete with weeds, from providing essentially no competition to competing very aggressively. This text focuses on the major field crops of Illinois, corn and soybean. Early studies, with a variety of weed species, tended to show nearly equal competitive ability of corn and soybean, with some differences. Very tall-growing weeds, if left for the entire season, were sometimes less competitive in corn than in soybeans, mainly because they could overtop soybeans and cause greater losses from shading. Weeds that rarely grew taller than soybeans often caused less yield loss in soybeans than in corn, again due to the excellent shading provided by a healthy stand of soybean.

Crop varieties and hybrids can vary substantially in response to weed competition, with those that canopy earlier and provide more shading being the most competitive. For the most part, this aspect has not been exploited to any great degree, but it is currently being investigated in crops where a limited number of herbicide options exist, such as sweet corn. A number of studies have shown that increasing crop populations within the row, up to a point, can increase the competitive ability of the crop, with no deleterious effect on crop growth or yield.

Row spacing and time of planting can greatly influence a crop's competitive ability. Especially for soybean, narrow row spacings have enhanced the ability to compete with weeds, so that under current production practices, soybean may be more competitive than corn. When planted in wide rows, soybeans and corn are probably more equal in their competitiveness. Time of planting for both corn and soybeans is earlier now than several decades ago, but this does not always enhance competitive ability. Very early planting, combined with reduced or no tillage, allows for greater weed competition as well as for a different suite of weed species to be present than historically has been common. Clearly, weeds that are established at the time of crop emergence begin to compete with the crop earlier than weeds that emerge only after the crop emerges.

With modern production practices and herbicides, do corn and soybeans differ in the ability to compete with weeds? Conclusive evidence is lacking, but many speculate that there is probably not much difference in most instances. However, soybeans, especially when vigorous varieties are grown at high populations in narrow rows, usually have an edge over corn in competitive ability, assuming that complete weed control is achieved with herbicides prior to crop canopy closure and that neither crop will be cultivated.

Weed Variables

Weeds have been able to reproduce, survive, and compete for centuries, at least partly due to their diversity. Species of weeds, and sometimes biotypes within species, can vary greatly in growth habits and ultimately in their ability to compete with crops. Germination patterns differ markedly and sometimes erratically, causing differences in potential for competition, which can vary from year to year. Emergence and growth also vary from slow to even rapid and almost unpredictable. Different species and biotypes appear to respond differentially to various environmental conditions—only some years are a so-called nightshade year or smartweed year or nutsedge year, whereas in most areas of Illinois, every year is a foxtail or velvetleaf year. Most recent years could be described as lambsquarters and pigweed years, and few could dispute the increased prevalence of waterhemp years recently across much of the state.

Obviously, as demonstrated in many competition studies, weeds produce markedly differing amounts of growth per individual plant and reach widely varying heights. These studies have allowed the development of relative competitive indices that can be somewhat helpful in determining the severity of problems presented by stands of various weed species. For example, it obviously requires more foxtail plants than cocklebur or giant ragweed plants to produce the same degree of competition with corn or soybean.

The density or population of weeds required to cause a consistent yield reduction in crops has been difficult to establish. Many research studies have addressed this issue and helped establish some of the thresholds and guidelines currently available. In general, corn and soybeans can withstand low populations of weeds throughout the season without suffering yield or harvest losses; losses tend to

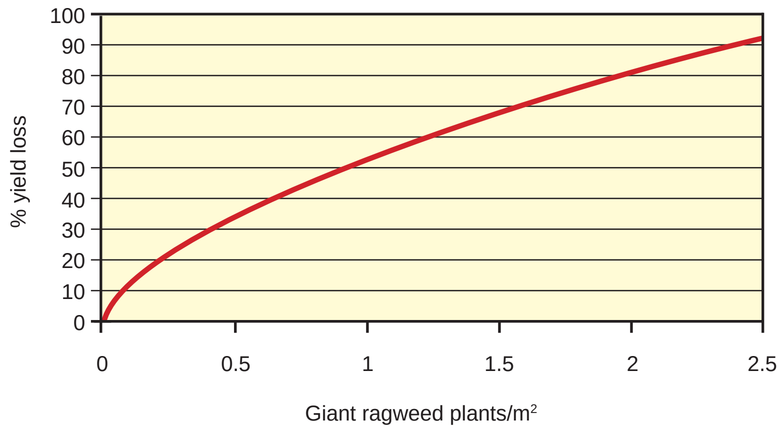

Figure 12.7. The impact of giant ragweed density on soybean yield.

increase linearly with increases in weed population up to some population level above which further yield reductions tend to subside (see **Figure 12.7** for an illustration of the impact of giant ragweed density on soybean yield).

Establishing consistent thresholds or numbers of weeds that cause a specific yield reduction is difficult across many locations, years, and weather patterns. A synthesis of competition experiments conducted across several states and over many years suggests that improved techniques may be needed to establish and refine thresholds, since variation across locations and years almost always occurs and can be considerable. This should not be surprising, and it is most likely due to differences in environmental conditions, with special emphasis on weather patterns. General threshold guidelines would be possible, as long as a range of likely responses is given, and could cover a majority of situations.

Lessons from Research

Numerous experiments over the years have attempted to define the critical duration of weed competition in corn and soybean and to determine the optimal time to implement weed management practices. One type of experiment is designed to determine the early-season weed-free interval needed before the crop can effectively compete with later emerging weeds and then progress independently for the remainder of the season, with no crop quantity, quality, or harvesting losses. Such experiments are especially useful in determining how much time a soil-applied herbicide needs in order to be effective after planting.

In general, for many of the weed species encountered in corn and soybean production systems of the northern U.S., the interval ranges from 3 to 6 weeks, with 4 to 5 weeks being the most frequent range needed. It is important to note that some of these studies initiated the interval at planting, while others began at crop emergence (a potentially significant difference, depending on the season and the weather). Most studies were conducted with healthy crop stands in 30- to 40-inch rows, with the objective being to obtain 4 to 5 weeks without weed competition, after which the weeds were kept under control by crop shading and one or more "lay-by" cultivations. In sharp contrast, cultivators are not used today nearly as much as they once were, and weed management after crop emergence is administered in the form of postemergence herbicides if soil-applied treatments do not last sufficiently long.

It is also important to note that these rules of thumb were developed with good crop stands and, for the most part, with the most common row crop weeds, most of which tend to emerge fairly uniformly, not in multiple flushes well into the season. As mentioned here and again later, a review of available data indicates that in most studies, there has been considerable variation from year to year, probably due to differing environmental conditions, so *it is very difficult, if not impossible, to set a specific weed-free interval that is acceptable with all species and across all locations and years.*

Another factor to consider is that many of these studies were conducted either by seeding unimbibed weed seeds at various times after crop planting or by removing natural weed populations as needed for a specified period. These two methods effect different results, and how these results compare with a herbicide treatment that lasts the same amount of time is not defined. Does a lower dosage of a herbicide still cause some growth inhibition of later emerging weeds? These and other unanswered questions suggest extreme caution about pronouncing exact periods that are to apply over a wide variety of conditions.

Another type of experiment is designed to determine how long weeds can remain in the crop and eventually be removed with no resultant deleterious effects on quantity and quality of crop yield. In previous years this was important so that producers would know how early one needed to cultivate between the rows, as many older herbicides were applied only in a band over the row. With the growing prevalence of broadcast, selective postemergence herbicides, these types of studies became relatively more important for providing guidelines in timing postemergence herbicide applications. Until fairly recently, such competition studies were often conducted by growing various populations of weeds from crop and weed emergence until the weeds were removed either mechanically or by hand. The weeds were removed at some time after either crop planting or emergence or until certain weed heights or stages. As a general guideline, many of these studies tended to show that a moderate population of weeds could remain growing with the crop for up 3 to 6 weeks after planting, and once removed, cause little or no crop yield loss. These types of experiments also have considerable variation in results, so again *it is difficult to set specific intervals that will be valid over widely diverse conditions.*

In assessing these experiments, one needs to consider the weed species involved and their respective populations. In general, denser weed populations should be removed earlier, while less dense populations can be left to compete longer. From an applied standpoint, a problem with many competition studies is that only one weed species is considered, whereas producers' fields often contain a number of species with varying populations. Experience would suggest that more emphasis should be placed on total weed biomass present at crop flowering and fruiting as the best indicator of loss likely to result from competition. However, this is generally well past the stage when control is possible or even feasible, and herbicides undoubtedly should be applied before this stage in most instances. *To reiterate, these types of studies are influenced greatly by the environment, which makes establishing concrete intervals arduous.*

The results of these experiments should also be closely examined with respect to how the competition (weeds) was removed. Some removed the weeds by hand but allowed any weeds that emerged afterward to grow, while others were hand-weeded throughout the season to simulate season-long control. Modern-day studies tend to focus on controlling either single species or a mixture growing at whatever population is present in the field, by applying selective postemergence herbicides at various weed sizes or growth stages. In interpreting the results of these studies, it is important to note whether the herbicide(s) used possessed any soil bioactivity that may have provided some control of weeds emerging following application. Additionally, the population and mixture of weeds are important to note. And of special importance is to note whether the weeds were actually controlled completely or not. This is important since any yield reduction noted and attributed to pre-application competition stress might actually have been partially due to post-application stress from weeds that were not controlled or from weeds that emerged after application.

Invariably, these experiments lead to a range of intervals for weed removal that work effectively under various conditions. Recommendations often tend to suggest removing competition at the average or even slightly earlier time because potentially adverse conditions might cause delays in herbicide application, resulting in weeds that would be very difficult to control. This may become especially important when dealing with weed species where later emergence might be a problem with herbicides that lack soil residual activity. Under this scenario, the conservative approach might involve adding a herbicide with soil residual activity to the mixture. As will be noted in the next section, *environmental conditions can cause significant variation in the results of these types of experiments.*

More than any other factors, soil and air temperature and soil moisture and rainfall before, during, and after initiation of competition experiments probably contribute most to the variation in results. Even the best-planned and best-conducted studies can vary considerably from location to location and year to year, often because of environmental conditions. These conditions affect weed emergence and growth, herbicide effectiveness, the competitive interaction between crop and weed, and the ability of the crop to recover from early weed competition once the weeds have been removed. *Primarily because of environmental conditions, one should be very cautious in setting precise guidelines for crop/weed competition, including thresholds for density, duration of weed-free intervals, and times of competition removal*. It would seem prudent to establish ranges of densities, times, and the like and/or to operate on the conservative side in these matters.

The total effect of weeds on crop plants is more correctly termed *interference*, which is the total of competition plus allelopathy. Allelopathy (the suppression of plant growth due to release of natural plant-derived substances) can and has been demonstrated, but with most of the soils and cropping situations in the Corn Belt, it is thought to be relatively minor and is very difficult to demonstrate. Thus this discussion has focused primarily on weed competition, which many consider significantly more important because it deals with plants competing for light, moisture, nutrients, and perhaps space. However, in dense infestations of weeds (such as grasses in corn), allelopathy could be a contributing factor to yield loss in addition to competition.

Competition for light may be one of the most important factors in reducing yields, especially with weeds that grow taller than the crop. Moisture stress, especially during and after removal of a very dense population of weeds, may be extremely important in how well the crop is able to recover. Many do not consider nutrient stress to be as important in the rich, fertile soils across much of the Corn Belt, but in coarse-textured soils and soils with low fertility, it may be more significant. Some research has demonstrated that weeds can exhibit "luxury consumption" of certain nutrients, such as nitrogen, to the detriment of the crop.

Those involved with developing weed management systems need to remember that the whole subject of crop–weed competition, while seemingly not simple, is even more complex in the marketplace. The fact that weed management decisions are made not only based on true crop–weed competition but on other factors as well is widely recognized. Yield and quality loss are not the only issues being considered by decision makers. Harvest difficulties and additions of weed seed to the soil seedbank are genuine concerns often not addressed in traditional competition research. Esthetic thresholds, as related to landowner perceptions, often necessitate weed control at much higher levels than what is required based simply on yield losses. Product guarantees and respray programs have also contributed to extraordinarily high levels of weed management expectations.

In summary. Numerous experiments have investigated crop–weed competition from a variety of aspects. The results of these studies can be helpful to those making decisions about weed management, as guidelines can be prepared that indicate in general the relative competitive ability of various weeds at various densities in the major crops of the Midwest. These experiments also provide guidance for the duration of weed-free conditions needed after crop emergence and for when weeds should be removed with postemergence herbicides. Other concerns, such as producer, neighbor, and landlord perceptions, may be as important as yield loss indications from crop–weed competition studies in determining the types of weed management systems implemented.

Weed Management Practices

Effective weed management practices include those that reduce the potential for weeds to adversely impact crop growth and yield. These practices often allow the crop to utilize all available resources necessary to achieve its yield potential. Weeds require many of the same resources for growth as crop plants, and any resource utilized by the weed is unavailable for use by the crop. The most common weed management practices in Illinois agronomic crops include cultural, mechanical, and chemical approaches.

Cultural weed management practices allow the crop to become established without experiencing any negative effects of weed interference. Proper crop variety selection and planting date, adequate soil fertility and pH, and crop row spacing are examples of factors that can be manipulated to improve the competitive ability of the crop.

Mechanical weed management involves physical disturbance of the weeds, through activities including pulling weeds, tilling the soil before or after weeds emerge, and mowing.

Chemical Weed Control

Herbicides are often the primary tools of choice for weed management across most acres of the Midwest. Many different herbicides and herbicide formulations are commercially available, including soil-applied and foliar-applied products, selective and nonselective products, products with long soil persistence, and products with no soil residual activity. The selection of which herbicide to use should be based on multiple factors, including soils, cropping rotations, tillage practices, and weed species. Sole dependence on herbicides may not necessarily provide the most economical or sustainable weed management. Integrating multiple practices reduces the likelihood of poor weed control due to unfavorable environmental conditions and reduces the intensity of selection for herbicide-resistant weeds.

Product Labels

Every herbicide product commercially available is required by law to have a label. The label provides a great deal of information about the product, including how it is to be applied, where, and in what quantity. The label is considered a legal document; using a herbicide in a manner inconsistent with its labeling is illegal. Herbicide labels change frequently, so be sure to consult the most current label when using a product. All pesticide products for sale in Illinois must be registered with the state government.

Application Rates

Herbicides applied at labeled rates should provide good weed control during the season of use while minimizing the potential for in-season crop injury and carryover into the following season. Herbicide application rates can vary according to many factors. Rates for soil-applied herbicides are greatly influenced by soil characteristics, such as organic matter content, texture, and pH. In general, heavy-textured soils high in organic matter often require a higher application rate than course-textured soils lower in organic matter. Application rates of postemergence herbicides are often determined by weed species and weed and crop size. For some postemergence products, higher application rates are suggested when certain weed species are present and/or when one or more weed species exceed a specified height or number of leaves.

Often several different commercially available formulations or premixes contain the same herbicide active ingredient. Much of the following text will demonstrate how to determine product equivalents and how to calculate amounts of active ingredient applied. Keep in mind that just because two or more products contain the same ingredient(s) does not necessarily mean they are applied at the same rates. *Always consult the respective product label to determine the appropriate application rate.*

Nomenclature

Across its lifetime a herbicide active ingredient may be sold by one or more companies and identified by one or more names. The three most common categories of names are trade, common, and chemical.

Trade names. The trade name is the name under which a product is commercially sold; it is often the name most familiar to users. Examples of trade names include Valor, Raptor, Yukon, Basagran, and Cobra. These names are typically trademarked by the manufacturer so that no other company can use them. Trade names come and go, and sometimes they are recycled (for example, Option was once the trade name of a soybean herbicide but is now the trade name of a corn herbicide). You thus cannot always rely on the trade name to know what active ingredient(s) a product contains.

Common names. Each common name is unique to a particular active ingredient. Common names are listed on the product label, usually in the active ingredient section. Flumioxazin, imazamox, halosulfuron plus dicamba, bentazon, and lactofen are the common names of the active ingredients contained in the commercial products Valor, Raptor, Yukon, Basagran, and Cobra, respectively. While more than one trade name may be used for a particular active ingredient, common names remain constant irrespective of trade names.

Chemical names. Herbicide chemical names may not be as familiar as trade names or common names. Like common names, a chemical name is unique to a particular active ingredient, describing its chemical composition. For example, Salvo is the trade name of a herbicide with the active ingredient known by the common name 2,4-D, whose chemical name in turn is 2,4-dichlorophenoxyacetic acid.

Active Ingredients

The active ingredient of a pesticide formulation is the component responsible for its toxicity (phytotoxicity in the case of herbicides) or its ability to control the target pest. The active ingredient is always identified on the pesticide label, either by common name (for example, atrazine) or chemical name (for example, 2,4-dichlorphenoxyacetic acid). The active ingredient statement may also include information about how the product is formulated and the amount of active ingredient contained in a gallon or pound of formulated product. For example, the Basagran label indicates that the active ingredient (bentazon) is formulated as the sodium salt, and 1 gallon of Basagran contains 4 pounds active ingredient.

Usually when a herbicide trade name is followed by a number and letter designation (4L, 75DF, 7EC, etc.), the number indicates the pounds of active ingredient in a gallon (for liquid formulations) or a pound (for dry formulations) of the formulated product. So, for example, Basagran 4L contains 4 pounds of active ingredient (bentazon) per gallon of formulated product, AAtrex 90DF contains 0.90 pounds of active ingredient (atrazine) per pound of formulated product, and Prowl 3.3EC contains 3.3 pounds of active ingredient (pendimethalin) per gallon of formulated product.

Many herbicide labels restrict the maximum amount of product to be used per application and/or per year. These maximum rates are generally presented in terms of the total amount of active ingredient that can be applied per acre and/or per year. Several calculations can be used to determine the amount of active ingredient applied at a given product use rate. This is one of the easiest:

$$\frac{\textit{lb active ingredient}}{\textit{applied per acre}} = \frac{\textit{gal or lb of product applied}}{\textit{acre}} \times \frac{\textit{lb active ingredient}}{\textit{gal or lb of product}}$$

So if we apply this equation to Basagran 4L, the amount of active ingredient (bentazon) applied at 2 pints (0.25 gallon) per acre of product is:

$$\frac{\textit{lb of bentazon (active ingredient)}}{\textit{applied per acre}} = \frac{0.25\ \textit{gal of product applied}}{\textit{acre}} \times \frac{4\ \textit{lb active ingredient}}{\textit{gal of product}} = \frac{1\ \textit{lb active ingredient}}{\textit{per acre}}$$

Types of Formulation

There are several ways to define formulation, but in essence it consists of the active ingredient and all associated components that make up the commercially available product. The active ingredient is responsible for controlling target weeds, but it rarely is the only component in a gallon or a pound of commercial herbicide. Other ingredients serve various functions, such as making the active ingredient safer and easier to handle, allowing the active ingredient to easily mix with water, and aiding herbicide uptake through plant leaves. These other components of a herbicide formulation are generally listed as inert ingredients on the product label, although they have important functions in making the active ingredient work as intended.

Several types of herbicide formulations are available, and a given herbicide active ingredient may be available in more than one formulation. Formulations are often des-

Table 12.3. Common examples of herbicide formulations.

Type of formulation	Description of formulation
Flowable or aqueous suspension (F, L, or AS)	Liquid formulation containing finely ground solids suspended in a liquid
Water-soluble concentrate	Liquid formulations that form a true solution when added to water
Emulsifiable concentrate (EC or E)	Liquid formulation containing solvents and emulsifiers that disperse the active ingredient in water
Water-dispersible granule or dispersible granule (WDG or DG)	Dry formulation in which the active ingredient is sorbed onto aggregated granular particles
Dry flowable (DF)	Dry formulation very similar to water-dispersible granules
Wettable powder (WP or W)	A finely ground dry formulation (often mineral clays) onto which the active ingredient is sorbed
Granule (G)	Dry formulation in which the active ingredient is coated onto an inert granule, ready to use without diluting in a liquid carrier

ignated on product labels as single or two-letter abbreviations. The more common herbicide formulations, along with their abbreviations, are presented in **Table 12.3**.

Acid equivalents. In some instances, the number preceding the formulation designation (L, EC, DF, etc.) indicates not pounds of active ingredient per gallon or pound, but rather acid equivalent per gallon or pound. Acid equivalent may be defined as that portion of a formulation (as in the case of 2,4-D ester, for example) that theoretically could be converted back to the corresponding or parent acid. Another definition is the theoretical yield of parent acid from a pesticide active ingredient that has been formulated as a derivative (esters, salts, and amines are examples of derivatives). For example, the acid equivalents of the isooctyl and ethyl acetate ester formulations of 2,4-D are 66% and 88%, respectively. Why would a herbicide (one that has the acid as the parent molecule) be formulated as a derivative of the parent acid? An illustration using 2,4-D follows.

The herbicide active ingredient 2,4-D, originally discovered in the 1940s, continues to show utility across a diversity of landscapes. The herbicide is a popular tool among homeowners for selectively controlling certain broadleaf weed species in turf, and it is frequently a component of burndown herbicide applications in no-till agronomic cropping situations. Many commercially available 2,4-D formulations and trade names exist, but not all formulations and products are identical.

One characteristic of 2,4-D-containing products of particular importance is the type of formulation. Most often, 2,4-D products are available as one of three formulations: acid, amine, or ester. Each type has unique characteristics that can influence where and how a particular product is used.

Figure 12.8 illustrates the chemical structure of 2,4-D. The molecule is considered a weak acid because the carboxyl hydrogen atom (the one to the far right) can dissociate, imparting a net negative charge to the molecule. In the dissociated (negatively charged) form, the acid molecule is very soluble in water but is not readily absorbed through a plant leaf. The waxy cuticle that covers the leaf surface is composed of many noncharged substances that reduce the ability of a charged molecule to penetrate and enter the plant. Somehow altering the parent acid form can influence how quickly and thoroughly it enters a plant through the leaf. These alterations produce derivatives that have physical and chemical properties different from the parent acid, such as increased ability to penetrate through a waxy leaf or increased water solubility for enhanced root uptake. The two most common derivatives of 2,4-D acid are amines and esters.

Esters are formed by reacting the parent acid with an alcohol, while amine salts are formed when the parent acid is reacted with an amine. The isooctyl ester is a very common ester formulation of 2,4-D, and the ammonium salt is perhaps the most common amine formulation. Other esters and amine salt formulations, however, are commercially available.

As previously mentioned, these different types of derivatives impart different characteristics to the formulation. For example, the isooctyl ester formulation is more soluble in hydrophobic ("water-avoiding") substances, like waxes, while amines are more soluble in hydrophilic ("water-loving") substances. In practical terms, esters are better able than amines to penetrate the waxy leaf surface of weeds, whereas amines are more easily moved into the soil by rainfall for root uptake (an important characteristic in certain brush-control applications).

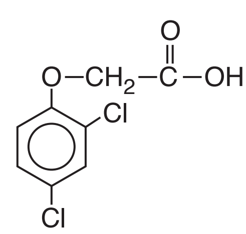

Figure 12.8. 2,4 D parent acid.

Table 12.4 provides some general comparisons between the amine and ester formulations of 2,4-D. These comparisons are somewhat relative since the specific type of amine salt or ester chain length can influence some characteristics. For example, ester formulations are considered more volatile (the change from a liquid state to a vapor state) than amine formulations, but the actual volatility potential of the ester formulation is influenced by the length of the ester chain (the number of carbon atoms). Also remember that different derivatives can impact the amount of active ingredient contained in a quantity of formulated product. To accurately compare among various products, calculations of "equivalency" should be based on the amount of acid equivalent contained in the formulation rather than the amount of active ingredient. An example follows of how to calculate acid equivalents, using ester formulations of 2,4-D as examples.

2,4-D can be formulated as various esters. The chain length of the ester can vary, but it is most commonly eight carbon atoms long (isooctyl ester). For this example, consider two ester formulations of 2,4-D: the first has only two carbon atoms forming the ester, and the second has eight carbons forming the ester. The parent acid is the same in these two formulations; the only difference is the length of the ester. These can be visualized in several diagrams.

Figure 12.8 illustrates the parent acid of 2,4-D; **Figure 12.9** shows the parent acid formulated with a two-carbon side chain, and **Figure 12.10** shows an eight-carbon side chain. While the carbon atoms of the side chain may modify some aspect of herbicide performance, it is the parent acid (**Figure 12.8**) that acts at the target site within the plant. The additional carbon atoms of the ester side chain add weight to the formulation and may increase the amount of active ingredient of a formulation, but these atoms do not increase the amount of parent acid in the formulation. If these formulations were commercially available, and someone wanted to know how much of the parent acid each contained, the calculation would be based on the acid equivalents, not the active ingredients, of the formulations.

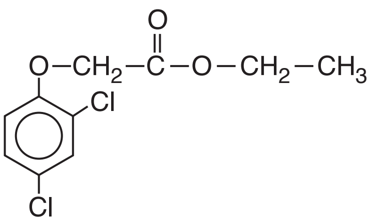

Figure 12.9. 2,4-D ethyl acetate ester.

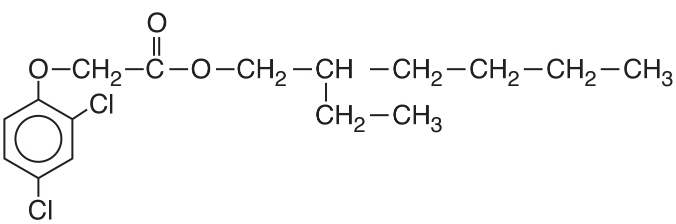

Figure 12.10. Isooctyl ester of 2,4 D.

Assume that both the two-carbon and eight-carbon ester formulations (**Figures 12.9 and 12.10**, respectively) are commercially available and that each formulation contains 4 pounds of *active ingredient* per gallon. The application rate for both products is 1 pint per acre. Since the application rates and the pounds of active ingredient per gallon are identical for the two formulations, the amount of active ingredient applied would be the same for each. Verify this by performing the calculations previously illustrated for determining the amount of active ingredient applied. Even though the amounts of active ingredient applied are the same for the two formulations, the amounts of *acid* applied are *not* the same. Remember, it is the parent acid that binds to the target site to control the weed; the ester portion of the formulation is not involved in binding to the target site. What, then, is required to determine the amount of acid applied (i.e., the acid equivalent)?

The first step is to determine the amount of acid equivalent in a gallon of formulated product. Some labels indicate the amounts of both active ingredient and acid equivalent in a formulation, while others list only active ingredient. If the pounds acid

Table 12.4. Comparisons between amine and ester formulations of 2,4-D.

Amine salt	Ester
High water solubility	Generally insoluble in water
Low solubility in oils and waxes	Higher solubility in oils and waxes
Slow absorption into plant leaves	Faster absorption into plant leaves
No or very low volatility potential	Low to high volatility potential
Clear or slightly amber colored in water	Milky when mixed in water
Does not mix well with liquid fertilizers	More compatible with liquid fertilizers
Less preferred formulation for no-till burndown applications	Preferred formulation for no-till burndown applications
Reduced probability of crop injury following postemergence application	Greater probability of crop injury following postemergence application
Preferred formulation for in-crop (i.e., corn) applications when air temperatures exceed 85 °F	Less preferred formulation for in-crop (i.e., corn) applications when air temperatures exceed 85 °F

equivalent is specified on the product label, all one need do to determine the pounds acid equivalent applied per acre is to substitute pounds acid equivalent for pounds active ingredient in the equation presented previously for calculating the pounds active ingredient applied. For this example, assume that neither 2,4-D label indicates the amount of acid equivalent.

The formula that can be used to calculate the amount of acid equivalent in a gallon of formulated product is:

$$\textit{acid equivalent} = \frac{\textit{molecular weight of the acid} - 1}{\textit{molecular weight of the salt or ester}} \times 100$$

Some molecular weights (i.e., how much the molecule weighs) are needed to complete these calculations. The molecular weight of the parent 2,4-D acid is 221.04. The molecular weight of the two-carbon ester formulation is 29.02 (weight of the two carbons and five hydrogens) + 221.04 (weight of the parent acid) = 250.06. The molecular weight of the eight-carbon ester formulation is 333.25.

The acid equivalent of the **two-carbon** ester formulation is:

$$\textit{acid equivalent} = \frac{221.04 - 1}{250.06} \times 100 = 88\%$$

Thus, the amount of *acid equivalent* in one gallon of formulated product is:

$$88\% \textit{ acid equivalent} \times \frac{4 \textit{ lb active ingredient}}{\textit{gal}} = 3.52 \textit{ lb ae}$$

The acid equivalent of the **eight-carbon** ester formulation is:

$$\textit{acid equivalent} = \frac{221.04 - 1}{333.25} \times 100 = 66\%$$

Thus, the amount of *acid equivalent* in 1 gallon of formulated product is:

$$66\% \textit{ acid equivalent} \times \frac{4 \textit{ lb active ingredient}}{\textit{gal}} = 2.64 \textit{ lb ae}$$

Again, each product is applied at 1 pint (0.125 gallon) per acre, and because each formulation contains 4 pounds active ingredient per gallon, the amounts of *active ingredient* applied are equal. The amounts of *acid* (that part of the formulation that actually controls the weed) applied for each formulation are *not* equal.

The amount of *acid* applied per acre with the **two-carbon** ester formulation is:

$$\begin{array}{c}\textit{lb of acid equivalent}\\ \textit{applied per acre}\end{array} = \frac{0.125 \textit{ gal of product applied}}{\textit{acre}} \times \frac{3.52 \textit{ lb ae}}{\textit{gal of product}} = \begin{array}{c}0.44 \textit{ lb ae}\\ \textit{per acre}\end{array}$$

The amount of *acid* applied per acre with the **eight-carbon** formulation is:

$$\begin{array}{c}\textit{lb of acid equivalent}\\ \textit{applied per acre}\end{array} = \frac{0.125 \textit{ gal of product applied}}{\textit{acre}} \times \frac{2.64 \textit{ lb ae}}{\textit{gal of product}} = \begin{array}{c}0.33 \textit{ lb ae}\\ \textit{per acre}\end{array}$$

This example demonstrates that more 2,4-D *acid* is applied with the two-carbon ester formulation than with the eight-carbon formulation. In practical terms, more of the part of the formulation that actually controls the weeds was applied with the two-carbon ester formulation. To compare the herbicidally active portion of two ester, salt, or amine formulations, product equivalents should be calculated on the *acid equivalent.*

If only one formulation of a salt or ester product is commercially available, it wouldn't really matter if one calculated active ingredient or acid equivalent. For example, Pursuit is formulated as the ammonium salt of imazethapyr, but currently this is the only salt formulation commercially available for use in agronomic crops. There are, however, several commercial formulations of 2,4-D and glyphosate. Not all of these formulations contain the same amount of *acid equivalent*, so to determine equivalent rates among different formulations, calculations should be based on acid equivalent rather than active ingredient.

Since the commercialization of glyphosate-resistant soybean varieties in 1996, the number of glyphosate-containing products commercially available has increased dramatically. Currently, more than 50 such products are registered for use in Illinois agronomic crops, and that number is expected to continue increasing. Keeping track of product names and formulations can be daunting.

When selecting one of these products for weed control, keep several important considerations in mind: How much acid equivalent (ae) does the formulation contain? Should a spray additive (such as nonionic surfactant) be added to the tank, or does the formulation contain a "built-in" additive system? Are factors such as rain-free interval and toxicity category similar in the products you are considering? Once these questions have been answered and you have narrowed down the list of products you're interested in purchasing, how can you compare costs? Should price comparisons be based simply on cost per gallon of formulated product? As in determining equivalent application rates, producers should compare prices on an acid equivalent basis.

To compare prices among glyphosate-containing products you need to do a few simple calculations. First, determine what rate to apply based on weed spectrum and size. For well-timed applications, a rate of 0.75 lb ae/acre can be very effective on many broadleaf and grass species. Once you have determined the application rate, calculate how many fluid ounces of each product are needed for this rate. Next, convert the price per gallon for each product to price per fluid ounce. Finally, multiply the number of fluid ounces needed to achieve the 0.75 lb ae/acre rate for each product by the cost per fluid ounce. An example to illustrate these calculations follows.

You decide to apply a glyphosate-containing product at 0.75 lb ae/acre when most broadleaf weeds are 4 to 6 inches tall. You are deciding between two glyphosate-containing products and want to know which offers the lowest cost per acre (for purposes of this example, assume additive requirements, if any are required by label, are identical for each product). "Glyfo A," a potassium salt, contains 4 lb ae per gallon and costs $23 a gallon. "Glyfo B," an isopropylamine salt, contains 3 lb ae per gallon and costs $21.75 a gallon.

Start by calculating how many fluid ounces are needed for an application rate of 0.75 lb ae/acre:

Glyfo A:

$$\frac{0.75\ \mathit{lb\ ae}}{\mathit{acre}} \times \frac{1\ \mathit{gal}}{4\ \mathit{lb\ ae}} \times \frac{128\ \mathit{fl\ oz}}{\mathit{gal}}$$

$$= 24\ \mathit{fl\ oz}$$

Glyfo B:

$$\frac{0.75\ \mathit{lb\ ae}}{\mathit{acre}} \times \frac{1\ \mathit{gal}}{3\ \mathit{lb\ ae}} \times \frac{128\ \mathit{fl\ oz}}{\mathit{gallon}}$$

$$= 32\ \mathit{fl\ oz}$$

Next, divide the price per gallon by 128 to determine price per fluid ounce:

Glyfo A:

$$\frac{\$23.00}{128\ \mathit{fl\ oz}} = \$0.1797/\mathit{fl\ oz}$$

Glyfo B:

$$\frac{\$21.75}{128\ \mathit{fl\ oz}} = \$0.1699/\mathit{fl\ oz}$$

Finally, multiply cost per fluid ounce by the number of fluid ounces needed to achieve an application rate of 0.75 lb ae/acre:

Glyfo A:

$$\frac{\$0.1797}{\mathit{fl\ oz}} \times \frac{24\ \mathit{fl\ oz}}{\text{acre}} = \$4.31/\mathit{acre}$$

Glyfo B:

$$\frac{\$0.1699}{\mathit{fl\ oz}} \times \frac{32\ \mathit{fl\ oz}}{\text{acre}} = \$5.44/\mathit{acre}$$

So while a gallon of Glyfo A costs $1.25 more than a gallon of Glyfo B, calculating costs on an acid equivalent basis reveals that the per-acre cost is $1.13 less with Glyfo A than with Glyfo B.

Determining how many pounds of acid equivalent are contained in a given formulation may seem the most daunting part of this exercise, but several references are available that list the amount of acid equivalent in many commercially available glyphosate formulations. **Table 12.5** compares a number of glyphosate-containing products based on the amount of acid equivalent per gallon. The table also lists the amount of product (in fluid ounces) needed to apply a range of acid equivalents (0.375–1.5 lb per acre).

Herbicide isomers. Herbicide isomers may not be very familiar to weed management practitioners, but they are becoming increasingly common in the marketplace. In essence, herbicide isomers are variations of a molecule, put together in slightly different arrangements. One isomer of a particular active ingredient is generally much more herbicidally active than the other isomer. A small amount of chemistry can help explain stereoisomers and how they are relevant in today's weed management arena.

A good starting point might be to define the term *stereoisomer.* Stereoisomers are molecules that have the same atoms bonded to each other but differ in how the atoms are arranged in space. **Figure 12.11** and **Figure 12.12** will serve as examples for the following discussion. **Figure 12.11** illustrates a 5-carbon ring molecule with two chlorine atoms attached to it; one chlorine atom is positioned

Table 12.5. Glyphosate-containing herbicides.

Active ingredient/gal	Acid equivalent/gal	Product rate equivalent to (lb acid equivalent/A) 0.375	0.56	0.75	1.13	1.5
		fl oz				
4	3	16	24	32	48	64
5	3.68	13	19.5	26	39	52
5.4	4	12	18	24	36	48
5.14	4.17	11.5	17	23	35	46
5.5	4.5	11	16	21	32	43
6.16	5	10	14	19	29	38

above the plane of the ring, while the other is positioned below. **Figure 12.12** shows the same 5-carbon ring with the same two chlorine atoms, but here both chlorine atoms are positioned above the plane of the ring. Each molecule contains the same number of atoms—5 carbon and 2 chlorine—but the spatial arrangement of the chlorine atoms differs, which is what differentiates this pair of stereoisomers. An analogy of stereoisomers is a person's two hands; each hand consists of the same components, but they are assembled differently. You cannot rotate your right hand to make it a left hand, and vice versa.

So how is a differential orientation of atoms or substituent groups (i.e., stereoisomers) relevant to weed management? Even though two molecules may have the same types and numbers of atoms and differ only in the orientation of one or more atoms or groups, differential orientations can greatly affect the biological activity of the molecules. If, for example, the molecules depicted in **Figure 12.11** and **Figure 12.12** were herbicides, the orientation of the chlorine atoms in **Figure 12.11** might cause that isomer to bind much more effectively at the herbicide target site within the plant, whereas the orientation of the chlorine atoms in **Figure 12.12** might not allow this isomer to bind the target site at all. One might reason that if the molecule depicted in **Figure 12.11** is more herbicidally active than the molecule depicted in **Figure 12.12**, it would be better to manufacture or use a product containing the **Figure 12.11** molecule only. While this notion is valid, the process used to manufacture certain herbicides results in a combination of isomers (that is, a mixture of the two molecules) in the commercially available formulation. An example of stereoisomer chemistry in weed management is the active ingredient metolachlor.

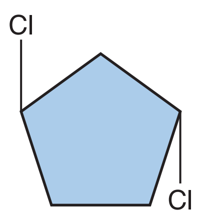

Figure 12.11. A 5-carbon ring with two chlorine atoms, one positioned above the plane of the ring and the other below.

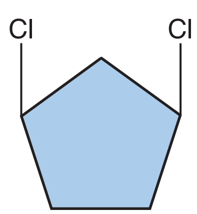

Figure 12.12. The same 5-carbon ring as shown in Figure 12.11, but here both chlorine atoms are positioned above the plane of the ring.

Metolachlor first became commercially available during the 1970s and was sold under the trade name Dual. The process used to manufacture Dual resulted in two isomers of metolachlor present in the commercial formulation. One isomer, designated the S-isomer, is much more herbicidally active than the other, designated the R-isomer. Dual and the subsequent product Dual II each contained a 50:50 mixture of the active (S) and inactive (R) isomers of metolachlor. (Dual became Dual II when a safener was added to the original formulation to reduce the potential for adverse crop response.) Application rates for these "nonresolved" formulations were determined based on this 50:50 mixture of active and inactive isomers.

In the 1990s, improvements in technology allowed manufacturers to increase the amount of active (S) isomer in a formulation, and Dual II became Dual II Magnum. The "Magnum" formulations (Dual II Magnum, Bicep II Magnum, Bicep Lite II Magnum) still contain the same active ingredient(s) as always, but they now contain a higher proportion of the active or resolved (S) isomer compared with the older formulations (Dual and Dual II, Bicep and Bicep II, Bicep Lite and Bicep Lite II). Specifically, the Magnum formulations contain an 88:12 mixture of the active (S):inactive (R) isomers compared with a 50:50 mixture of the active (S):inactive (R) isomers found in the Dual and Dual II formulations. So what is a practical implication of having a formulation containing more of the active isomer? Since a higher proportion of the active isomer is present in the Magnum formulations, application rates are reduced approximately 35% compared with the original formulation.

Perhaps another illustration will be of value. Say, hypothetically, you were to count out 100 molecules from a container of Dual II and 100 molecules from a container of Dual II Magnum. Assuming the rules of probability hold, the 100 molecules of Dual II would be 50 active molecules (the S or resolved isomer) and 50 inactive molecules (the R or unresolved isomer). The 100 molecules of Dual II Magnum would be 88 active and 12 inactive molecules.

Assuming the unresolved isomer doesn't contribute much to weed control, it takes less Dual II Magnum than either Dual or Dual II to obtain the critical number of S-metolachlor molecules needed for weed control. For example, if 50 molecules of S-metolachlor (the active isomer) are needed to achieve control of a particular weed species, how many total molecules of Dual/Dual II and Dual II Magnum would you need in order to apply at least 50 molecules of S-metolachlor? You would need 100 total molecules of Dual or Dual II (50:50 mixture) to get 50 molecules of S-metolachlor, whereas you would need only 57 total molecules of Dual II Magnum (88:12 mixture) to get 50 molecules of S-metolachlor. Stated another way, if you were to apply the same product rate of Dual and Dual II Magnum, you would apply less active isomer per acre from the Dual formulation.

Figure 12.13 and **Figure 12.14** illustrate this concept. The circles represent equal volumes of herbicide. **Figure 12.13** was taken from a container of a nonresolved metolachlor-containing herbicide (50:50 mixture of S and R isomers) while **Figure 12.14** was taken from a container of a resolved metolachlor formulation (88:12 mixture of S and R). Each circle contains the same number of total molecules (designated S and R), but a different proportion of S and R isomers.

This information should help those who purchase herbicides made up of stereoisomers better understand some of the differences among commercially available products. Currently there are many metolachlor and S-metolachlor products on the market, and there appears to be some confusion about product equivalents among these many formulations. For example, equivalent rates may be defined several ways, including equivalent amounts of active ingredients, equivalent amounts of active isomers, or simply the rates allowed by the respective product label. These are not always synonymous or interchangeable.

Table 12.6 lists several examples of products containing metolachlor or S-metolachlor. One should not assume that applying the same rate of each product necessarily results in applying the same amount of active ingredient or active isomer. In particular, it should be noted that while applying the same product rates of an S-metolachlor-containing product and metolachlor-containing product can provide similar amounts of total active ingredient, the amounts of the active isomer applied can vary considerably.

Herbicide premixes. Herbicide premixes are commercially formulated products containing more than one herbicide active ingredient. Combining two or more active ingredients in a formulated product can provide several advantages, including a broader weed control spectrum than any individual component has alone, reduced potential for physical or chemical incompatibility problems, and reduced cost compared with purchasing the components separately and mixing them.

Herbicide premixes can be confusing with respect to components, product equivalents, application rates, and other factors. **Table 12.7** compares two commercially available corn herbicide premixes used in Illinois. The first column lists the trade name and formulation of the herbicide, and the second provides the common names for the components. For example, Harness Xtra (trade name) 5.6L (formulation) is composed of the active ingredients acetochlor (common name) and atrazine (common name). The second column also indicates the amount of active ingredient (or sometimes acid equivalent) of each component per gallon or pound of formulated product.

The third column lists an application rate for each premix, and the fourth column indicates how much of each active

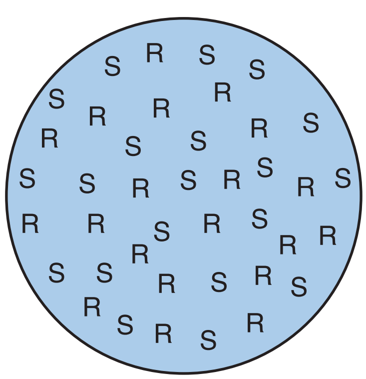

Figure 12.13. A droplet taken from a container of a nonresolved metolachlor-containing herbicide (50:50 mixture of S and R isomers). Note the equal numbers of S and R letters.

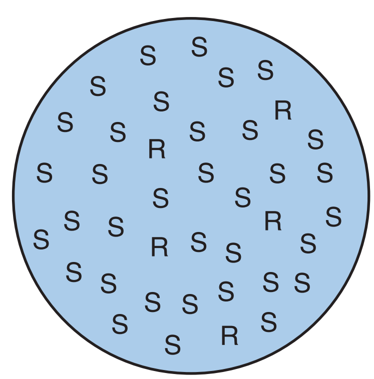

Figure 12.14. A droplet taken from a container of a resolved metolachlor-containing herbicide (88:12 mixture of S and R isomers). Note the higher proportion of S letters relative to R letters.

Table 12.6. Metolachlor- and S-metolachlor-containing herbicides.

Product	Active ingredient	Active ingredient/ gal	R:S mixture (ratio)	If you apply (product/ A):	You have applied	
					lb/ai	lb active isomer
Dual	metolachlor	8 lb	50:50	2.5 pt	2.5	1.25
Dual II	metolachlor	7.8 lb	50:50	2.5 pt	2.43	1.218
Dual Magnum	S-metolachlor	7.62 lb	88:12	1.67 pt	1.59	1.399
Dual II Magnum	S-metolachlor	7.64 lb	88:12	1.67 pt	1.59	1.403
"Generic I" brand	metolachlor	8 lb	50:50	1.67 pt	1.67	0.835
"Generic II" brand	metolachlor	7.8 lb	50:50	1.67 pt	1.62	0.814

ingredient is applied at that application rate. For example, 2.5 quarts of Harness Xtra 5.6L provides 1.94 lb acetochlor active ingredient and 1.56 lb atrazine active ingredient. Note here that while application rates of commercial products are usually expressed in ounces, pounds, pints, or quarts of product per acre, active ingredients are usually expressed in units of pounds active ingredient or acid equivalent per acre.

The last column lists product equivalents for each premix component when applied at the application rate listed in the third column. The 2.5-quart rate of Harness Xtra 5.6L provides the same amount of acetochlor and atrazine contained in 2.21 pints of Harness 7E and 3.13 pints of AAtrex 4L, respectively.

The application rate of Harness Xtra 5.6L listed in **Table 12.7** is 2.5 quarts per acre. Instead of 2.5 quarts, suppose someone would like to know how much acetochlor and atrazine are applied at a 2-quart rate of Harness Xtra 5.6L.

First, convert 2 quarts to gallons:

$$\frac{2\ qt}{acre} \times \frac{1\ gal}{4\ qt} = 0.5\ gal$$

Next, calculate how much acetochlor and atrazine active ingredient are contained in 0.5 gallon of Harness Xtra 5.6L.

$$\frac{0.5\ gal}{acre} \times \frac{3.1\ lb\ ai\ acetochlor}{gal}$$

$$= 1.55\ lb\ ai\ acetochlor\ per\ acre$$

$$\frac{0.5\ gal}{acre} \times \frac{2.5\ lb\ ai\ acetochlor}{gal}$$

$$= 1.25\ lb\ ai\ acetochlor\ per\ acre$$

Finally, determine product equivalents based on these active ingredient amounts:

$$\frac{1.55\ lb\ ai\ acetochlor}{acre} \times \frac{1\ gal\ Harness}{7\ lb\ ai}$$

$$\times \frac{8\ pt}{gal} = 1.77\ pt\ Harness\ 7E$$

$$\frac{1.25\ lb\ ai\ acetochlor}{acre} \times \frac{1\ gal\ Harness}{4\ lb\ ai}$$

$$\times \frac{8\ pt}{gal} = 2.5\ pt\ AAtrex\ 4L$$

Principles of Soil-Applied Herbicides

Soil-applied herbicides remain an important part of weed management programs in corn and soybean production systems. Early preplant (EPP), preplant incorporated (PPI), and preemergence (PRE) surface are the most common types of herbicide applications to soil. EPP applications are typically made several weeks prior to planting and are more common in corn fields than soybean fields. PPI applications were once very common, but they have declined in recent years with the growing adoption of conservation tillage. PRE applications are generally made within one week of crop planting. Regardless of when or

Table 12.7. Comparison of two herbicide premixes.

Herbicide	Components (ai/gal or lb)	If you apply/A:	You have applied (ai):	Product equivalents:
Bicep II Magnum 5.5L	S-metolachlor = 2.4 lb atrazine = 3.1 lb	2.1 qt	S-metolachlor = 1.26 lb atrazine = 1.63 lb	Dual II Magnum 7.64E = 1.32 pt AAtrex 4L = 3.26 pt
Harness Xtra 5.6L	acetochlor = 3.1 lb atrazine = 2.5 lb	2.5 qt	acetochlor = 1.94 lb atrazine = 1.56 lb	Harness 7E = 2.21 pt AAtrex 4L = 3.13 pt

how a herbicide is applied to the soil, the effectiveness of soil-applied herbicides is influenced by several factors.

For a soil-applied herbicide to be effective, it needs to be available for uptake by the weed seedling (usually before the seedling emerges, but some soil-applied herbicides can control small emerged weeds under certain conditions). Processes such as herbicide adsorption to soil colloids or organic matter can reduce the amount of herbicide available for weed absorption. Soil-applied herbicides do not prevent weed seed germination; rather, they are first absorbed by the root or shoot of the seedling and then exert their phytotoxic effect. Generally, this happens before the seedling emerges from the soil. For a herbicide to be absorbed by weed seedlings, the herbicide must be in the soil solution or vapor phase (i.e., an available form). How is this achieved? The most common methods for herbicides to become dissolved into the soil solution are by mechanical incorporation or precipitation. EPP applications in no-till systems attempt to increase the likelihood that sufficient precipitation will be received before planting to incorporate the herbicide. If, however, no precipitation is received between application and planting, mechanical incorporation (where feasible) will, in most instances, adequately move the herbicide into the soil solution. Herbicide that remains on a dry soil surface after application may not provide much effective weed control and is subject to various dissipation processes, some of them described in subsequent paragraphs.

Many weed species, in particular small-seeded ones, germinate from fairly shallow depths in the soil. The top 1 to 2 inches of soil is the primary zone of weed seed germination and should thus be the target area for herbicide placement. Shallow incorporation can be achieved by mechanical methods or precipitation. Which method is more consistent? Precipitation provides for fairly uniform incorporation, but mechanical incorporation reduces the absolute dependence on receiving timely precipitation. How much precipitation is needed and how soon after application it should be received for optimal herbicide performance depends on many factors, but generally 1/2 to 1 inch of rain within 7 to 10 days is sufficient.

Herbicides remaining on the soil surface, or those placed too deeply in the soil, may not be intercepted by the emerging weed seedlings. Herbicides on the soil surface are subjected to several processes that reduce their availability. Volatility (the change from a liquid to gaseous state) and photolysis (degradation due to absorption of sunlight) are two common processes that can reduce the availability of herbicides remaining on the soil surface. Volatility potential is determined by several properties of the soil and the herbicide formulation, while photolysis is dependent primarily on herbicide properties.

Dry soil conditions are conducive for planting, but they may also reduce the effectiveness of soil-applied herbicides. If herbicide applications are made prior to planting and no precipitation is received between application and planting, a shallow mechanical incorporation prior to planting may help preserve much of the herbicide's effectiveness.

Principles of Postemergence Herbicides

Postemergence herbicides are a key part of an integrated weed management program. Applications made after crops and weeds have emerged allow for identifying the weed species present and assessing the severity of infestation so that herbicide selection can be tailored to the particular field. Postemergence herbicide applications minimize the interactions of the herbicide with factors associated with soil (such as texture and organic matter content), but they often magnify interactions between the herbicide and prevailing environmental conditions.

To achieve weed control with postemergence herbicides, the herbicide must come in contact with the target, be retained on the leaf surface prior to absorption into the plant, be able to reach the site of action within the plant, and finally induce some phytotoxic response. If for any reason one or more of these steps is restricted or limited, the level of weed control can be expected to decline.

The plant cuticle serves as an outer protective layer, or "barrier," that restricts the amount of water lost by the plant through transpiration. It also serves a variety of other functions, and the cuticle is often considered the primary barrier that limits herbicide absorption. The cuticle is composed primarily of waxes and cutin, substances that effectively limit water movement out of the leaf (transpiration) or into it (absorption). The type and amount of wax that comprises the cuticle influences the degree of wetting that can be achieved, and this composition can change with plant age and in response to changes in the environment. Older plants and plants under environmental stress generally have more wax or a different structure of the wax comprising their cuticles and are thus more difficult to wet. One of the main functions of certain spray additives is to enhance herbicide penetration through the cuticle.

Plant age and size, relative humidity, soil moisture, and temperature are other factors that influence absorption of postemergence herbicides. Younger, smaller plants usually absorb herbicide more rapidly than older, more mature plants. Many postemergence herbicide labels recommend applications be made when target weeds are small and caution about reduced effectiveness if applications are made to larger plants. Labels of postemergence herbicides may also suggest that users delay applications if weeds are under "adverse environmental conditions." Examples of such adverse environmental conditions may include prolonged periods without significant precipitation (resulting in dry soil) or low air temperatures. On the other hand, high relative humidity, adequate soil moisture, and moderate to warm air temperatures all favor enhanced herbicide absorption. Remember that if conditions occur that enhance herbicide absorption into weeds, conditions also are favorable for enhanced absorption into the crop, which may result in crop injury.

Postemergence herbicides vary in their mobility within the plant. Some demonstrate very limited movement following absorption and are commonly referred to as “contact” herbicides. Others can move extensively within the vascular elements of the plant and are referred to as “translocated” herbicides. Contact herbicides do show some movement following absorption, but they do not move nearly as extensively as translocated herbicides. Thorough spray coverage of the plant foliage is very important with contact herbicides but somewhat less important with translocated herbicides.

Almost every postemergence herbicide has a preharvest interval specified on the label or a crop developmental stage beyond which applications should not be made. Labels of some products indicate both a developmental stage and a preharvest interval. A preharvest interval indicates the amount of time that must elapse between herbicide application and crop harvest. Such intervals are established to allow sufficient time for the herbicide to be broken down or metabolized in the plant. Additionally, the preharvest interval reduces the likelihood of herbicide residue remaining on the harvested portion of the crop. Failure to observe the preharvest interval may result in herbicide residue in the crop in excess of established limits. In addition to preharvest intervals, there are restrictions on many postemergence herbicides labels about whether the treated crop may be used for livestock feed or whether treated fields may be grazed as forage.

Another interval that is important to observe is the rotational crop interval. Nearly all herbicide labels, both soil-applied and postemergence, list rotational crop intervals that specify the time that must elapse between herbicide application and planting a rotational crop. This becomes particularly important with late-season herbicide applications. Such intervals are established to reduce the likelihood that sufficient herbicide residues will persist in the soil that could adversely affect the rotational crop. Some herbicide rotational restrictions are based solely on time, while others are influenced by different factors, such as soil pH and the amount of precipitation received after herbicide application.

Additives for postemergence herbicides. Additives are compounds added to a herbicide formulation or spray mixture that in some way modify the characteristics of the spray solution. Additives either are included in the commercial herbicide formulation or are added to the spray mixture prior to application. Different types of spray additives perform different functions, such as improving herbicide uptake into the target vegetation, reducing the number of very small droplets so as to reduce physical drift, and enhancing herbicide performance on certain weed species. Some of the most common additives for postemergence herbicides are nonionic surfactants (NIS), crop oil concentrates (COC), and ammonium fertilizer salts. These are used to increase the effect of the herbicide on the target plants.

Nonionic surfactants lower the surface tension of spray droplets, thus increasing spray coverage, so they are frequently referred to as spreaders or wetting agents. Herbicide labels often specify that the NIS should contain a minimum of 75% to 80% active ingredient or otherwise use a higher rate of NIS. NIS is usually applied at 0.5 to 1 pint per acre, or 0.125% to 0.5% on a volume basis.

Ammonium fertilizer adjuvants are added to increase herbicide activity on certain weed species, including velvetleaf. The two most common ammonium fertilizers used are ammonium sulfate (AMS) and urea ammonium nitrate (UAN) solution (28-0-0). AMS is used at 8.5 to 17 pounds per 100 gallons of spray solution. UAN is used at 2 to 4 quarts per acre, or 2% to 4% by volume. Contact herbicide labels may specify that fertilizer adjuvants replace NIS or COC, while translocated herbicides often specify the addition of UAN or AMS to NIS or COC.

Crop oil concentrates are phytobland oils with emulsifiers added to allow mixing with water. The oil may be of petroleum (POC) or vegetable (VOC) origin. Oils increase spray penetration through the leaf cuticle. Most herbicide labels allow POC or VOC, but some may specify one or the other only. COCs are used at 1 to 2 pints per acre, or 0.5% to 1% by volume.

Compatibility agents are spray additives that improve mixing, especially for soil-residual herbicides that are applied with a liquid fertilizer spray carrier. Herbicide labels often specify a “jar test” to determine the need for a compatibility agent when mixing herbicides with liquid fertilizer. The rate is usually 1 to 4 pints per 100 gallons of spray mix.

Drift reduction agents are added to the spray tank to reduce small droplet formation and thus minimize drift potential. The use rate per 100 gallons of spray is generally 2 to 10 fluid ounces of concentrated forms and 2 to 4 quarts of dilute forms (1% to 2% active ingredient).

Buffer-surfactants or buffer-compatibility agents contain organic phosphatic acids that provide an acidifying effect on spray mixes where a pesticide is affected by alkaline water. Most herbicides do not need a buffering agent, and some sulfonylureas should not be acidified because herbicide degradation is accelerated.

How Herbicides Work

Herbicides are frequently categorized into families according to various similarities. Examples of classification categories include mode of action, application timing, and chemical structure. Herbicide mode of action describes the metabolic or physiological plant process impaired or inhibited by the herbicide. Essentially, mode of action refers to how the herbicide acts to inhibit plant growth. Herbicide site of action describes the specific location(s) within the plant where the herbicide binds. Site of action thus identifies the herbicide target site within the plant. Though the most common herbicide classification schemes utilize mode of action, much ambiguity exists with respect to that herbicide classification.

While understanding herbicide mode of action is beneficial, classifying herbicides by site of action may be more useful from the standpoint of resistance management. Herbicide resistance in plants is often due to an alteration of the binding site in the target plant. Rotating herbicides based on these different binding sites or sites of action may provide for more reliable classification, in contrast with the ambiguity of classification based on herbicide mode of action, whose systems include anywhere from seven to 13 different categories. Some of these systems describe mode of action categories as "cell membrane disruptors," "seedling growth inhibitors," and "amino acid synthesis inhibitors." Rotating herbicides based on these categories could cause confusion among growers. For example, the mode-of-action category "amino acid synthesis inhibitors" would place the herbicides Pursuit (imazethapyr) and Roundup (glyphosate) in the same family, whereas classification by site of action would place these two herbicides into two distinctly different families, allowing growers to more accurately rotate herbicides for resistance management.

The University of Illinois Extension publication *Utilizing Herbicide Site of Action to Combat Weed Resistance to Herbicides* presents a color-coded herbicide classification system based on 14 sites of action. The system is intended to enhance growers' ability to rotate herbicides based on site of action, in order to slow further development of herbicide-resistant weed biotypes. The table, reproduced here on the next page, separates herbicide sites of action into 14 "primary" colors. Herbicide chemical families sharing a particular site of action are coded in shades of the same color. The table also can be used to determine the sites of action of individual herbicide premix components.

Weed Resistance to Herbicides

Herbicide-resistant weed biotypes continue to plague farmers across much of Illinois. Biotypes are populations within a species that possess characteristics not common to the species as a whole. In this case, the "uncommon characteristic" is resistance to a particular herbicide. Understanding how herbicide resistance develops is an important initial step in designing effective weed-management strategies that deter the selection for resistant biotypes. **Table 12.8** provides a listing of weed species in Illinois that have biotypes resistant to particular herbicide families.

The terminology used when discussing herbicide resistance can be confusing. The most common terms are defined as follows:

Herbicide resistance: the inherited ability of a plant to survive and reproduce following exposure to a dose of herbicide normally lethal to the wild type.

Herbicide tolerance: the inherent ability of a plant species to survive and reproduce after herbicide treatment.

Notice in the definition of resistance, the word "plant" is used, whereas "species" is used in the definition of tolerance. Stated another way, a resistant plant is a member of a species that, as a whole, is susceptible to a given herbicide. The resistant plant is a **biotype** of that species that is no longer susceptible to the herbicide. Tolerance implies that a species has never been susceptible to a given herbicide.

Other terms related to herbicide resistance include the following:

Cross-resistance: Resistance to a herbicide that a plant may not have been previously exposed to but that has a mode or site of action similar to the herbicide that selected for the resistant biotype.

Multiple-resistance: Resistance to more than one class of herbicides with very different modes or sites of action, usually involving more than one basis for resistance.

Some examples may help to eliminate confusion about these terms. A producer who has grown continuous corn on the same field for many years has used atrazine (a photosynthesis-inhibiting herbicide) each year for weed control. The producer notices that in recent years the control of common lambsquarters has been poor. The local extension educator collects seed from the common lambsquarters and confirms during the winter that the weed is *resistant* to atrazine. The producer decides to switch to simazine (another photosynthesis inhibitor) the following year, but again finds the control of common lambsquarters to be poor. Further investigation reveals that the common lambsquarters is also resistant to simazine. Because the plants are resistant

HERBICIDE CLASSIFICATION BY SITE OF ACTION

SITE OF ACTION	WSSA GROUP	CHEMICAL FAMILY	ACTIVE INGREDIENT	HERBICIDE
Inhibition of acetyl CoA carboxylase (ACCase)	1	Aryloxyphenoxy propionate	fenoxaprop fluazifop quizalofop	Puma Fusilade DX Assure II
		Cyclohexanedione	clethodim sethoxydim	Select, Select Max Poast, Poast Plus
Inhibition of acetolactate synthase (ALS)	2	Sulfonylurea	chlorimuron chlorsulfuron foramsulfuron halosulfuron idosulfuron nicosulfuron primisulfuron prosulfuron rimsulfuron sulfometuron thifensulfuron tribenuron	Classic Telar Option Permit --------- Accent Beacon Peak Resolve Oust Harmony GT XP Express
		Imidazolinone	imazamox imazapyr imazaquin imazethapyr	Raptor Arsenal Scepter Pursuit
		Triazolopyrimidine	flumetsulam cloransulam	Python FirstRate
Inhibition of microtubule assembly	3	Dinitroaniline	benefin ethalfluralin pendimethalin trifluralin	Balan Sonalan Prowl, Pendimax Treflan, others
Synthetic auxins	4	Phenoxy	2,4-D MCPA MCPP	Weedone, others various various
		Benzoic acid	dicamba	Banvel, Clarity
		Carboxylic acid	clopyralid fluroxypyr picloram triclopyr	Stinger Starane Tordon Garlon
Inhibition of indoleacetic acid transport	19	Semicarbazone	diflufenzopyr	--------
Inhibition of photosynthesis at photosystem II site A	5	Triazine	atrazine ametryn prometon simazine	AAtrex, others Evik Pramitol Princep
		Triazinone	hexazinone metribuzin	Velpar Sencor
		Uracil	bromacil terbacil	Hyvar Sinbar
Inhibition of photosynthesis at photosystem II site B	6	Nitrile	bromoxynil	Buctril
		Benzothiadiazole	bentazon	Basagran
Inhibition of photosynthesis at photosystem II site A - different binding behavior	7	Urea	diuron linuron tebuthiuron	Karmex Lorox Spike
Photosystem I - electron diversion	22	Bipyridilium	paraquat diquat	Gramoxone Inteon Diquat
Inhibition of EPSP synthase	9	None accepted	glyphosate	Roundup, Touchdown, others
Inhibition of glutamine synthetase	10	None accepted	glufosinate	Liberty
Inhibition of lipid biosynthesis - not ACCase inhibition	8	Thiocarbamate	butylate EPTC	Sutan + Eradicane
Bleaching: Inhibition of DOXP synthase	13	Isoxazolidinone	clomazone	Command
Bleaching: Inhibition of 4-HPPD	27	Isoxazole	isoxaflutole	Balance PRO
		Triketone	mesotrione	Callisto
		Pyrazolone	topramezone	Impact
Inhibition of protoporphyrinogen oxidase (Protox or PPO)	14	Diphenylether	acifluorfen fomesafen lactofen	Ultra Blazer Flexstar, Reflex Cobra, Phoenix
		N-phenylphthalimide	flumiclorac flumioxazin	Resource Valor
		Aryl triazinone	sulfentrazone carfentrazone	Authority Aim
Inhibition of synthesis of very-long-chain fatty acids (VLCFA)	15	Chloroacetamide	acetochlor alachlor metolachlor S-metolachlor dimethenamid	Harness, TopNotch, Degree IntRRo, Micro-Tech, Partner various Dual II Magnum, others Outlook
		Oxyacetamide	flufenacet	Define

Table 12.8. Weed species in Illinois that include herbicide-resistant biotypes and the herbicide families to which the biotypes are resistant.

Species		
Common name	**Scientific name**	**Resistant to herbicide family or families**
Common lambsquarters	*Chenopodium album*	Triazine
Smooth pigweed	*Amaranthus hybridus*	Triazine, ALS inhibitors
Kochia	*Kochia scoparia*	Triazine, ALS inhibitors
Common waterhemp	*Amaranthus rudis*	Triazine, ALS inhibitors, PPO inhibitors, glyphosate
Eastern black nightshade	*Solanthum ptycanthum*	ALS inhibitors
Giant ragweed	*Ambrosia trifida*	ALS inhibitors
Common ragweed	*Ambrosia artemisiifolia*	ALS inhibitors
Common cocklebur	*Xanthum strumarium*	ALS inhibitors
Shattercane	*Sorghum bicolor*	ALS inhibitors
Giant foxtail	*Setaria faberi*	ALS inhibitors, ACCase inhibitors
Horseweed	*Conyza canadensis*	Glyphosate

to both atrazine and simazine, they are said to exhibit *cross-resistance.* The next year, the producer decides to use a postemergence application of glyphosate (an amino acid synthesis inhibitor) to control the common lambsquarters; once again poor control results. Investigations reveal that the common lambsquarters is also resistant to glyphosate, a situation defined as *multiple-resistance.* A documented example of multiple-resistance is a biotype of waterhemp from Illinois that has demonstrated resistance to such herbicide families as the acetolactate synthase (ALS) inhibitors, triazines (atrazine, simazine), and protoporphyrinogen oxidase (PPO) inhibitors.

Origin of resistance. To slow the selection of herbicide-resistant weeds, one should have a basic understanding of how a resistant weed population develops. The natural-selection theory is widely regarded as the most plausible explanation for the development of resistance. The theory states that herbicide-resistant biotypes have always existed at extremely low numbers within particular weed species. When a herbicide effectively controls the majority of susceptible members of a species, only those plants that possess a resistance trait can survive and produce seed for future generations.

What is meant by “selection pressure” in regard to herbicide-resistant weeds? Herbicides are used to control a wide spectrum of weeds. By controlling susceptible members of a weed population, we are essentially using herbicides as agents to “select for” biotypes that are naturally resistant to the herbicide. When most of the susceptible members of a weed population are controlled, the resistant biotypes are able to continue growing and eventually produce seed. The seed from the resistant biotypes ensures that the resistance trait carries into future seasons. If the same herbicide is used year after year, or several times during a single season, the resistant biotypes continue to thrive, eventually outnumbering the normal (susceptible) population. In other words, relying on the same herbicide (or herbicides with the same site of action) for weed control creates selection pressure that favors the development of herbicide-resistant weeds.

The development of a herbicide-resistant weed population can be summarized by the following principle: *The appearance of herbicide-resistant weeds is the consequence of using a herbicide with a single site of action year after year or of repeating applications of a herbicide during the growing season to kill a specific weed species not controlled by any other herbicide or in any other manner.* This principle has three key components:

1. A herbicide with a single site of action.
2. Repeated use of the same herbicide.
3. The absence of other control measures.

By understanding these components and developing weed-control systems with them in mind, producers can greatly reduce the probability that herbicide-resistant weeds will develop in their fields.

Management Strategies to Minimize Herbicide-Resistant Weeds

The best solution for minimizing herbicide-resistant weeds is to reduce the intensity of their selection. In the past, as new weed problems were discovered, the usual solution has been to develop new herbicides. Today, the high cost of developing a new herbicide makes good management practices the best method for dealing with herbicide-resistant weeds. The following strategies may help slow selection for herbicide resistance:

- Scout fields regularly to identify resistant weeds. Respond quickly to changes in weed populations to restrict the spread of plants that may have developed resistance.
- Rotate herbicides with different sites of action. Do not make more than two consecutive applications of herbicides with the same site of action against the same weed unless other effective control practices are included in the management system. Consecutive applications can

be single applications in 2 years or two split applications in 1 year.

- Apply herbicides in tank-mixed, prepackaged, or sequential mixtures that include multiple sites of action. Both herbicides in the mixture must have substantial activity against potentially resistant weeds, as well as similar soil persistence.
- As new herbicide-resistant and herbicide-tolerant crops become available, their use should still not result in more than two consecutive applications of herbicides with the same site of action against the same weed unless other effective practices are included in the management system.
- Combine mechanical control practices (such as rotary hoeing, cultivating, and even hand weeding) with herbicide treatments for a near-total weed-control program.
- Clean tillage and harvest equipment before moving from fields infested with resistant weeds to fields that are not infested.
- Railroads, public utilities, highway departments, and similar organizations using total-vegetation-control programs should be encouraged to use practices that do not lead to the development of herbicide-resistant weeds. Resistant weeds resulting from areas of total vegetation control frequently spread to cropland. Chemical companies, state and federal agencies, and farm organizations can help in this effort.

Several criteria may be used to diagnose a herbicide-resistant weed problem correctly:

- All other causes of herbicide failure have been eliminated.
- Other weeds on the herbicide label (besides the one in question) were controlled effectively.
- The field has a history of continuous or repeated use of the same herbicide or herbicides with the same site of action.
- The weed species was controlled effectively in the past. Weed control in the field has been based entirely on herbicides, without mechanical control.

With these management strategies and diagnosis criteria in mind, how does one go about correctly identifying a resistant weed population? We know that initially resistant weed biotypes are present at extremely low frequencies within a particular population. It stands to reason, then, that because of such a low initial frequency, resistance will most likely first be noticed within a particular field as a few individual weeds that were not controlled. In other words, resistant weeds do not usually infest an entire field within 1 year. Typically, the resistant weed population is initially confined to small, isolated patches. If the same herbicide-control program is followed repeatedly, these patches begin to encompass a larger and larger proportion of the field, until finally the resistant weeds appear as the dominant species. So a producer who encounters an entire field of resistant weeds has most likely had a resistant population in the field for more than 1 year.

Crop Injury and Herbicides

Crop response, meaning injury, caused by herbicides applied for in-crop weed control can range from no visible response to nearly complete crop loss. Determining the reason or reasons for observed crop injury can be challenging, as several interacting factors may contribute to the severity of response. If the cause is readily discernible, the explanation and prognosis also may be straightforward, but if multiple factors contribute to crop injury, the process of assessment and prognosis may become less precise.

Crop genetics can influence the degree of injury response. Certain corn hybrids, for example, are sensitive to 2,4-D (and other herbicides, for that matter) and may exhibit a great deal of injury following herbicide application. The labels of many corn herbicides, especially postemergence herbicides, have precautionary statements about the potential for certain hybrids to be more sensitive than others to a particular active ingredient. If you are concerned that a particular hybrid may be sensitive to a certain herbicide or herbicide family, contact the seed company representative for information.

If more than one formulation of a particular active ingredient is commercially available, the choice of formulation, especially for postemergence applications, also can influence the occurrence of corn injury. For example, ester formulations of 2,4-D tend to be absorbed through the leaf surface faster than amine formulations. Applying 2,4-D esters postemergence with additives such as COC, or tank-mixing herbicides with formulations that can “behave” similarly to a spray additive, can increase the rate of 2,4-D uptake into the corn, potentially leading to enhanced corn injury.

The environment has a large influence on the severity of crop injury symptoms from both soil-applied and postemergence herbicides. High air temperatures and relative humidity levels favor enhanced absorption of postemergence herbicides. Adequate soil moisture levels and low relative humidity can enhance uptake of soil-applied herbicides. Rapid herbicide absorption into the crop plant may temporarily overwhelm the plant’s ability to break down the herbicide, leading to injury symptoms.

Apart from enhancing herbicide uptake, environment-induced crop stress can enhance crop injury from herbicides.

Cool air temperatures and wet soil conditions are good examples of environmental conditions that can induce stress. Why is a crop under stress more likely to be injured by a selective herbicide? In most cases, herbicide selectivity arises from the crop's ability to metabolize (break down) the herbicide to a nonphytotoxic form before it causes much injury. For example, a grass-control herbicide used in corn cannot discriminate between giant foxtail and a corn plant; the herbicide attempts to control the corn just as it attempts to control the giant foxtail. When the corn is growing under favorable conditions, it rapidly metabolizes the herbicide before excessive injury occurs. If, however, the corn plant is under stress (which could be caused by a variety of factors), its ability to metabolize the herbicide may be slowed enough that injury symptoms develop.

The herbicide itself can influence the severity of crop injury, and spray additives applied with a postemergence herbicide or tank-mix combinations may enhance crop response. Always read all label suggestions and precautions related to spray additives that should be either included or avoided when applying herbicides postemergence.

13

Managing Insect Pests

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Technically, an insect pest of crops is any species that feeds on crops and thus competes with producers for crop yield or quality. However, the mere presence of a crop-feeding insect is not enough to establish a species as a pest that requires expenditures for its management. The status of any given pest (major or minor) depends largely on how often and in what numbers it occurs, as well as the economics of managing the pest. Factors that contribute to choices about insect management include the market value of the crop, the cost of controlling the pest relative to its potential for causing crop loss, the susceptibility of the crop to the pest, and the environment, all of which are variable. Consequently, effectively managing insect pests of field crops requires considerable knowledge about the pests and the factors that affect their populations.

Tables 13.1 through 13.4 (which are described and appear later in the chapter) are abridged lists of insect pests of alfalfa, corn, soybean, and wheat in Illinois, species that represent a broad range of pest types, from key pests to those that infrequently cause economic losses. Not all species that occur in these crops are listed; rather, we included those that are encountered with relative frequency, at least in some regions of the state, or that represent unique threats. For example, blister beetles present in alfalfa hay may be toxic to livestock, particularly horses. We also included pests that transmit disease pathogens—aphids transmit viruses that cause diseases in wheat, bean leaf beetles transmit the virus that causes bean pod mottle in soybean, corn flea beetles transmit the bacterium that causes Stewart's bacterial wilt and leaf blight of corn, and wheat curl mites transmit the virus that causes wheat streak mosaic. For a more complete list of insect pests of field crops in Illinois, consult the tables in Chapter 2 in *Illinois Pesticide Applicator Training Manual 39-2: Field Crops* (2004, University of Illinois).

Note: Use of the term insects *in this chapter also includes insect relatives, such as mites.*

Although more than 100 species of insects can cause injury to alfalfa, corn, soybean, and wheat in Illinois, usually only a few species are capable of causing significant economic losses in crop yield or quality. These few species are often referred to as "key pests" because most producers develop their insect management strategies with these pests as a focus. Some key pests threaten crops annually, whereas others pose serious threats only when environmental conditions favor their survival and development.

Following are the key insect pests of the primary Illinois field crops:

- Alfalfa—alfalfa weevil, potato leafhopper
- Corn—corn rootworms, corn borers (European and southwestern), cutworms (primarily black cutworm), ear-attacking caterpillars, subterranean insects
- Soybean—bean leaf beetle, Japanese beetle, soybean aphid, twospotted spider mite
- Wheat—aphids, armyworm, Hessian fly

The species chosen for this list could be debated, but our rationale was to include insects characterized by one or more of four criteria: They occur relatively frequently at levels that threaten crop yields or quality; they can cause significant crop losses under certain circumstances (drought conditions, for example); they are the source of regular expenditures for control tactics; and they cannot be controlled after crop injury has been detected.

This chapter provides information about developing insect management strategies for alfalfa, corn, soybean, and wheat in Illinois, with focus on key pests, although we also provide observations about others. However, we do not include detailed lists of insect-resistant cultivars, insecticides, or other management tactics. Such details, which change fairly often, can be found at the University of Illinois Integrated Pest Management (IPM) website, www.ipm.illinois.edu. This site also will direct you to *the Bulletin* (www.ipm.illinois.edu/bulletin), a newsletter published weekly throughout the growing season to provide updates on current and pending situations regarding insects, weeds, and plant diseases as well as crop conditions. Current recommendations for management of specific insect pests and the issues associated with insect management tactics are addressed frequently in *the Bulletin*. More information about specific insects and scouting guidelines can be found in the *Field Crop Scouting Manual* and the accompanying CD (2004, University of Illinois).

Developing Insect Management Strategies

Broadly speaking, there are two strategies for managing insects that attack alfalfa, corn, soybean, and wheat in Illinois—preventive and curative (also referred to as therapeutic and remedial in other publications). There are benefits and limitations to both strategies, but both have merit under appropriate circumstances. The choice of strategies requires knowing the biology and ecology of the target pests, as well as a thorough understanding of the potential for any given pest to cause economic losses. The frequency of occurrence of a pest, the type of injury it causes, and the expectations for success of selected management tactics also dictate whether preventive or curative strategies are most suitable.

Preventive and curative strategies and their associated tactics should be integrated into a comprehensive approach of managing insect pests with environmentally and economically sound practices, which is one working definition of IPM. Integrating strategies and tactics safeguards against ecological disruptions, such as pest resistance or destruction of natural enemies, that often develop as a consequence of widespread reliance on a single tactic.

Preventive strategies are used primarily for insects that cannot be controlled easily or effectively after crop injury is discovered. Preventive strategies may incorporate cultural control tactics (farming practices such as crop rotation, tillage, and weed control), planting insect-resistant crops, and applying insecticides. *Curative strategies* usually focus on timely field scouting during the crop-growing season, followed by the use of insecticides if the density of an insect pest has reached or exceeded the economic threshold, a guiding principle of insect pest management programs.

Economic thresholds for insects usually are defined as the numbers of insects or the amount of crop injury that warrants a control tactic to prevent increasing numbers of insects from reaching economic-injury levels (**Figure 13.1**). An economic-injury level is the number of insects or the level of injury at which the cost of control equals the value of crop loss, and economic crop loss occurs when the value of crop loss exceeds the cost of control. Economic thresholds can be employed in conjunction with preventive strategies (for example, numbers of western corn rootworms in corn or soybean fields during the preceding year), but they are most commonly associated with the use of insecticides to control most insects that infest alfalfa, corn, soybean, or wheat during the growing season. Economic thresholds and guidelines for their use have been determined for many, although not all, insect pests that attack field crops in Illinois. Static thresholds are provided as rules of thumb in this chapter. However, it is important to note that economic thresholds should be dynamic because they are influenced by fluctuating variables such as crop value, costs of control, and crop susceptibility, the last of which can be affected by crop stress and a crop's relative tolerance of or resistance to insect attack. In general, economic thresholds decrease as crop value increases, increase as cost of control increases, and decrease as crop susceptibility increases. When dynamic economic thresholds are available for a given insect pest, we provide the necessary reference(s) to access them.

It is also important to recognize that making decisions about insect pest management should be placed in context with other factors. Natural enemies of pests (predators, parasitoids, and pathogens) and weather that is unfavorable for survival and development of pests may suppress their populations. Sharp declines in densities of some insect pests (often referred to as "population crashes") have been associated with epizootics of disease pathogens (**Figure 13.2**), large populations of predators, and inclement weather conditions. Consequently, estimates of densities of insect pests and/or the amount of crop injury should be accompanied by assessments of the potential impact of natural enemies and impending weather conditions.

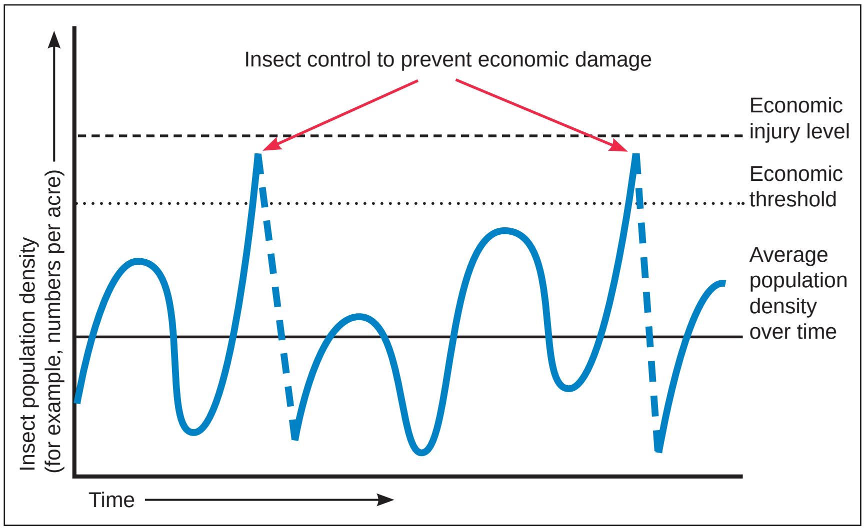

Figure 13.1. The relationship of average insect population density over time, economic threshold, and economic injury level, with insect control decisions indicated.

The following sections include basic plans for developing insect management strategies for alfalfa, corn, soybean, and wheat in Illinois. The plans incorporate relevant information associated with the key pests of each crop as well as expectations for their management. Some details about the pests (such as descriptions and scouting procedures) are not included because such information is widely available in print and on the Internet. Insect control tactics, including the use of transgenic crops and insecticides, are discussed in general terms, excluding references to specific products. Consult references with current insect management information for recommendations about specific insect control products.

Figure 13.2. Armyworm larvae infected with virus.

In summary, developing a sound insect management program for insects that may threaten production of field crops in Illinois requires knowledge about these factors:

- the biology, ecology, relative frequency, and crop loss potential for the key pests of the crop
- the basic principles (scouting tactics, economic thresholds) associated with key pests and occasional pests
- the impact of natural enemies and weather on populations of insect pests
- the practicality and consistency of effectiveness of different insect management tactics for key pests and occasional pests
- the economic, ecological, and environmental consequences of insect management activities

Alfalfa

Because of its perennial and lush growth, alfalfa is an excellent habitat for many insects, including species destructive to alfalfa and other crops, species that inhabit the alfalfa but have little or no effect on the crop, pollinating insects, incidental visitors, and predators and parasitoids of other insects. Because of the presence of so many beneficial insects in alfalfa, it is very important that chemical insecticides be used judiciously and only when necessary to avert significant economic losses.

Many species of insects can reduce alfalfa yield, impair forage quality, or reduce the vitality and longevity of the crop (see **Table 13.1** for an incomplete list of pests of alfalfa found in Illinois). However, only the alfalfa weevil and potato leafhopper are considered key pests. These two insects threaten the alfalfa crop at distinctly different times—alfalfa weevils threaten the first cutting, potato leafhoppers threaten the second and third cuttings—so insect management strategies for alfalfa should span its growing season. Failure to manage economically threatening numbers of either pest on any given cutting can affect the yield of subsequent cuttings and reduce the long-term productivity of the stand.

Developing insect management strategies for alfalfa begins with the purchase of seed—different varieties of alfalfa have different levels of tolerance or resistance to alfalfa weevils and/or potato leafhoppers. Currently there are no alfalfa varieties truly resistant to alfalfa weevils, although some varieties tolerate light to moderate feeding by the larvae. For potato leafhoppers, however, there are

Table 13.1. Insect and mite pests of alfalfa in Illinois.

Chew on leaves (defoliators) and/or stems	Suck plant fluids	Feed on below-ground plant parts
alfalfa blotch leafminer[a] alfalfa caterpillar alfalfa weevil blister beetles[b] clover leaf weevil cutworms[b] fall armyworm[c] grasshoppers[b] serpentine leafminers[b] webworms[b,c]	cowpea aphid pea aphid plant bugs[b] potato leafhopper spittlebugs[b]	clover root curculio cutworms[b,c]

Insects chosen for inclusion are encountered with relative frequency, at least in some regions of the state, or represent unique threats.
[a]Larvae (maggots) mine between leaf surfaces, rather than chew on leaves.
[b]More than one species.
[c]Primarily a pest of small alfalfa plants in new seedings.

many glandular-haired alfalfa varieties that are resistant to this very important pest. After the variety of alfalfa has been selected and seeded, insect management plans can be developed separately for the two key pests.

Alfalfa weevil. Newly hatched alfalfa weevil larvae feed in the growing tips of alfalfa plants in the spring, relatively early in southern counties and later in northern counties. An early sign of injury is pinholes in newly opened leaves. As larvae grow larger, they shred and skeletonize the leaves (**Figure 13.3**). Heavily infested fields appear frosted because of the loss of green leaf tissue. Anything that slows spring alfalfa growth increases the impact of weevil injury. Adults may also cause some injury a little later in the spring (leaves appear feathered, stems may be scarred), but the injury usually is not economic. However, both surviving larvae and newly emerged adults may affect regrowth after the first cutting in some years. They remove early shoot growth, depleting food reserves in the roots and reducing the stand.

Figure 13.3. Alfalfa weevil larva (inset) and injury to leaves. (Larger photo courtesy Matt Montgomery.)

The key to effective management of alfalfa weevils is timely monitoring. To determine when to begin scouting, development of alfalfa weevil larvae can be estimated with degree days accumulated after January 1 (www.isws.illinois.edu/warm/pestdata). However, in general, growers should inspect their fields from the time alfalfa begins to grow until first harvest and should examine the stubble after the first cutting of alfalfa has been removed. A rule of thumb for control of alfalfa weevils on the first crop of alfalfa is that treatment may be warranted when there are 3 or more larvae per stem and 25% to 50% of the tips have been skeletonized, depending on the height of the crop and the vigor of growth. Tall, rapidly growing alfalfa can tolerate considerable defoliation without a subsequent loss in yield.

Tables that incorporate the value of alfalfa hay and the cost of control may be consulted to determine if numbers of alfalfa weevils have exceeded economic levels. A primary source for this information is *Pest Management of Alfalfa Insects in the Upper Midwest*, published by Iowa State University in 1999. The decision-making table is excerpted, cited, and explained in early-season issues of *the Bulletin* (www.ipm.illinois.edu/bulletin) nearly every year.

After harvest of alfalfa, control may be warranted when larvae and adults are feeding on more than 50% of the crowns and regrowth is prevented for 3 to 5 days. This amount of injury usually requires 4 to 8 larvae per square foot.

Parasitic wasps and a fungal disease may regulate alfalfa weevil populations in the spring. When scouting, look for signs of parasitism and for diseased weevils (discolored, moving slowly, or not moving at all). When natural enemies and pathogens suppress weevil numbers, insecticide treatments may not be necessary.

Grazing and early cutting at first harvest are also effective tactics for managing alfalfa weevils in some areas, assuming that yield and quality are not compromised.

Potato leafhopper. Because potato leafhoppers do not overwinter in Illinois, they usually do not appear in alfalfa fields in Illinois until prevailing winds transport them from farther south in late April or early May. Nymphs develop from the eggs deposited by the immigrant females, and both nymphs and adults suck fluids from alfalfa plants (**Figure 13.4**). Several generations occur throughout the summer before cold temperatures kill the leafhoppers in the fall.

Nymphs cause more injury than adults. Initial injury is characterized by a V-shaped yellow area at the tips of the leaflets, often called “hopperburn” or “tipburn.” As the injury progresses, the leaves become completely yellow and

Figure 13.4. Potato leafhopper nymph (left) and adult. (Photo courtesy Marlin E. Rice.)

may turn purple or brown and die. Severely injured plants are stunted and bushy. Leafhopper injury also causes plants to produce more sugars and less protein and vitamin A, resulting in lower-quality alfalfa. If leafhoppers deplete root reserves of the late-season growth of alfalfa, the plants will be less hardy and may not survive the winter.

Sampling with a 15-inch-diameter sweep net before injury appears is the best method for monitoring populations of potato leafhoppers in alfalfa. By the time symptoms of injury appear, considerable yield and nutritional quality may have been lost. Economic thresholds are based on the number of leafhoppers per sweep of the sweep net. Tender, regrowing alfalfa is particularly susceptible to potato leafhopper injury, so scouting after a cutting is critical. Taller, more mature alfalfa can tolerate more leafhopper injury, and economic thresholds vary accordingly. As a rule of thumb, an insecticide may be warranted for alfalfa up to 3 inches tall when there is an average of 0.2 leafhopper per sweep. The treatment thresholds for 3- to 6-inch alfalfa, 6- to 12-inch alfalfa, and alfalfa taller than 12 inches are 0.5, 1, and 2 leafhoppers per sweep, respectively.

Tables that incorporate the value of alfalfa hay and the cost of control may be consulted to determine if numbers of potato leafhoppers have exceeded economic levels. A primary source for this information is *Pest Management of Alfalfa Insects in the Upper Midwest* (Iowa State University, 1999). Numerous decision-making tables have been published and are accessible from IPM websites in many states (e.g., Pennsylvania State University, paipm.cas.psu.edu/fldcrop/table18.htm).

As indicated earlier, glandular-haired alfalfa is resistant to moderate densities of leafhoppers. However, these varieties will not prevent leafhopper infestations during the first year of seeding, during seedling regrowth immediately after cutting, or during years when leafhopper infestations are severe. It is also important to note, however, that the economic thresholds developed for potato leafhoppers in alfalfa are higher in glandular-haired alfalfa, which can tolerate higher densities of this pest.

Corn

Corn has relatively more significant and frequently occurring insect pests than all other field crops grown in Illinois. Consequently, knowledge about the potential threats posed by several different insect species in different areas of the state is essential for developing sensible and effective insect management strategies for corn.

Collectively, corn rootworms, corn borers, cutworms, ear-attacking insects, and subterranean insects meet all of our criteria for key pests, including regular expenditures for their control with transgenic Bt corn hybrids and/or seed- or soil-applied insecticides. (See **Table 13.2** for an incomplete list of pests of corn found in Illinois.) Because these insect control products are used by corn growers to prevent yield losses caused by multiple pests and are the foundation of most insect management strategies for corn, they will be discussed in more detail. However, it is important to note that the use of these products is not warranted in all fields all of the time. The use of insect control products should be integrated with other tactics, including such preventive measures as crop rotation and weed control. In addition, insect management strategies for corn should include timely field scouting and knowing how and when to make insect-control decisions. A basic scouting plan for corn in Illinois should include looking for particular pests at particular times:

- early-season insects, such as cutworms, white grubs, and wireworms, shortly after crop emergence
- first-generation corn borers in early to mid-June (European corn borers statewide, southwestern corn borers in southern Illinois)
- corn rootworm adults and western bean cutworm eggs and larvae (primarily in northern counties) in July
- second-generation corn borers in late July and early August (European corn borers statewide, southwestern corn borers in southern Illinois)

Dedication to this basic scouting plan will enable corn growers to note the presence or absence of insect pests at critical times throughout a growing season and to assess the frequency of occurrence of insect pests in their fields over time.

Table 13.2. Insect and mite pests of corn in Illinois.

Feed on below-ground plant parts	Feed at, just above, or just below the soil surface	Chew on leaves (defoliators) and/or stems	Tunnel inside plants	Feed on silks, ears	Suck plant fluids
corn rootworm larvae[a] grape colaspis larvae seedcorn beetles[a] seedcorn maggot slugs[a,c] white grubs[a] wireworms[a]	billbug adults[a] cutworms[a] stink bugs[a] webworms[a]	armyworm cereal leaf beetle corn blotch leafminer[b] corn earworm corn flea beetle corn rootworm adults[a] cutworms[a] fall armyworm grasshoppers[a] slugs[a,c] southern corn leaf beetle webworms[a] yellowstriped armyworm	billbug larvae[a] European corn borer southwestern corn borer stalk borer	corn earworm corn rootworm adults[a] fall armyworm grape colaspis adults grasshoppers[a] Japanese beetle sap beetles[a] western bean cutworm woollybear caterpillars[a]	chinch bug bird cherry-oat aphid corn leaf aphid English grain aphid stink bugs[a] twospotted spider mite thrips[a]

Insects chosen for inclusion are encountered with relative frequency, at least in some regions of the state, or represent unique threats.
[a]More than one species.
[b]Larvae (maggots) mine between leaf surfaces, rather than chew on leaves.
[c]A mollusk, not an insect or mite.

Preventive Insect Control Products for Corn

Bt corn. Bt corn is a type of corn that has been genetically altered through biotechnology by inserting genes from the soil bacterium *Bacillus thuringiensis* (usually abbreviated as Bt) into the corn genome. Bt genes trigger production of toxic proteins that kill certain insects when the insects feed on the growing corn plants. Bt corn hybrids first became available commercially in the mid-1990s, primarily for management of European and southwestern corn borers. In 2003, the first Bt corn hybrids that express a protein to kill corn rootworm larvae were registered for commercial use.

Transgenic traits for insect control have been "stacked" in elite corn hybrids with traits for herbicide tolerance, resulting in double-, triple-, and quad-stacked hybrids. Bt corn hybrids available from most seed companies now offer protection against some or all (depending on the hybrid) of the following insect pests of corn in Illinois—black cutworm, corn earworm, corn rootworms (northern and western), European corn borer, fall armyworm, southwestern corn borer, stalk borer, and western bean cutworm.

To preserve the durability and effectiveness of Bt corn, the United States Environmental Protection Agency (EPA) mandates insect resistance management (IRM) strategies for Bt corn. The key IRM strategy for Bt corn is planting refuges of corn that does not include the Bt trait for the target insect(s). In general, a refuge ensures survival of target insects that are not exposed to Bt toxins, enabling these Bt-susceptible insects to mate with the rare individuals that possess a gene that imparts resistance to Bt.

As Bt corn products and programs change, IRM guidelines and requirements will change, too. However, as of 2009, corn producers who plant Bt corn are required to plant at least 20% of their acres to non-Bt corn. We recommend that refuge acres be planted within or adjacent to the field of Bt corn to ensure the best mixing of susceptible and potentially resistant insects. Some options for the arrangement of refuge acres with Bt corn are presented in **Figure 13.5**. For a thorough explanation about the importance of managing Bt corn technology and specifics about planting refuges, visit the National Corn Growers Association "Insect Resistance Management" website (ncga.eweb3.socket.net/node/168).

Bt corn hybrids are convenient and effective insect management tools, and corn growers have enthusiastically adopted their use to control or suppress the most important and sometimes difficult-to-control insect pests of corn in North America. However, the benefits of Bt corn will continue to be realized only if it is grown responsibly and is integrated with other insect management tactics.

Seed-applied insecticides. In the late 1990s, chloronicotinyl insecticides were introduced as seed treatments that would protect corn against attack by several insects. The convenience and promised efficacy of these products generated so much demand that their use has become widespread. Most corn seeds now are treated with either a low or high rate of a chloronicotinyl insecticide.

Chloronicotinyl insecticides, also known as nicotinoids or neonicotinoids, are systemic, meaning they are absorbed by treated plants and translocated to other plant tissues. Insects are killed either by contact with the chemical in the soil or by feeding on plant parts into which the chemical has been translocated.

All rootworm Bt corn seed is treated with a low rate of a chloronicotinyl insecticide because the Bt toxin for

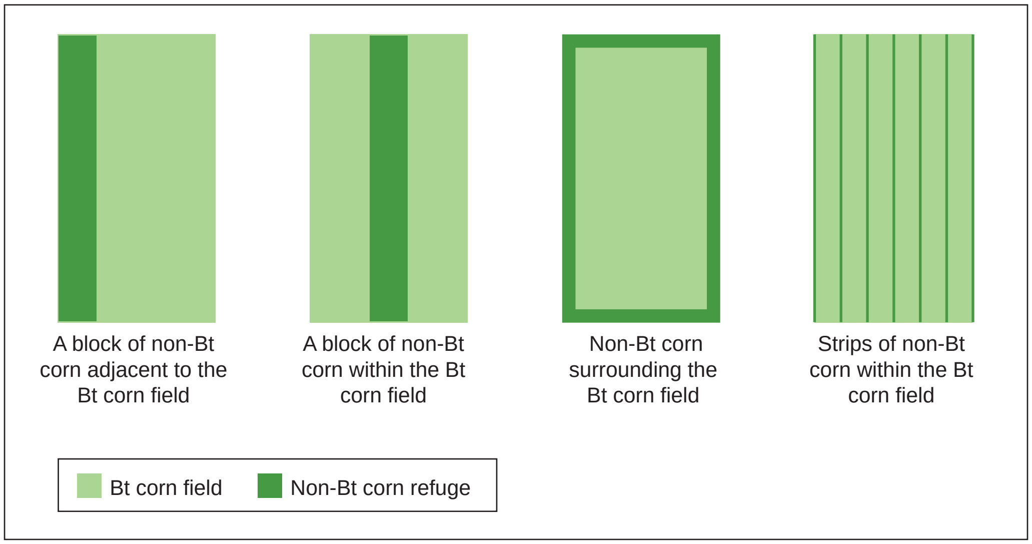

Figure 13.5. Types of arrangements of non-Bt corn refuge acres with Bt corn.

rootworms does not control other soil-inhabiting insects, such as white grubs and wireworms. The low rate of seed-applied insecticides also is labeled for control of a few aboveground pests such as corn flea beetle and southern corn leaf beetle. Seed of many non-Bt corn hybrids is treated with either a low or high rate of a chloronicotinyl insecticide, with the higher rate directed toward control of corn rootworm larvae.

Research has not demonstrated that the widespread use of chloronicotinyl insecticides in corn seed treatments is warranted. There are limited data regarding the efficacy of these products against several of the target species. However, research conducted over several years has shown that seed-applied chloronicotinyl insecticides are not very effective for control of corn rootworm larvae when rootworm infestations are heavy.

Soil-applied insecticides. From the 1950s until the introduction of chloronicotinyl seed treatments and rootworm Bt corn, soil-applied insecticides were the primary preventive tactic for control of insects that feed on belowground parts of corn plants. For 40 years, millions of corn acres in Illinois were treated annually with soil insecticides, although their use in many fields was not always warranted. The widespread use of rootworm Bt corn hybrids and chloronicotinyl seed treatments has reduced the number of corn acres treated with soil insecticides. However, soil insecticides remain a viable alternative for control of rootworms and can be applied to the corn refuges associated with rootworm Bt corn. In addition, soil insecticides protect against other soil-inhabiting insects, such as white grubs and wireworms, insects that cannot be controlled effectively after the injury they cause has been discovered.

Most soil insecticides are applied during planting, either directly into the seed furrow or as a 6- to 8-inch band over the planted row. The placement and rate of application of a soil insecticide depend on both the product and the target insect(s). Both granular and liquid formulations of soil insecticides are available. In general, soil insecticides are effective for controlling rootworms and other soil-inhabiting insect pests, but their efficacy can be compromised by unfavorable environmental conditions, such as too much or too little soil moisture.

Key Insect Pests of Corn

Corn rootworms. Northern and western corn rootworms are the most important insect pests of corn in North America. Although northern corn rootworms are capable of causing significant injury to corn in Illinois, the western corn rootworm is the predominant and most injurious rootworm species in the state. Most of the information here applies primarily to western corn rootworms, although the management tactics discussed are relevant for both species unless indicated otherwise.

Corn rootworm larvae hatch from overwintered eggs in May and June. If corn has been planted in the field, larvae begin feeding on roots. Rootworm larvae survive on the roots of corn and more than a dozen species of grass, such as foxtail species. They cannot survive on the roots of soybean and other broadleaf species.

Newly hatched corn rootworm larvae tunnel into root tissue; older larvae feed on the outside of the roots (**Figure 13.6**). As the larvae grow and continue to feed, they often prune roots back to the stalk (**Figure 13.7**). Large densities of corn rootworm larvae may cause extensive damage to the root system, reducing the efficient uptake of water and nutrients. Severe root pruning may cause plants to lodge (**Figure 13.8**). Yield losses are most acute when both root pruning and lodging occur. After larvae complete feeding, they pupate within small earthen cells, where they transform to adults.

Western corn rootworm adults (**Figure 13.9**) begin to emerge in late June and early July. Although they will feed on corn leaves and weed blossoms, they prefer corn silks

Figure 13.6. Corn rootworm larvae feeding at the base of a corn plant.

Figure 13.7. Severe pruning injury caused by corn rootworm larvae.

Figure 13.8. Corn lodged as a result of severe rootworm larval injury.

and pollen. Typically, the adults chew on fresh, green silks at the ear tip, injury that may interfere with pollination. Rootworm adults mate, and the females lay eggs in the soil from late July to early September. The eggs of western corn rootworms remain in the soil until the following spring, when the larvae hatch. There is only one generation of western corn rootworms each year.

For many years after their first appearance in Illinois in 1964, western corn rootworms could be managed effectively by annually rotating corn and soybean in the same field. The females laid eggs only in corn fields, and larvae could not survive on soybean roots. However, by the mid-1990s, a variant western corn rootworm had become established in several counties in east-central Illinois and northwestern Indiana. Research has determined that variant western corn rootworm females lay eggs in soybean fields, although they also will lay eggs in corn fields and fields planted with other crops such as alfalfa. Consequently, crop rotation no longer is reliable for managing western corn rootworms in areas where the variant has become established. The range of the variant western corn rootworm has expanded to include most of the northern two-thirds of Illinois as well as regions of other states—the northern two-thirds of Indiana, southeastern Iowa, southern Michigan, western Ohio, and southern Wisconsin.

Most corn growers prevent injury caused by corn rootworm larvae by planting a rootworm Bt corn hybrid, applying a soil insecticide, or planting corn after soybean, which is still an effective tactic in southern Illinois, where the variant western corn rootworm is not established. Rootworm Bt corn hybrids and soil insecticides usually provide effective control of corn rootworm larvae, although incidents of inadequate root protection by all rootworm control products have been noted.

Scouting for western corn rootworm adults in the summer is recommended for determining whether a preventive tactic is needed the following year. The recommended scouting procedures and thresholds for western corn rootworm adults are different for corn planted after corn and corn planted after soybean. If a producer intends to plant corn after corn, counting western corn rootworm adults on corn plants every week from mid-July through August is recommended. As a rule of thumb, an average of 0.75 western corn rootworm adults per plant suggests that a rootworm control product is warranted when corn is planted the next year. If a producer intends to plant corn after soybean in an area where the variant western corn rootworm is established, placement of yellow sticky traps in soybean fields from late July through August is recommended. As a rule of thumb, an average of 5 to 10 western corn rootworm adults per trap per day suggests that a rootworm control product is warranted when corn is planted the next year.

More detailed information about these scouting procedures and interpretation of results is accessible at the University of Illinois IPM website (www.ipm.illinois.edu/fieldcrops/insects/western_corn_rootworm/index.html).

Management of corn rootworm adults is necessary only if their feeding on corn silks interferes with pollination. Application of a chemical insecticide to prevent silk-clipping damage is warranted if there is an average of 5 or more adults per plant, the beetles are clipping silks to within half an inch of the ear tip, and pollination is not complete.

Corn borers (European and southwestern). European and southwestern corn borers are among the most important insect pests of corn in North America; both are capable of causing significant yield losses. European corn borers are present throughout the state of Illinois, whereas southwestern corn borers usually are not found very far north of Illinois Route 50.

Both species of corn borer usually complete two generations per year in Illinois. The injury caused by the first generation of both species is similar—feeding on leaves in corn whorls in June, followed by tunneling of larger larvae in the stalks (June–July). Newly hatched larvae of the second generation of European corn borers feed initially on leaf-collar tissue and pollen that accumulates in the leaf-collar areas, after which more mature larvae tunnel into the stalks (**Figure 13.10**), ear shanks, and ears. Second-generation southwestern corn borer larvae also tunnel into corn stalks (**Figure 13.11**), eventually tunneling to the base of the plant, where they girdle the stalk internally while excavating an overwintering cell.

Tunneling by corn borer larvae causes yield loss due to interference with the transport of nutrients and water in the stalk and leaves. In addition, tunneling weakens cornstalks and predisposes them to stalk rot organisms, often causing stalks to lodge or break. Feeding in the ear shank may result in ear drop. The second generation of both species causes more economic damage than the first generation.

Before Bt corn hybrids were available for corn borer control, management of both European and southwestern corn borers required timely scouting for first-generation larvae and their injury and for second-generation egg masses, followed by well-timed insecticide applications before the larvae tunneled into corn stalks. Management worksheets were developed to aid in making decisions about control of first- and second-generation European corn borers with insecticides. These worksheets are accessible as "calculators" at the University of Illinois IPM website (www.ipm.illinois.edu/fieldcrops/insects/european_corn_borer/index.html) and are still useful for managing European corn borers in non-Bt corn, including the refuges associated with Bt corn.

Figure 13.9. Western corn rootworm adult.

Figure 13.10. European corn borer larva.

Figure 13.11. Southwestern corn borer larvae, pupae, and stalk tunneling. (Photo courtesy Ron Hines.)

Bt corn hybrids that express proteins that are toxic to corn borers are extremely effective for controlling both species, with expectations of at least 99% control. We speculate that the widespread planting of Bt corn hybrids for corn borer control has reduced densities of European corn borers dramatically since the mid-1990s, with historic lows being recorded in 2007 and 2008. In light of the very low numbers of European corn borers in many areas, some corn growers have questioned the continued need for Bt corn hybrids for corn borer control. However, many elite Bt corn hybrids express proteins for control of both corn rootworms and corn borers, and most corn growers wish to continue planting "stacked" hybrids because of their effectiveness, convenience, and yield benefits. So compliance with IRM strategies, including planting refuges with corn that does not express the Bt protein for corn borer control (see **Figure 13.5**), is essential for the long-term viability of the technology.

Cutworms (primarily black cutworm). Although several species of cutworms feed on young corn plants, the most economically threatening species in Illinois is the black cutworm. Other cutworm species, such as the claybacked cutworm and sandhill cutworm, may cause significant stand loss, but their distributions are limited, so their overall impact is relatively minor.

Black cutworms do not overwinter in Illinois. Prevailing winds during March through May assist black cutworm adults migrating northward from southern states. When they arrive in Illinois, female black cutworms typically seek small winter annual weeds on which to lay eggs. After hatching, the small larvae feed on the weeds until herbicides kill the weeds, after which larger larvae begin feeding on corn seedlings.

Small black cutworm larvae feed on the leaves of seedling corn plants. Such leaf feeding does not result in economic damage, but the injury is an early warning that larger larvae will cut off seedlings just above, at, or below the soil surface or will chew into the base of the plant (**Figure 13.12**). Plants cut off below the growing point do not survive, and a significant reduction in plant population may result in significant yield loss. Although plants cut off above the growing point usually survive, there is evidence that such injury may contribute to yield losses.

As the larvae grow in size, they consume larger numbers of corn seedlings. A single cutworm will cut three or four seedlings if the plants are in the two-leaf stage or smaller. After corn plants reach the four-leaf stage, a single cutworm will cut only one or two plants during the remainder of its larval stage. Development through six or seven instars (stages of larval development) requires approximately a month, after which the larvae pupate and then transform into adults. Adults of the second and later generations typically do not lay their eggs in corn fields, so only the first generation of black cutworms threatens corn production in Illinois.

Pheromone traps can be used to monitor for black cutworm moths flying into Illinois in the spring. Although the numbers of moths captured in these traps do not necessarily correlate with larval injury in given fields, spring moth captures provide an early warning of the pest's appearance. Degree days accumulated from the date of an intense capture of moths (nine or more captured in one to two nights) can be used to estimate black cutworm larval development (www.isws.illinois.edu/warm/pestdata).

Figure 13.12. Black cutworm larva and injury to small corn plant. (Photo courtesy Robert Bellm.)

Control of winter annual weeds in the fall reduces the potential that black cutworm females will lay eggs in the field when they arrive in Illinois the following spring. Seed-applied chloronicotinyl insecticides, some soil insecticides, and some Bt corn hybrids provide protection against black cutworms. However, these products may not provide adequate control of large infestations of large black cutworm larvae, so early-season scouting for the larvae and signs of their injury to corn seedlings is strongly encouraged. As a rule of thumb, a "rescue" insecticide application may be warranted if 2% to 5% of corn seedlings are cut below ground or 6% to 8% are fed on or cut above ground and black cutworm larvae are still feeding.

Ear-attacking caterpillars. In the past, caterpillars that fed on the ears of field corn were largely ignored, primarily because they were difficult to control and yield losses attributed to their injury were poorly understood. However, Bt corn hybrids that express proteins that are toxic to corn borers also control or suppress corn earworms and fall armyworms, both of which feed in corn ears. In addition, the western bean cutworm has become fairly well established in northern Illinois, and this species is also capable of causing significant injury to corn ears. Collectively, ear-attacking caterpillars can be considered key pests of corn.

Fall armyworms do not overwinter in Illinois, and corn earworms likely survive the winter only in southern Illinois. Consequently, infestations of both insects originate primarily from immigration of moths from farther south. The adults of both species lay eggs in corn fields, often

Figure 13.13. Fall armyworm larva (inset) and injury to corn leaves.

Figure 13.14. Corn earworm larva and injury to corn ear. (Photo courtesy Mitch Wirth.)

Figure 13.15. Western bean cutworm larva (inset) and injury to corn ear. (Larva photo courtesy Jim Donnelly.)

preferring later planted fields, and larvae that hatch from the eggs feed on leaves (**Figure 13.13**). Injury to leaves appears ragged and often messy—considerable frass, or caterpillar excrement, is produced from the caterpillars' feeding. Although this injury typically does not cause economic losses, it indicates the presence of the caterpillars and the potential for injury to corn ears. Adult female corn earworms also lay eggs on corn silks, and newly hatched larvae usually enter the ears at the tips (**Figure 13.14**).

The western bean cutworm has spread rapidly eastward from the Great Plains since 2000, being found for the first time in Illinois in 2004. Western bean cutworms overwinter as prepupae in Illinois, but adults do not emerge until late June or July. Females lay eggs on the upper leaves of corn, and young larvae eventually move downward on the plant to feed on silks and ears, entering the ears through the tips or the sides, often chewing directly through the husks (**Figure 13.15**). Multiple larvae can infest one ear, causing significant injury to developing kernels.

Although there are scouting procedures for all three species, all of these ear-attacking caterpillars are difficult to control with chemical insecticides, especially after the larvae enter the corn ears. Economic thresholds for corn earworms and fall armyworms are often based on the percentage of plants with whorl injury, and they are unreliable relative to yield loss caused by damage to the ears. An insecticide application may be warranted for control of western bean cutworms if 8% of the plants have egg masses and/or small larvae. In most instances, however, insecticides applied after ear-attacking caterpillars have entered the ears are not effective.

The current primary tactic for managing ear-attacking caterpillars in field corn is planting corn hybrids that express Bt proteins that are toxic to one or more of these pests. Please note that not all Bt corn hybrids are effective for controlling all ear-attacking caterpillars.

Figure 13.16. Wireworm larvae.

Figure 13.17. White grub larva (inset) and injury to corn seedling. (Photo courtesy Kevin Nelson.)

Figure 13.18. Grape colaspis larva (inset) and injury to corn seedlings. (Larva photo courtesy Benjamin Kaeb.)

Subterranean insects. This category includes all insects that feed on corn plants below ground except corn rootworm larvae and black cutworms, with primary emphasis on grape colaspis larvae, white grubs, and wireworms. Although these pests often are referred to as "secondary," we include them as key pests because corn growers regularly spend money to control them with seed- or soil-applied insecticides, and the pests cannot be controlled effectively after injury has been detected.

Several species of wireworms (**Figure 13.16**) attack the seed or drill into the base of the stem below ground, damaging or killing the growing point. Aboveground symptoms are wilted, dead, or weakened plants and spotty stands. Grape colaspis larvae and a few species of white grubs (primarily *Phyllophaga* species) (**Figure 13.17**) feed primarily on corn roots early in the season, usually stripping off the fine roots. Injury symptoms above ground include spotty stands, stunting, wilting, and purpling of the leaves and stems, the purpling a result of the plants' inability to take up phosphorous. Injury caused by grape colaspis larvae also results in browning of the tips and edges of corn leaves on small plants (**Figure 13.18**).

It is doubtful that any of these insects occur at economic levels in more than a relatively small percentage of fields every year; however, anticipating their occurrence is difficult. In addition, insecticides are not effective against these pests after the injury has been detected, and the only solution may be replanting (an expensive response) if stand reduction is significant. Consequently, most corn growers rely on experience and past history with these pests to develop management strategies, or they simply rely on seed- or soil-applied insecticides as a form of insurance. Bt corn hybrids do not control grape colaspis larvae, white grubs, or wireworms, although the chloronicotinyl insecticide on the seed should provide some protection. However, control by seed-applied insecticides may not be satisfactory when infestations are heavy.

Soybean

Although significant transformations in insect management have occurred with transgenic Bt corn, soybean insect management in the Midwest still mainly involves regular field scouting to determine whether a chemical insecticide is warranted to prevent yield loss—a curative approach. One preventive tactic is planting seed treated with a chloronicotinyl insecticide, usually in combination with a fungicide, with expectations for early-season protection against insects such as bean leaf beetle, seedcorn maggot, and soybean aphid. The benefits derived from the chloronicotinyls in these seed treatments are still uncertain. More promising is the eventual availability of soybean varieties with resistance to soybean aphids, which will provide soybean growers with a preventive tactic that can be integrated easily into insect management strategies for soybean.

Currently, insect management strategies for soybean should focus primarily on timely field scouting and knowing how and when to make insect-control decisions; see **Table 13.3** for an incomplete list of pests of soybean found in Illinois. A basic scouting plan for soybean in Illinois should include looking for particular insects at particular times:

- early-season insects, such as bean leaf beetle, shortly after crop emergence
- defoliators (insects that chew holes in leaves, such as bean leaf beetle, green cloverworm, and Japanese beetle) and insects or mites that suck plant fluids in June and July, such as soybean aphid and twospotted spider mite
- soybean aphids in late July and August
- late-season defoliators and pod feeders, such as bean leaf beetle and grasshoppers, in late July and August

Dedication to this basic scouting plan will enable soybean growers to note the presence or absence of insect pests at critical times throughout a growing season and to assess the frequency of occurrence of insect pests in their fields over time.

One other recommended skill for making insect control decisions in soybean is the ability to accurately assess the percentage defoliation caused by defoliators. Examples of different levels of soybean defoliation are shown in **Figure 13.19**. Although economic thresholds based on percentage defoliation of soybean have been called into question because of their “age” (they were developed in the 1970s and 1980s), they currently are the most widely published and consistently used thresholds for soybean defoliators. General percentage defoliation levels necessary for treatment with an insecticide range from 40% to 50% during vegetative stages (to about stage V7); 15% to 20% during flowering, pod development, and pod fill; and more than 25% from pod fill to harvest. These thresholds can be used to assess the need for an insecticide application for control of any soybean defoliator, and they will not be repeated in discussions of the key pests that follow.

Bean leaf beetle. Bean leaf beetles overwinter as adults and become active very early in the spring, flying first to alfalfa and clover fields to feed. As soon as soybean plants begin to emerge, the beetles abandon alfalfa and clover fields to colonize soybean fields, where they feed on cotyledons, leaves, and stems (**Figure 13.20**). After they finish feeding, they lay eggs in the soil to begin the first generation.

Adults of the first generation usually emerge in July. The beetles feed on soybean foliage, leaving small holes in the leaves. If the infestation is severe, soybean plants may be completely riddled with holes. The beetles again lay eggs in soybean fields, and a second generation occurs. Adults of the second generation usually emerge in August. They remain in soybean fields as long as there are tender plant parts to chew on. They may chew on pods after the leaves deteriorate, and their feeding creates scars that provide an avenue of infection by certain plant pathogens (**Figure 13.21**). Mild infection results in seed staining; severe infection results in seed decay.

Table 13.3. Insect and mite pests of soybean in Illinois.

Feed on belowground plant parts	Chew on leaves (defoliators) and/or stems	Suck plant fluids	Tunnel inside plants	Feed on pods
bean leaf beetle larvae grape colaspis larvae seedcorn maggot slugs[a,b] white grubs[a] wireworms[a]	bean leaf beetle blister beetles[a] corn earworm cutworms[a] fall armyworm grape colaspis adults grasshoppers[a] green cloverworm Japanese beetle slugs[a,b] thistle caterpillar (adult known as painted lady butterfly) webworms[a] western corn rootworm adults woollybear caterpillars[a] yellowstriped armyworm	plant bugs[a] potato leafhopper soybean aphid soybean thrips stink bugs[a] twospotted spider mite whiteflies[a]	European corn borer soybean stem borer (also known as Dectes stem borer) stalk borer	bean leaf beetle corn earworm grasshoppers[a] stink bugs[a]

Insects chosen for inclusion are encountered with relative frequency, at least in some regions of the state, or represent unique threats.
[a]More than one species.
[b]A mollusk, not an insect or mite.

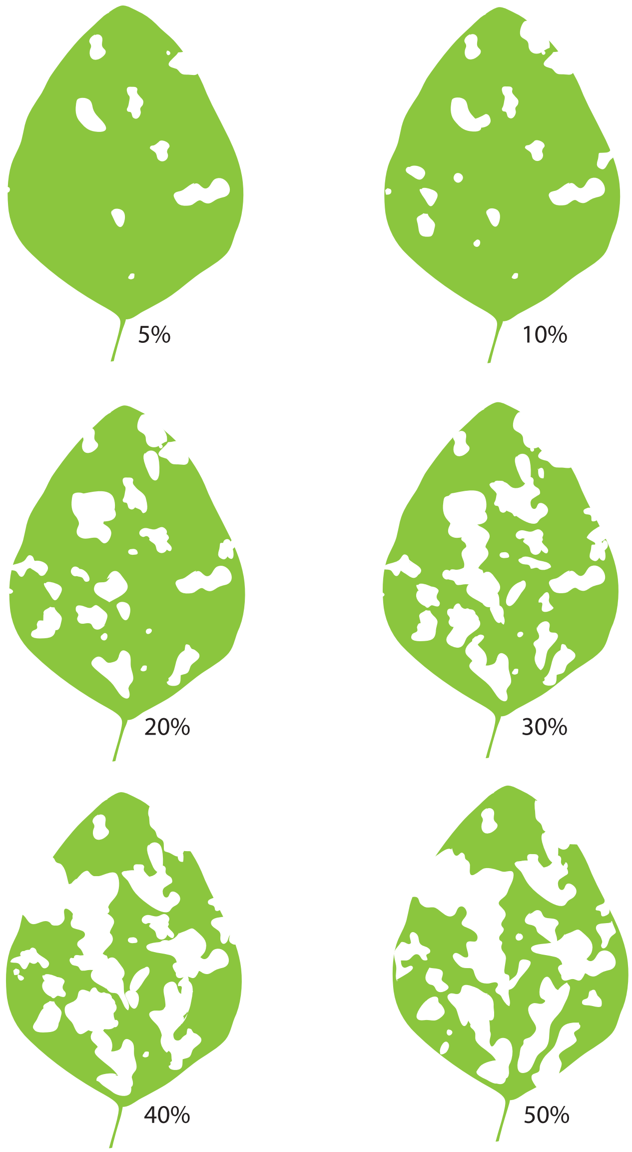

Figure 13.19. Different levels of defoliation of soybean leaves. (Illustration originally published in *Soybean Insects: Identification and Management in Illinois*, 1982, University of Illinois.)

Figure 13.20. Bean leaf beetle (inset) and injury to seedling soybeans. (Beetle photo courtesy Marlin E. Rice.)

Figure 13.21. Bean leaf beetle injury to soybean pods.

Research has shown that seed treatments with chloronicotinyl insecticides effectively control bean leaf beetles that feed on seedling soybeans. Because of the large densities of beetles required to cause economic injury to seedling soybean (16 per foot of row in the early seedling stage or 39 per foot of row at stage V2), foliar-applied insecticides to control bean leaf beetles in seedling soybeans are infrequently justified.

Bean leaf beetles also may transmit the bean pod mottle virus. The virus may overwinter in the adults, so the insect may infect soybeans relatively early in the year. However, the actual timing of transmission is still unknown. Therefore, management guidelines to prevent bean leaf beetles from transmitting the virus have not been established.

An insecticide may be economically justified during the pod-filling stage if percentage defoliation and numbers of beetles per foot of row exceed established economic thresholds. An insecticide for control of adults feeding on pods may be warranted when 5% to 10% of the pods are injured and the leaves are still green.

Japanese beetle. Numbers of Japanese beetles have been very large in some areas of Illinois over the past few years, and defoliation in soybean fields has been conspicuous. Because defoliation of soybeans by Japanese beetles occurs almost exclusively in the upper canopy, the effect on yield is poorly understood. However, their large numbers and very visible activity (they move around a lot, especially on hot days) elicit responses that often result in insecticide applications.

Japanese beetles overwinter as grubs in the soil throughout Illinois. As temperatures warm up in the spring, the grubs begin feeding on the roots of grasses, including corn. Shortly thereafter, Japanese beetles pupate and transform into adults, which begin emerging in June. Japanese beetle adults feed on more than 300 species of plants, including soybean, corn, and many fruits and ornamental plants. By mid- to late July, the very active adults begin feeding on the leaves in flowering soybean fields (**Figure 13.22**). When they finish feeding for the summer, the females lay eggs in the soil, and the grubs develop to the third (and final) instar to overwinter. There is only one generation per year.

Standardized percentage defoliation thresholds can be used for making decisions about controlling Japanese beetles. However, for reasons indicated previously, the correlation between defoliation by Japanese beetles and soybean yield is not clear. Furthermore, defoliation often is not evident throughout an entire field because the beetles occur in clumps, often confined to field edges or other small areas. Consequently, soybean producers are strongly encouraged to assess the situation throughout a field to determine whether "spot treatment" with an insecticide will address the problem.

Figure 13.22. Japanese beetles feeding on soybean leaves. (Photo courtesy Ron Hines.)

Soybean aphid. Soybean aphids were discovered for the first time in North America late in 2000, spreading throughout the Midwest very rapidly thereafter. This species quickly became established as the most important insect pest of soybean throughout the Midwest. Before 2008, widespread outbreaks of soybean aphids occurred primarily during odd-numbered years, with the most economically damaging outbreak occurring in many states in 2003. However, a widespread, economically damaging outbreak occurred in 2008, breaking the every-other-year cycle for this pest. Localized outbreaks of soybean aphids have occurred every year since their discovery.

The soybean aphid has a complex life cycle, with as many as 18 generations annually. Two different host plants are required by the aphid. The aphids spend the winter as eggs on their primary host, buckthorn (*Rhamnus* species), a woody perennial. Nymphs (immature aphids) hatch in the spring, develop through four instars, and become adults that begin giving birth to living young for the next generation. After two to three generations on buckthorn, winged females fly away in search of their secondary host, soybean. Soybean aphids colonize soybean fields and can increase their numbers rapidly—doubling in 3 to 4 days, depending on temperature. On actively growing soybean plants, colonies are found on leaves near the tops of the plants (**Figure 13.23**). On reproductive soybean plants, aphids are found on the undersides of leaves and on stems and pods. When an infestation in a given field becomes very large, winged aphids fly away to seek other soybean fields. Soybean aphids can be found in soybean fields from about mid-June to mid-September in Illinois. Winged aphids begin to fly back to buckthorn in September to complete the annual cycle.

Soybean aphids suck fluids from soybean leaves and stems, causing injured leaves to crinkle or cup. The consequences of their feeding injury include early defoliation, shortened stems, stunting, reduced numbers of pods and seeds, and reduced seed weight. Sooty mold also develops on the honeydew that aphids excrete, causing heavily infested plants to appear dirty. Heavy infestations of soybean aphids can cause significant reductions in yield.

A foliar-applied insecticide may be warranted when densities of soybean aphids reach or exceed 250 aphids per plant, a widely acknowledged economic threshold. However, economic yield loss usually does not occur until densities of aphids reach or exceed 675 aphids per plant (the economic injury level). The economic threshold is conservative to allow for the time necessary to schedule an insecticide application. It is also important to note the presence and activity of predators of soybean aphids, especially the multicolored Asian lady beetle. Large numbers of predators and other natural enemies (parasitoids, pathogens) may prevent soybean populations from reaching the economic injury level.

Twospotted spider mite. We include twospotted spider mite as a key pest of soybean because of its capacity to cause devastating yield losses during widespread, prolonged drought conditions. However, localized outbreaks of twospotted spider mites often occur during years when

Figure 13.23. Soybean aphids on a soybean leaflet. (Photo courtesy Jim Morrison.)

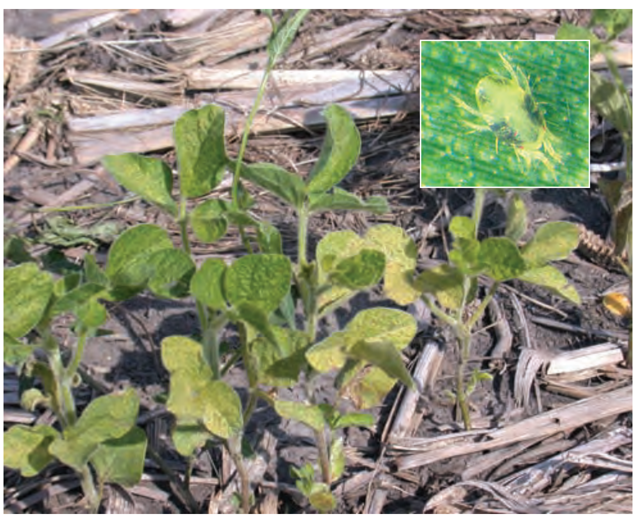

Figure 13.24. Twospotted spider mite (inset) and injury to soybeans. (Mite photo courtesy Marlin E. Rice.)

hot, dry conditions also are localized, so scouting for signs of their presence is recommended every year. If soybeans have an adequate supply of moisture, the mites usually do not cause much, if any economic damage.

Twospotted spider mites usually overwinter as females in areas covered with vegetation or plant debris, often along field edges. They also may overwinter on winter annual weeds within cultivated fields. In the spring, females begin laying eggs on plant leaves. Larvae with six legs emerge from the eggs and progress through two nymphal stages, each with eight legs. After the last nymphal molt, the eight-legged adults emerge. Spider mites complete a generation in 1 to 3 weeks, depending on environmental conditions (primarily temperature), and there are multiple generations within a growing season.

Spider mites crawl from weed hosts to soybean plants, so infestations usually appear first along field edges or in spots within a field. Mites can also move throughout fields by "ballooning"—spinning webs and moving to a position on a leaf from which they can be blown aloft. They can also move from row to row by bridging (moving across leaves in contact) when the canopy is nearly closed.

Spider mites puncture plant cells and suck plant fluids. Damaged plant cells do not recover. Initial injury results in a yellow speckling of the leaves (**Figure 13.24**). Heavy infestations cause leaves to wilt and die, and yield losses can be substantial. Another sign of the presence of spider mites is the webbing they produce on the undersides of the leaves.

Because numbers of twospotted spider mites can increase rapidly during hot, dry weather and because infestations can spread relatively quickly within a field, spider mites must be discovered and treated early to prevent significant yield losses. Reliable economic thresholds have not been developed, so insecticide applications are warranted primarily if prolonged hot, dry weather is expected after symptoms of mite injury begin to appear. Spot treatments along field edges may prevent further movement of spider mites into the field, although scouting throughout the field is strongly encouraged.

Wheat

Few insects cause recurring economic damage to wheat in this state. However, because most wheat is grown in southern counties, where temperatures frequently are suitable for insect survival and development, there is always potential for insect pest problems. Wheat grown in northern Illinois is threatened infrequently by insect problems.

Insect management strategies for wheat in Illinois include components of host plant resistance, cultural control, and the use of insecticides, and they begin with the purchase of wheat seed. (See **Table 13.4** for an incomplete list of pests of wheat found in Illinois.) Varieties resistant to Hessian flies are available, although Hessian flies can develop biotypes that can overcome the genes for their resistance. Wheat growers also can purchase wheat seed treated with a chloronicotinyl insecticide, which will protect wheat seedlings from aphids and reduce the risk of their transmitting the barley yellow dwarf (BYD) virus. Foliar-applied insecticides in the fall are warranted primarily if colonies of aphids begin to increase, although insects that devour seedlings (fall armyworm, for example) should also be monitored.

Insect management for wheat continues with the date of seeding. For decades, "fly-free" dates (dates by which Hessian fly adults have died) have been published, and we still encourage wheat growers to plant after the fly-free dates in their regions. As the term implies, wheat planted after fly-free dates is not exposed to egg-laying female Hessian flies. Wheat planted after the fly-free date also is less susceptible to the BYD and wheat streak mosaic viruses, transmitted by aphids and mites, respectively. Estimates of fly-free dates for wheat in Illinois are provided in Chapter 5.

After wheat begins growing in the spring, regular monitoring for insects is recommended. Numbers of aphids can increase in the spring when environmental conditions are favorable, although yield losses associated with their feeding injury in the spring are not common. Defoliators, such as armyworms and cereal leaf beetles, are the most common insect pests of wheat in the spring, and excessive defoliation may result in significant yield losses. Foliar-applied insecticides are warranted when numbers and injury caused by these pests exceed economic thresholds.

Aphids. Four different species of aphids occur in wheat fields in Illinois—bird cherry-oat aphid, corn leaf aphid (**Figure 13.25**), English grain aphid, and greenbug. All aphids can increase their numbers very quickly. However, there has been very little research to indicate that economic yield losses result from aphid feeding (sucking plant fluids) in Illinois wheat.

Of greater concern with aphids in wheat is their ability to transmit viruses that cause BYD disease. The potential for transmission of the viruses by aphids that colonize wheat in the fall has elicited the use of preventive tactics, such as chloronicotinyl insecticide seed treatments and foliar-applied insecticides in the fall. However, the guidelines for controlling aphids in wheat in the fall are not very well

Figure 13.25. Corn leaf aphids.

developed in Illinois, so foliar-applied insecticides often are applied as insurance treatments. We are not convinced that their widespread use is warranted annually.

When numbers of aphids begin to increase in the spring, there is potential that yield loss might occur from their feeding injury. As a rule of thumb, insecticide may be warranted when numbers reach or exceed 25 to 50 aphids per stem (depending on species: 25 greenbugs, 30 corn leaf or bird cherry-oat aphids, 50 English grain aphids), up to the boot stage. Insecticides are not recommended for aphid control from the dough stage to maturity.

Armyworm. Few armyworms overwinter in Illinois, but some partly grown larvae probably survive the winter under debris in southern counties. Moths that migrate from southern states into Illinois add to the resident population, and large numbers may trigger an outbreak, depending on environmental condition. So the key to effective management of armyworms in wheat is regular field scouting in the spring.

Armyworm moths may lay numerous eggs in wheat fields, especially in areas with thick stands. Young larvae scrape the leaf tissues; older larvae feed from the edges of the leaves (**Figure 13.26**) and consume all of the tissue, working their way up from the bottom of the plants. Injury to the lower leaves causes no economic loss, but injury to the upper leaves, especially the flag leaf, can result in yield reduction. After armyworms devour the flag leaves, they often chew into the tender stem just below the head, causing the head to fall off. After the grain matures or is harvested, the larvae will migrate into adjacent corn fields. Although there are two or three generations each year in Illinois, only the first generation threatens wheat production.

Early detection of an armyworm infestation is essential for effective management. Examine dense stands of wheat for larvae first. Because armyworm larvae feed at night or on overcast days, they usually are found on the ground under plant debris. If the number of armyworms exceeds 6 non-

Table 13.4. Insect and mite pests of wheat in Illinois.

Chew on leaves (defoliators) and/or stems	Suck plant fluids	Tunnel inside plants
armyworm cutworms[a] cereal leaf beetle grasshoppers[a] wheat head armyworm[b]	bird cherry-oat aphid chinch bug corn leaf aphid English grain aphid greenbug Hessian fly wheat curl mite	stalk borer

Insects chosen for inclusion are encountered with relative frequency, at least in some regions of the state, or represent unique threats.
[a]More than one species.
[b]Also feeds on developing grain.

Figure 13.26. Armyworm larva in wheat.

parasitized larvae (at least 3/4 to 1-1/4 in. long) per foot of row, an insecticide may be warranted.

Weather and natural enemies are the major causes of reductions in armyworm numbers. Hot, dry weather promotes the development of parasitoids and diseases, reducing populations of armyworms. Cool, wet weather is most favorable for an outbreak.

Hessian fly. Although Hessian flies have not caused economic damage to wheat in Illinois for many years, their continuing presence and development of new biotypes pose a constant threat to wheat growers. Consequently, planting wheat after fly-free dates and destroying volunteer wheat are widely recommended throughout the United States.

The Hessian fly overwinters as a full-grown maggot inside a puparium. In the spring, maggots change into pupae inside the puparia and emerge as adults. After females have mated, they lay eggs in the grooves on the upper sides of wheat leaves. After hatching from eggs, the maggots move behind the leaf sheaths and begin feeding on the stem. The maggots feed for about 2 weeks and then form a puparium in which they pupate, usually well before harvest time. The small brown puparium, commonly called a "flaxseed," can be found behind leaves next to the stem (**Figure 13.27**). Hessian flies remain in this stage in the stubble throughout the summer. Flies emerge again in late summer and seek egg-laying sites on volunteer wheat plants or on fall-seeded wheat. After hatch, the fall generation of maggots begins feeding on seedling plants.

Figure 13.27. Hessian fly puparium, or "flaxseed" (left), and larva. (Photo courtesy Kevin Black, Growmark.)

Wheat infested in the fall usually is stunted, and the leaves are dark blue-green, thickened, and more erect than healthy leaves. Severely damaged plants may die during the winter. In the spring, injured plants appear much like they do in the fall. In addition, infested plants often break over when the heads begin to fill.

Because foliar-applied insecticides are neither practical nor reliable for control of Hessian flies, the best preventive tactics are destruction of wheat stubble and volunteer wheat and planting resistant or moderately resistant wheat varieties after the fly-free dates. Where wheat is seeded on or after the fly-free date for a specific location, Hessian fly adults usually emerge and die before the crop is out of the ground. Seed-applied chloronicotinyl insecticides provide some protection against Hessian flies and are recommended, particularly if wheat must be planted before the fly-free dates.

14

Managing Diseases

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Diseases that can affect yield and quality of field crops in Illinois are numerous. For plant diseases to develop, certain components of the disease triangle must be present **(Figure 14.1).** These components are a susceptible host crop, a plant pathogen able to infect the host crop, and an environment that favors disease development.

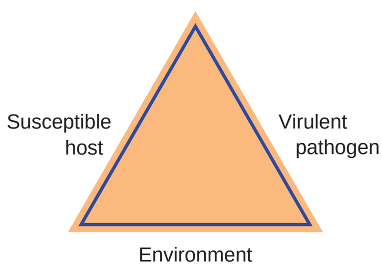

Figure 14.1. The plant disease triangle.

In general, plant diseases of field crops in Illinois are caused by biotic pathogens belonging to one of four groups: bacteria, fungi, nematodes, and viruses. Examples of important diseases that cause losses in Illinois field crops can be taken from each of these pathogen groups. Tactics used to manage these pathogens can vary, so it is essential to know the cause of the problem. (More details on the importance of diagnosis follow).

Principles of Plant Disease Control

Management practices designed to reduce plant diseases affect specific components of the disease triangle. Multiple practices need to be deployed to limit more than a single component, an approach known as integrated disease management. Integrating different management practices often results in better disease reduction and helps reduce selection pressures. Pathogens are affected by selection pressures when certain individual management practices are used (i.e., some host-resistant genes and some fungicides), and this can result in new "races" of the pathogen or fungicide-resistant strains of the pathogen being selected.

The first step in managing a plant disease is to diagnose the problem. Diagnosing a disease from symptoms alone is not always possible, and some pathogens can cause similar symptoms. Misidentification can lead to inappropriate control recommendations (e.g., applying a fungicide to control a bacterial disease), so properly identifying the problem is critical. Magnification with a hand lens or microscope may help in observing spores or fruiting bodies of some plant-pathogen fungi **(Figure 14.2).** When diagnosis is not possible with the tools and resources you have available, collect and send affected plant samples to a plant diagnostics lab. The University of Illinois Plant Clinic (plantclinic.cropsci.illinois.edu) serves Illinois producers during the growing season.

Fungicides

When used appropriately, fungicides can be effective disease management tools. For field crops grown in Illinois, fungicides generally are applied as seed treatments or as foliar sprays. Under some circumstances, fungicides can be applied through irrigation (chemigation) or in-furrow. When applying a fungicide, be sure to follow the directions on the product label.

In general, fungicides are most effective when they are applied just before or at the onset of disease development.

Some content was written by Dean Malvick and Terry Niblack for the previous edition of the Illinois Agronomy Handbook *(2002).*

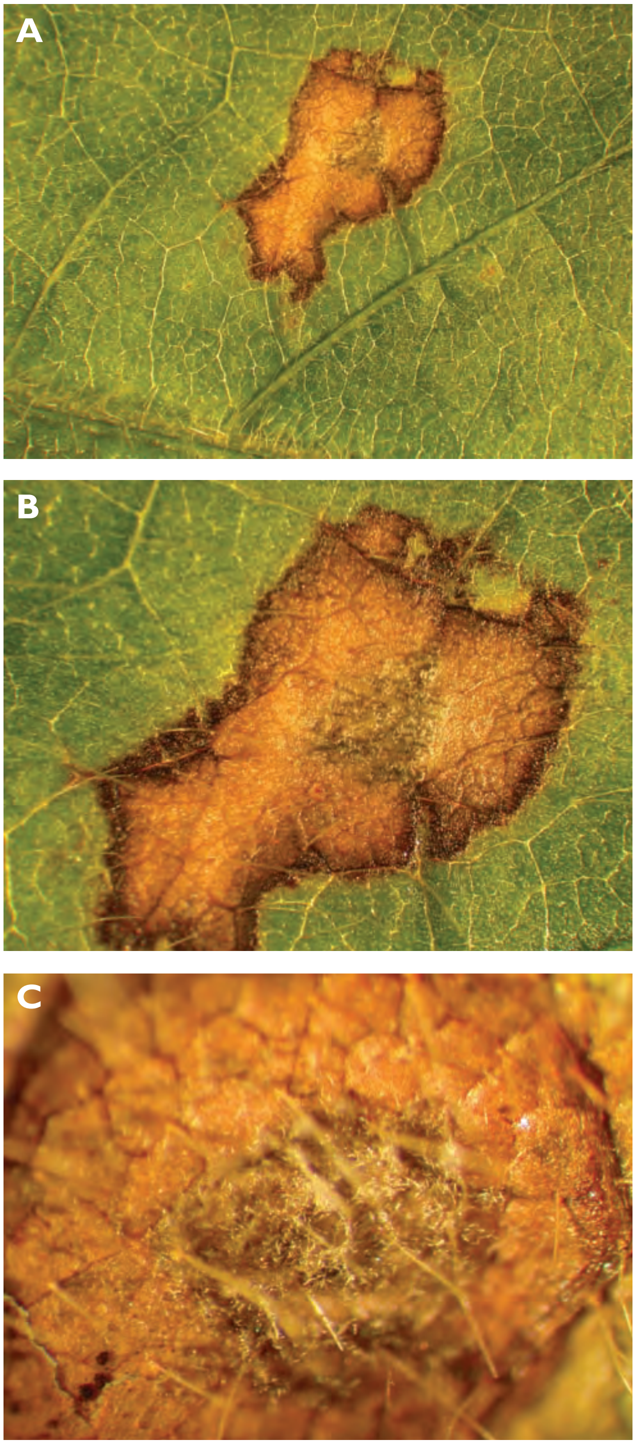

Figure 14.2. A) Low magnification of a soybean leaf with a "leaf spot" symptom. B) Medium magnification showing a grayish "clump" in the center of the leaf spot. C) High magnification showing that the "clump" is actually full of fungal spores.

Some fungicides have only preventative activity, meaning they are effective only when applied with this timing. Other fungicides may still be effective even after the fungal pathogen has invaded the plant tissue; they have what is referred to as early-infection, or curative, activity. (The term "curative" is used loosely here, as a curative fungicide will not "cure" damage that has already occurred.)

Fungicides differ in their ability to move within a plant. Some fungicides are strictly contact fungicides; they remain on the surface of the plant only (**Figure 14.3A**). Others are systemic fungicides, which means they are absorbed into the plant tissue and may move within the plant. Systemic fungicides currently available for use on field crops grown in Illinois are either locally systemic (move into the plant with some redistribution; **Figure 14.3B**) or upwardly systemic (move upwardly in the plant through the xylem; **Figure 14.3C**); none of them is fully systemic (able to move up and down throughout the plant).

Fungicide Resistance Management

Unfortunately, it is possible for fungal plant pathogens to develop resistance to a fungicide. This phenomenon has occurred worldwide in various cropping systems. Currently, no plant pathogens that affect field crops in Illinois are known to be fungicide-resistant, but the potential for them to develop is real.

Fungicide resistance can occur when a selection pressure is placed on a fungal plant pathogen population. Characteristics of both the fungicide and the pathogen play a role in the magnitude of the selection pressure and the risk of resistance occurring. Fungicides with a single site of action may be more at risk for resistance developing than those with multiple sites of action. Plant-pathogenic fungi with a lot of genetic variability in the population may be more prone to developing resistance to fungicides. The genetic variability in a plant population may be greater in certain fungi that undergo sexual reproduction. Fungi that cause diseases with multiple repeating stages within the same growing season (i.e., some foliar diseases) also may be more likely to develop resistance to a fungicide.

The Fungicide Resistance Action Committee (FRAC) is an international organization developed to address the issue of fungicide resistance. The FRAC codes are a system of numbers and letters used to distinguish fungicide groups based on mode of action and chemical class. Fungicides with the same FRAC code designation are similar, and a fungus that has developed resistance to a particular fungicide likely will be resistant to other fungicides with the same code. FRAC codes of fungicides currently registered for use on field crops grown in Illinois are shown in **Table 14.1**. A complete list of codes is available at www.frac.info.

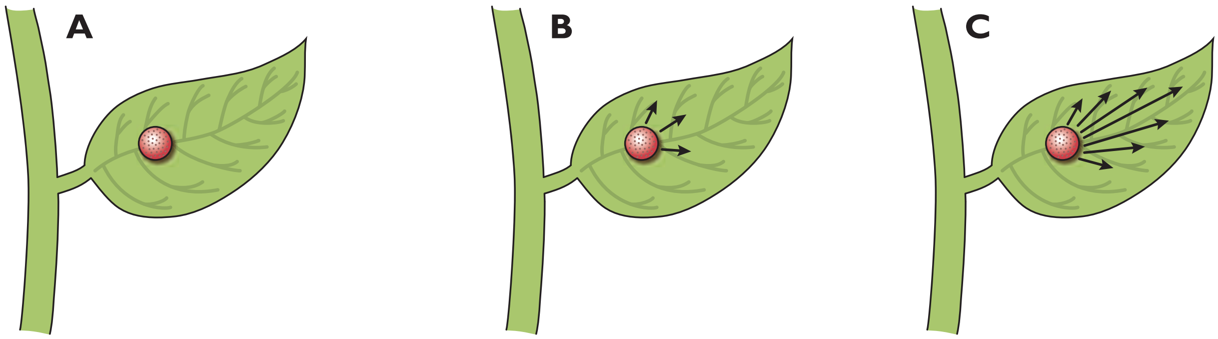

Figure 14.3. A) Contact fungicides stay on the outer surface and do not enter the plant. B) Locally systemic fungicides are absorbed but remain close to the site of uptake with some redistribution. C) Upwardly systemic fungicides move upwardly through the plant from the site of uptake.

A number of practices can minimize the risk that a fungus will become resistant to a fungicide. The best fungicide resistance management programs utilize all available practices to prolong the effectiveness and the life of the fungicides:

● **Apply a fungicide only when necessary.** Scout fields for disease and take into consideration disease risk factors such as variety susceptibility to disease, previous crop, and disease history of the field. Applying a fungicide only when necessary will help reduce the selection of fungicide-resistant pathogens.

● **Apply fungicides with different modes of action.** Applying mixtures of fungicides with different modes of action may help reduce the selection pressure placed on the pathogen population. This is only effective, however, if both fungicides control the target disease. If more than one application of a fungicide during a season is anticipated, then a fungicide with a different mode of action should be used each time.

● **Follow label recommendations.** Following the label, in addition to being the law, is another important component of fungicide resistance management. Some fungicides have restrictions on the number of applications allowed during a season and on back-to-back applications. Following label rates is also important; when sublethal doses of a fungicide are applied, the risk of fungicide resistance may increase.

Using Foliar Fungicides for Reasons Other than Disease Control

In some cases, fungicides may have an effect on plants without a foliar disease being present. Plants may react to fungicides in different ways, but one reaction sometimes observed is a stay-green effect. Results of research by university scientists have shown that the appearance of a stay-green effect is inconsistent, and that when it is present, it may not result in a yield increase. It is recommended that the decision to apply a foliar fungicide be based on disease management considerations only.

Managing Diseases by Crop

Alfalfa

Alfalfa can be affected by a number of diseases, which include seedling blights, root and crown rots, and leaf blights. Losses can be minimized by an integrated management approach that includes these steps:

● Grow winter-hardy, disease-resistant varieties.

● Plant high-quality, disease-free seed produced in an arid area.

● Provide a well-drained, well-prepared seedbed.

Table 14.1. Fungicide Resistance Action Committee (FRAC) codes of fungicides registered for use on common field crops grown in Illinois.

FRAC Code	Chemical group	Example	Risk of fungicide resistance
1	Methyl benzimidazole carbamates (MBC)	Topsin M	High
3	Demethylation inhibitors (DMI; includes triazoles)	Prosaro	Medium
4	Phenylamides	Apron XL	High
7	Carboxamides	Vitavax	Medium
11	Quinone outside inhibitors (QoI; includes strobilurins)	Headline	High
12	Phenylpyrroles	Maxim	Low to medium
14	Aromatic hydrocarbons	PCNB	Low to medium
M	Multi-site activity; inorganics	Bravo	Low

A complete list of FRAC codes can found at www.frac.info (click on "Publications").

- Use crop rotation with nonlegumes.
- Cut in a timely manner to minimize loss to foliar blights.
- Use proper fertilization practices and maintain proper pH.
- Avoid cutting or overgrazing during the last 5 or 6 weeks of the growing season.
- Control insects and weeds.
- Cut only when foliage is dry.
- Destroy unproductive stands.
- Follow other suggested agronomic practices.

Table 14.2 lists alfalfa diseases in Illinois and the effectiveness of various management methods. No control measures are necessary or practical for several of the common alfalfa diseases, including bacterial blight or leaf spot, downy mildew, and rust. For most diseases, producers should select resistant varieties.

Planting disease-resistant varieties. Many newer varieties offer resistance to bacterial wilt, Fusarium wilt, Verticillium wilt, anthracnose, Aphanomyces root rot, and Phytophthora root rot; however, no varieties are resistant to all diseases. Alfalfa producers should identify the pathogens common in their areas and select varieties according to local adaptability, high-yield potential, and resistance to those common pathogens.

Choosing planting sites and rotating crops. The choice of planting site often determines which diseases are likely to occur, because most pathogens survive between

Table 14.2. Alfalfa diseases that reduce yields in Illinois and the relative effectiveness of various control measures.

Disease	Plant winter-hardy, resistant varieties	Use high-quality seed	Have a well-drained soil, pH 6.5 to 7	Use correct crop rotation	Achieve adequate, balanced fertility	Cut in mid- to late-bud stage	Avoid late cutting and planting	Avoid rank growth and high stubble	Maintain insect and weed control
Bacterial wilt	1		2	3	3	3			3
Dry root and crown rots, decline	3	3	2	2	2		2	3	2
Phytophthora root rot	1		2	2	3		2		
Aphanomyces root rot	1		2	2	3		2		
Fusarium wilt	1		3	2	3		2	3	3
Verticillium wilt	1	2			3		3		
Anthracnose	1		3	1	2			2	3
Spring black stem	3	2	3	1	3	2		2	3
Summer black stem		2	3	2	3	2		2	3
Common or Pseudopeziza leaf spot	3		3	2	2	2		2	3
Stemphylium or zonate leaf spot	3	2		2	3	2		2	3
Lepto or pepper leaf spot	3		3	2	3	2		2	3
Yellow leaf blotch		2	3	2	2	2		2	3
Stagnospora leaf and stem spot			3	2	3	2		2	3
Rhizoctonia stem blight		2	2		2	2		2	3
Seed rot, damping-off		2	2	3	2				3
Sclerotinia crown and root rot[a]	2	3	2	2	2	3	2	2	2
Virus diseases		3							2

1 = Highly effective control measure; 2 = moderately effective control measure; 3 = slightly effective control measure. A blank indicates no effect or that the effect is unknown.

[a]Avoiding fall seeding is moderately effective for managing Sclerotinia crown and root rot.

growing seasons on or in crop debris, volunteer alfalfa, and alternative host plants. Aphanomyces, Pythium, and Phytophthora seedling blights generally are more common in heavy, compacted, or poorly drained soils and survive in infected root tissues. Leaf-blighting fungi survive in undecayed leaf and stem tissues, and they may die once residues decay. Other pathogens are dispersed by wind currents and can be found in almost any field, so planting site selection alone will not ensure a healthy crop. Alfalfa mosaic virus, for example, is transmitted by aphids that may be blown many miles.

The diseases strongly associated with continuous alfalfa production include bacterial wilt, anthracnose, a variety of fungal crown and root rots, Phytophthora root rot, Fusarium wilt, Verticillium wilt, spring and summer blackstem, common and Lepto leaf spots, bacterial leaf spot, and Stagnospora leaf and stem spot. The incidence of many diseases can be reduced by rotating crops and using tillage to encourage residue decomposition before the next alfalfa crop is planted. Since most alfalfa pathogens do not infect plants in the grass family, rotation of 2 to 4 years with corn, small grains, sorghum, and forage grasses will help reduce disease levels.

Cutting at the right time. Cut heavily diseased stands before bloom and before the leaves fall to maintain the quality of the hay and remove the leaves and stems that are the source of infection for later diseases. This will help ensure that later cuttings have a better chance of remaining healthy. Cutting in the mid- to late-bud stage, harvesting at 30- to 40-day intervals, and cutting the alfalfa short are practices that help to control most leaf and stem diseases of alfalfa. Cutting only when foliage is dry also minimizes the spread of fungi and bacterial that cause leaf and stem diseases, wilts, and crown and root rots.

Controlling insects and weeds. Insects commonly create wounds by which wilt, bacteria, and crown-rotting and root-rotting fungi enter plants. Insects also reduce plant vigor, increasing the risk of stand loss from wilts and root and crown rots.

Do not allow a thick growth of weeds to mat around alfalfa plants. Weeds reduce air movement; they slow drying of foliage and lead to serious crop losses from leaf and stem diseases. Seedling stands under a thick companion crop, such as oats, are commonly attacked by leaf and stem diseases. Weeds can also harbor viruses that can be transmitted to alfalfa by aphid feeding. Control broadleaf weeds in fencerows and drainage ditches, along roadsides, and in other waste areas. Whenever possible, do not grow alfalfa close to other legumes, especially clovers, green peas, and beans. Many of the same pathogens that infect alfalfa also attack these and other legumes.

Corn

Managing corn diseases requires an integrated approach to limit disease and yield losses. The use of disease-resistant hybrids, crop rotations, various tillage practices, balanced fertility, fungicides, control of other pests and weeds, and various other cultural practices is needed to provide the broadest spectrum of control of corn pathogens. **Table 14.3** lists diseases known to cause yield losses in Illinois and the relative effectiveness of various control measures.

Planting disease-resistant hybrids. The use of resistant hybrids is the most economical and efficient method of disease control. Although no single hybrid is resistant to all diseases, hybrids with combined resistance to several major diseases are available. Corn producers should select high-yielding hybrids with resistance or tolerance to major diseases in their area.

Rotating crops. Many common pathogens require the presence of a living host crop for growth and reproduction. Examples of such corn pathogens include many of the foliar diseases (Helminthosporium leaf diseases, Physoderma brown spot, Goss's wilt, gray leaf spot, eyespot) and nematodes. Rotating to nonhost crops (i.e., soybean) "starves out" these pathogens, resulting in a reduction of inoculum levels and the severity of disease. Continuous corn, especially in combination with conservation tillage practices that promote large amounts of surface residue, may result in severe outbreaks of disease.

Tilling. Tillage programs that encourage rapid residue decomposition before the next corn crop is planted help reduce population of pathogens that overwinter in or on crop debris. Although a clean plowdown is an important disease-control practice, the possibility of soil loss from erosion must be considered. Other measures can provide effective disease control if conservation tillage is implemented. Examples of diseases partially controlled by tillage include stalk and root rots, Helminthosporium leaf diseases, Physoderma brown spot, Goss's wilt, gray leaf spot, anthracnose, ear and kernel rots, eyespot, and nematodes.

Managing fertility. Balanced fertility and fertility levels play an important role in development of diseases such as Stewart's wilt, seedling blights, leaf blights, smut, stalk rots, ear rots, and nematodes. Diseases may be more severe where there is excess nitrogen and a lack of potassium, or both. Healthy, vigorous plants are more tolerant of diseases and better able to produce a near-normal yield.

Using foliar fungicides. The decision to apply a foliar fungicide should be based on the levels of disease incidence and severity and on certain risk factors. Factors that increase the risk of foliar diseases include these: previ-

Table 14.3. Corn diseases that reduce yields in Illinois and the relative effectiveness of various control measures.

Disease	Resistant or tolerant hybrids	Crop rotation	Clean plow-down	Balanced fertility	Fungicides: Seed treatment	Fungicides: Foliar spray	Other controls and comments
Seed rots and seedling blights	2			3	1		Plant high-quality, injury-free seed into soils that are 50 °F and above. Prepare seedbed properly, and place fertilizer, herbicides, and insecticides correctly.
Stewart's bacterial wilt	1			3			Early control of flea beetles may be helpful on susceptible hybrids; some insecticide seed treatments may provide this control.
Goss's bacterial wilt	1	1	2				Rotations of 2 or more years provide excellent control.
Helminthosporium leaf blights (northern leaf blight, northern leaf spot, southern leaf blight)	1	2	2	3		1	Foliar fungicide applications may be needed only on susceptible hybrids when conditions are favorable for disease.
Gray leaf spot	2	2	2			1	See comments for Helminthosporium leaf blights.
Physoderma brown spot		1	3	2			
Yellow leaf blight and eyespot	1	2	1			2	See comments for Helminthosporium leaf blights.
Anthracnose	1	2	1	3			
Common and southern rusts	1					1	Foliar fungicides for common rust may only be needed when infection occurs early or in late-planted fields.
Common smut	2	3	3	3			Avoid mechanical injuries to plants, and control insects.
Crazy top and sorghum downy mildew		1	3	3			Avoid low wet areas, and plant only downy mildew-resistant sorghums in sorghum-corn rotations. Control of shattercane (an alternate host) is very important.
Stalk rots (Diplodia, charcoal, Gibberella, Fusarium, anthracnose, Nigrospora)	2	2	2	2			Plant adapted, full-season hybrids at recommended populations and fertility. Control insects and leaf diseases. Scout at 30–40% moisture to determine potential losses.
Ear and kernel rots (Diplodia, Fusarium, Gibberella, Physalospora, Penicillium, Aspergillus, others)	2	2	3	3			Control stalk rots and leaf blights. Hybrids that mature in a downward position with well-covered ears usually have the least ear rot. Ear and kernel rots are increased by bird, insect, and severe drought damage.
Storage molds (Penicillium, Aspergillus, others)							Store undamaged corn for short periods at 15–15.5% moisture. Dry damaged corn to 13–13.5% moisture before storage. Low-temperature-dried corn has fewer stress cracks and storage mold problems if an appropriate storage fungicide is used. Corn stored for 90 days or more should be dried to 13–13.5% moisture. Inspect weekly for heating, crusting, and other signs of storage molds.
Maize dwarf mosaic virus	1						Control johnsongrass and other perennial grasses (alternative hosts) in and around fields.
Wheat streak mosaic virus							Plant winter wheat (an alternative virus host) after the fly-free date, and control volunteer wheat. Separate corn and wheat fields. See *Report on Plant Diseases No. 123*.
Nematodes (lesion, needle, dagger, sting, stubby-root)		2	2	3			Clean plow-down helps reduce winter survival of nematodes. Nematicides may be justified in some situations. Submit soil samples for nematode analysis before applying nematicides.

1 = Highly effective control measure; 2 = moderately effective control measure; 3 = slightly effective control measure. A blank indicates no effect or that the effect is unknown.

ous crop was corn, or corn debris on the soil surface is prevalent; weather was rainy in July and August, with high dew points; a susceptible hybrid was planted; and the crop was planted later than normal. A summary of university corn fungicide trials in 12 states (Illinois, Indiana, Iowa, Kansas, Kentucky, Maryland, Minnesota, Missouri, Nebraska, North Dakota, Ohio, and Wisconsin) and one Canadian province (Ontario) in 2007 indicated that corn hybrids with good to excellent resistance to gray leaf spot and sprayed with a foliar fungicide had a yield benefit of 3 bushels per acre over the untreated, while hybrids with fair to poor resistance to gray leaf spot and sprayed with a foliar fungicide had a yield benefit of 6 bushels per acre over the untreated. The level of disease resistance in a corn hybrid is thus an important factor when making a fungicide application decision.

Soybean

Successful management of soybean diseases involves appropriately integrating resistant varieties, high-quality seed, tillage (where feasible), fungicides, scouting, and proper insect and weed control. Using multiple practices will provide the best management of diseases. **Table 14.4** indicates the effectiveness of these practices by disease.

Planting resistant varieties. Every soybean disease-management program should begin with selecting a variety with resistance to the diseases most common in the area. Many high-yielding public and private soybean varieties are available with resistance to important diseases, including Phytophthora root rot, soybean cyst nematode, and brown stem rot. Other less important diseases also can be controlled with resistant varieties. See Chapter 3 for more information on variety selection.

One major concern for soybean producers is the possible appearance of new or unexpected races of a pathogen. When race-specific resistant genes are used, this may place a selection pressure on the pathogen population, which may result in new races becoming able to overcome the resistance genes that were once effective. Examples of soybean pathogens that have different races in Illinois are the Phytophthora root rot pathogen (*Phytophthora sojae*) and the frogeye leaf spot pathogen (*Cercospora sojina*). Soybean cyst nematode populations are characterized as HG Types, but the examples provided also apply to soybean cyst nematode.

For Phytophthora root rot, there is the option of selecting *race-specific resistant varieties* and *non-race-specific tolerant varieties.* Race-specific resistant varieties contain one or more genes with resistance to specific races of a pathogen. This type of resistance is active from the time of planting until full maturity. It fails only where races occur that are not controlled by the genes in the plant. Non-race-specific tolerant varieties have a broad form of resistance to all races of the pathogen; however, they may not provide the level of protection needed where pathogen population levels are extremely high. This type of resistance (tolerance) is not active in the early seedling stage, and plants are considered susceptible until one or two trifoliolate leaves have developed. When non-race-specific tolerant varieties are used in fields with a history of Phytophthora root rot, using a seed treatment that contains either mefenoxam or metalaxyl may provide early protection until the plants become tolerant after trifoliolate leaf development.

Using fungicide seed treatments and foliar sprays. Historically, using fungicides as either seed treatments or foliar sprays has not been common. However, when the market price of soybeans is above $10 a bushel, fungicides may be more easily justified economically. Beginning in 2009, some soybean seed companies will be treating the majority of soybean seed being sold.

A benefit from a fungicide seed treatment is more likely to be observed in these circumstances:

- Planting early into cool soils or into no-tilled soils
- Planting into a field with a history of problems with stand establishment
- Having only poor-quality seed available (as a result of fungal infection rather than mechanical damage)

Foliar fungicides are highly effective in controlling some foliar diseases, including frogeye leaf spot, Septoria brown spot, and soybean rust. Varieties susceptible to frogeye leaf spot should be scouted at regular intervals for the appearance of the disease, and a fungicide application may be justified when conditions are favorable for frogeye leaf spot. Septoria brown spot can be found in almost every soybean field every year, but the yield loss caused by this disease generally is considered to be minimal. Only in years with excessive rainfall might a fungicide be considered for control of Septoria brown spot.

Foliar fungicides are the only tool currently available for managing soybean rust. Monitoring the movement and progression of soybean rust in the U.S. is important in determining the risk of its occurring in Illinois. The Soybean Rust IPM PIPE website (www.sbrusa.net) provides maps and information on the whereabouts of soybean rust in the U.S. during the growing season.

Understanding agronomic characteristics affecting disease development. The relative maturity of soybean cultivars can dramatically affect disease development. Early-maturing varieties are more commonly damaged by

Table 14.4. Soybean diseases that reduce or threaten yields in Illinois and the relative effectiveness of various control measures.

Disease	Resistant or tolerant varieties	Crop rotation	Clean plow-down	High-quality seed	Fungicides: Seed treatment	Fungicides: Foliar spray	Other controls and comments
Phytophthora root rot	1				2		Multiple races of the pathogen are present in Illinois soils. Race-specific resistant varieties and non-race-specific tolerant varieties are available. Fungicide seed treatments are effective only for the seed and seedling blight phases of this disease; higher rates may be needed for best control.
Seedling blights and root rots (Pythium, Rhizoctonia, and Fusarium)				2	2		Plant high-quality seed in a warm (>55 °F), well-prepared seedbed. Shallow planting may help establish uniform, vigorous stands.
Charcoal rot	3?		2	3			Some rotational crops (e.g., corn) also are susceptible. Management practices that avoid moisture stress may help escape infection.
Brown stem rot	1	1					Rotations of 2 or more years are necessary for control. Early-maturing varieties may be less affected than late-maturing varieties. Infection by soybean cyst nematode (SCN) may break resistance to brown stem rot; check affected fields for presence of SCN.
Sudden death syndrome	2						Avoid planting too early into cool soils. Management practices that reduce soil compaction may help reduce the likelihood of SDS. Infection by SCN may increase the likelihood of SDS; check affected fields for the presence of SCN.
Frogeye leaf spot	1	3	3			1	Varieties that contain the Rcs3 gene for resistance control all races of the fungus currently present in Illinois.
Cercospora leaf blight				2	2	2	
Septoria brown spot		3	3			1	
Powdery mildew	1					2	
Soybean rust						1	Monitoring the movement and progression of soybean rust in the U.S. is important in determining the risk of soybean rust's occurring in Illinois. The Soybean Rust IPM PIPE website (www.sbrusa.net) provides maps and information on the whereabouts of soybean rust in the U.S. during the growing season.
Downy mildew	2	2	2	2	2		Seed treatments containing metalaxyl or mefenoxam may provide control of seedborne downy mildew.
Bacterial blight, bacterial pustule, wildfire	1	2	2	2			Seeds should not be saved from fields heavily infected with these diseases.
Soybean mosaic, bean pod mottle, and bud blight viruses	2			2			Plant high-quality, pathogen-free seed. Some insecticide seed treatments may provide protection against early feeding by bean leaf beetles and soybean aphids that can transmit viruses. Damage from bud blight may be reduced by bordering soybean fields with 4 to 8 rows or more of corn or sorghum. This may be helpful where soybean fields border alfalfa or clover fields. Before planting, apply herbicides to control broadleaf weeds in fencerows and ditch banks.
Pod and stem blight, anthracnose, stem canker		2	2	2	2	2	
Sclerotinia stem rot (white mold)	2	3		2	2	2	No completely resistant varieties are available, but varieties differ in level of susceptibility. Avoiding infected seed and seed lots containing sclerotia will prevent introducing the disease into a field. Some seed treatments are effective in controlling infected seed. The effectiveness of foliar fungicides has been inconsistent.
Soybean cyst nematode	1	1					Avoid planting the same variety in the same field twice, and rotate varieties with different sources of resistance.

1 = Highly effective control measure; 2 = moderately effective control measure; 3 = slightly effective control measure. A blank indicates no effect or that the effect is unknown.

pod and stem blight, anthracnose, purple seed stain, and Septoria brown spot. The longer the time from maturity to harvest, the greater the likelihood of damage by these diseases. However, early-maturing varieties are generally less affected by brown stem rot.

Soybean growth habit also can affect disease development. Tall, bushy varieties may be more severely affected by Sclerotinia stem rot (white mold) than shorter, more compact varieties. Shorter varieties, however, also may be more prone to damage by water-splashed pathogens such as Septoria brown spot, pod and stem blight, and purple seed stain.

Planting dates also can affect diseases. Early-planted fields may have a greater incidence of seedling blights. Conditions in early spring favor these pathogens and may delay the emergence of the seedling soybean plants. Early planting also may increase the incidence of sudden death syndrome.

Crop rotation and tillage are very important in controlling most diseases of soybean. Most soybean pathogens depend on crop residues for overwintering and do not colonize other hosts. So when crop residues are removed or are completely decayed, or when rotation with nonhosts (corn, small grains, etc.) is used, pathogen populations and disease levels may decline over time.

Row spacing also can influence disease. Diseases that thrive in cool, wet conditions typically increase when soybean is planted in rows less than 30 inches. If previous soybean residue is present, earlier and more severe epidemics may occur. Diseases such as downy mildew and Sclerotinia stem rot (white mold) are greatly affected by high humidity. Narrow rows may increase both humidity and disease levels. If tall soybean varieties are planted, there may be little air circulation within the canopy, keeping the soybean canopy moist. Where Sclerotinia stem rot or downy mildew is a problem, wider rows or shorter beans may help reduce disease levels.

Wheat

Successfully managing wheat diseases involves appropriately integrating resistant varieties, high-quality seed, fungicide treatments, proper planting time and site, crop rotation, tillage, high fertility, and other cultural practices. **Table 14.5** indicates the effectiveness of these practices by disease.

Planting disease-resistant varieties and high-quality seed. Growing resistant varieties is the most economical and efficient method of controlling wheat diseases. Resistance to rust diseases, Fusarium head blight (scab), loose smut, Septoria/Stagonospora diseases, powdery mildew, and viral diseases is of major importance in Illinois. No single wheat variety is resistant to all major diseases, so varieties should be selected according to their local adaptability, yield potential, and resistance to the most common and serious diseases.

Seed that has been improperly stored (bin-run) will lose vigor and may develop problems in the seedling stage that continue throughout the season. Diseases such as bunt, loose smut, black chaff, ergot, Septoria/Stagonospora diseases, and scab may be carried on, with, or within the seed.

Choosing planting sites and rotating crops. The choice of a planting site often determines which diseases are likely to occur, because many pathogens survive on or in crop debris, soil, volunteer wheat, and alternative host plants. Site choice is most important in controlling Septoria/Stagonospora leaf and glume botches, Helminthosporium spot blotch, tan spot, scab, ergot, take-all, Fusarium and common root rots, crown and foot rots, Cephalosporium stripe, bunt or stinking smut, downy mildew, eyespot, Pythium and Rhizoctonia root rots, soilborne wheat mosaic virus, and wheat spindle streak mosaic virus. Other diseases are not affected by choice of planting site, including airborne and insect-transmitted diseases, among them barley yellow dwarf virus, wheat streak mosaic virus, and rust diseases.

Crop rotation is an extremely important means of reducing carryover levels of many common wheat pathogens. Diseases strongly associated with continuous wheat production include take-all, Helminthosporium spot blotch, tan spot, crown and foot rots, root rots, scab, Septoria/Stagonospora leaf and glume blotches, black chaff, powdery mildew, Cephalosporium stripe, soilborne wheat mosaic virus, wheat streak mosaic virus, downy mildew, eyespot, ergot, and anthracnose.

With many common wheat diseases, crop debris provides a site for pathogens to survive adverse conditions. Many of these pathogens do not survive once crop debris is decomposed. Rotations of 2 or 3 years with nonhost crops, coupled with other practices that promote rapid decomposition of crop residue, will reduce the carryover populations of these pathogens to very low levels. Soilborne wheat mosaic and wheat spindle streak virus increase when wheat is planted continuously in the same field. To control these diseases, rotations must cover at least 6 years.

Tilling. A clean plowdown may be of great help in disease control, but the losses to soil erosion should be carefully weighed against potential yield losses due to disease. Pathogens dispersed short distances by wind and splashing rain may infect crops early and cause more severe losses where debris from the previous wheat crop remains on the soil surface. The need for clean tillage is thus based on the prevalence and severity of diseases in the previous crop, other disease control practices available, the need for erosion control, rotation plans, and other factors.

Managing fertility. The effect of fertility on wheat diseases is quite complex. Adequate and balanced levels of nitrogen, phosphorous, potassium, and other nutrients will help reduce disease losses. This is particularly true with take-all, seedling blights, powdery mildew, anthracnose, and Helminthosporium spot blotch. Research has shown that both the level and form of nitrogen play an important role in disease severity. The severity of certain diseases is decreased by using ammonia forms of nitrogen (urea and anhydrous ammonia) and is increased by using nitrate forms. In other cases, the reverse is true. The general effect on disease severity caused by the nitrogen form used is specified in **Table 14.6.**

Deciding when to plant. Planting time can greatly influence the occurrence and development of a number of diseases. Early fall planting and warm soil (before the Hessian fly-free date) promote the development of certain seed rots and seedling blights, Septoria/Stagonospora leaf blotches, leaf rust, powdery mildew, Cephalosporium stripe, Helminothosporium spot blotch, wheat streak mosaic virus, soilborne wheat mosaic virus, barley yellow dwarf virus, and wheat spindle streak mosaic virus. Wheat that is planted early may have excessive foliar growth in the fall, which may favor the buildup and survival of leaf rust, powdery mildew, and Septoria/Stagonospora leaf blotches. Disease buildups in the fall commonly favor earlier and more severe epidemics in the spring. Many of these problems can be avoided if planting is delayed until after the Hessian fly-free date.

Using fungicide seed treatments and foliar fungicides. Wheat seed treatment trials in Illinois have been shown to increase wheat yields. Seed treatments can control diseases such as bunt, loose smut, Septoria/Stagonospora diseases, seed rots, and seedling blights. Failure to control seedling blights may result in serious winter-kill of diseased seedlings.

No single fungicide controls every disease. A combination of fungicides generally is necessary to control the broadest range of pathogens. When deciding whether to use a fungicide seed treatment, consider seedling disease history and anticipated seedbed conditions, product effectiveness, and application method. Seed treatments can lead to improved stand establishment but will not always result in increased yields.

Fusarium head blight (scab), Septoria/Stagonospora leaf and glume blotch diseases, powdery mildew, and rusts are diseases that appear at different severity levels in the state almost every year. They are favored by rainy weather and heavy dews. With proper applications of fungicides, these diseases can be managed. The decision to apply a foliar fungicide should be based on the prevalence of disease or on the risk of disease and the yield potential of the crop. As a general guideline, the upper two leaves (flag leaf and flag leaf-1) should be protected against foliar pathogens, since head-filling depends largely on the photosynthetic activity of these two leaves. Loss of leaves below flag leaf-1 usually causes little loss in yield.

Weekly scouting for foliar diseases should begin no later than the emergence of the second node (growth stage 6). If diseases are present and weather conditions favor continued disease development, consider a fungicide application. Be certain that diseases are correctly diagnosed to ensure proper fungicide selection. If foliar diseases are present or conditions are favorable for foliar diseases at the flag leaf emergence stage (growth stage 9), a fungicide application may be warranted at this time. For Fusarium head blight (scab) control, it is important to understand the current risk level of disease. The *Fusarium Head Blight Risk Assessment Tool* is an online tool developed to help predict the risk of Fusarium head blight (www.wheatscab.psu.edu).

In addition, the risk of Fusarium head blight may be increased when wheat follows corn and/or a susceptible variety is planted. If a fungicide will be applied for Fusarium head blight control, timing is critical. Results from research trials have indicated that the early anthesis stage (growth stage 10.5.1) is the best time to apply a foliar fungicide to control Fusarium head blight. It is important to know which fungicides have efficacy against it and which ones can be applied at this growth stage. Fungicides that contain a strobilurin fungicide active ingredient (Headline, Quadris, Quilt, Stratego) should never be applied at the 10.5.1 growth stage.

Table 14.5. Relative effectiveness of various methods of controlling the major wheat diseases in Illinois.

Disease	Resistant varieties	Crop rotation	Clean plow-down	Balanced fertility	Planting after fly-free date	Fungicides: Seed treatment	Fungicides: Foliar spray
Seedling blights			3	3	2	1	
Take-all[a]	2	1	3	2	2		
Stem rust	1				3		1
Leaf rust	1				3		1
Stripe rust	1				3		1
Septoria and Stagonospora leaf blotches[b]	1	2	2		2	3	1
Tan spot		2	2		3		1
Cephalosporium stripe		1					
Powdery mildew	1				3		1
Helminthosporium spot blotch		2			3		2
Bacterial blight; bacterial leaf streak[c]	1	3					
Loose smut[c]	1					1	
Bunt or stinking smut[c]						1	
Glume blotch[c]	1	2	2		3	2	1
Fusarium head blight (scab)[c,d]	2	1	3	3	3	2	2
Black chaff[c]							
Soilborne wheat mosaic virus	1	3			2		
Wheat spindle streak virus	1				1		
Wheat streak mosaic virus		3	3		2		
Barley yellow dwarf virus	1				1		

1 = Highly effective control measure; 2 = moderately effective control measure; 3 = slightly effective control measure. A blank indicates no effect or that the effect is unknown.
[a]Control virus diseases.
[b]Seed treatment will control seedborne infection only.
[c]Avoid bin-run seed; plant high-quality seed.
[d]Avoid planting into corn stubble.

Table 14.6. Effect of the form of nitrogen on wheat disease severity.

	Nitrogen form	
Disease	**Nitrate**	**Ammonium**
Root and crown diseases		
Take-all	Increase	Decrease
Fusarium root rot	Decrease	Increase
Helminthosporium diseases	Decrease	
Foliar diseases		
Powdery mildew	Increase	
Leaf and stem rust	Increase	Decrease
Septoria leaf blotch	Increase	

A blank cell means that there is no effect or data are not available.

15

Nematodes

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Nematodes are roundworms, similar to the animal parasites encountered in livestock and pets. Soil-dwelling nematodes are both good guys and bad guys in crop production. The good nematodes, which don't get much press, feed on fungi, bacteria, and other creatures that live in the soil and thereby recycle the nutrients contained in it (**Figure 15.1**). Tens of millions of mostly beneficial nematodes live in each square meter of cropland; however, a few of these microscopic roundworms—the plant-pathogenic nematodes—give all nematodes a bad name. This chapter addresses the most important plant-pathogenic nematodes in Illinois agriculture.

Figure 15.1. Bacterial-feeding nematodes. (Photo courtesy of E. Bernard.)

How Nematodes Damage Plants

Plant-pathogenic nematodes feed only on plants; in fact, they cannot sustain themselves on anything else. When their numbers increase to high levels, they can severely injure or kill plants, especially seedlings (**Figure 15.2**). In lower, more typical numbers, they can cause yield losses without causing obvious symptoms (**Figure 15.3**), and they can be involved in disease interactions with other pathogens, including viruses, fungi, and bacteria. Virtually every field has one or more potentially damaging nematode species. The potential for causing disease depends on several factors:

- the species and the number of nematodes in the field
- crop history, especially whether susceptible crops have been grown in the field in the past
- environmental factors, particularly those influencing the soil environment, such as moisture and temperature

Figure 15.2. Cornfield trial in soil heavily infested with root-feeding nematodes. (Photo courtesy of Greg Tylka.)

Most of the plant-pathogenic nematodes (referred to simply as nematodes from here) feed on plant roots, although some less common ones feed in various aboveground plant parts. The root-feeding nematodes are either ectoparasites (**Figure 15.4**), which feed from outside the root, or endoparasites (**Figure 15.5**), which feed from inside the root.

Figure 15.3. SCN-resistant (left) and SCN-susceptible (right) soybean varieties in a field heavily infested with soybean cyst nematode. Yield of the susceptible variety was 30% less than that of the resistant variety.

All plant-feeding nematodes feed by means of a stylet, a structure in the head of a nematode that allows it to pierce plant cell walls (**Figure 15.6**). The stylet

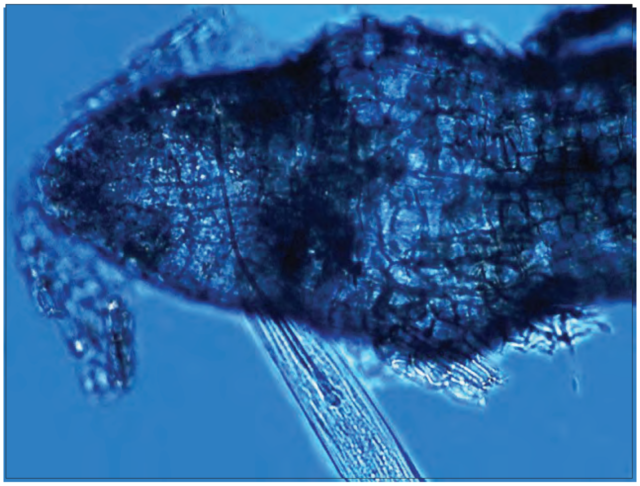

Figure 15.4. An ectoparasitic nematode (bottom center feeding on a root tip. (Photo courtesy of the Society of Nematologists.)

Figure 15.5. An endoparasitic nematode (stained red) feeding within a soybean root. (Photo courtesy of A. Colgrove.)

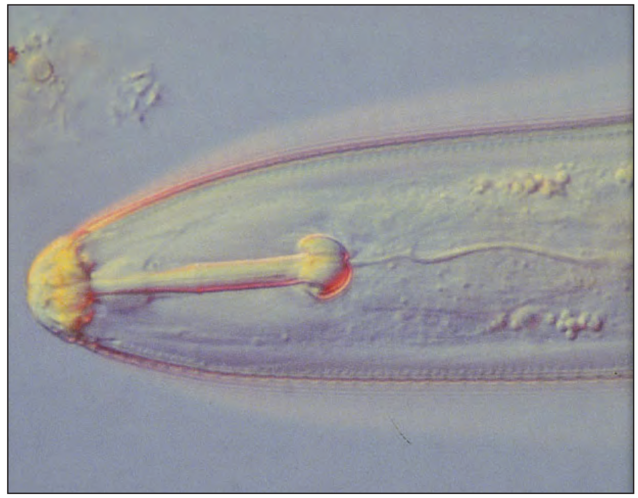

Figure 15.6. Close-up of the head of a root-feeding nematode. The stylet tip (not visible in this photo due to the head cap) is similar to a hypodermic needle in that its opening is on one side of the point. The rounded knobs at the base of the stylet anchor muscles extending forward to the head. When these muscles contract, the stylet protrudes, and the nematode can take in plant material, inject secretions, or both. (Photo courtesy of E. Bernard.)

Figure 15.7. Root-knot nematode–resistant (left) and –susceptible (right) soybean varieties showing the characteristic galling associated with root-knot infection. (Photo courtesy of the Society of Nematologists.)

Figure 15.8. Early-season symptoms of soybean cyst nematode infection (and perhaps other factors) include stunting and yellowing. (Photo courtesy of A. Wrather.)

tip (not visible in the figure), is similar to a hypodermic needle in that its opening is on one side of the point. The rounded knobs at the base of the stylet anchor muscles extending forward to the head. When these muscles contract, the stylet protrudes, and the nematode can take in plant material through the stylet, inject secretions, or both.

Although some ectoparasitic nematodes, such as needle nematode, can be devastating to crop plants (**Figure 15.2**), the endoparasitic types are generally much more damaging in terms of economic losses. Endoparasitic nematodes spend most of their lives within plant roots, interfering with root structure and function. In Illinois, the most important endoparasitic species are the cyst, root-knot, and lesion nematodes.

Scouting for Nematodes

With the single exception of root-knot nematodes, which cause characteristic galling on plant roots (**Figure 15.7**), root-feeding nematodes do not cause specific symptoms. Stunting and chlorosis (yellowing) are the most common visible symptoms of nematode parasitism, but symptoms like these (**Figure 15.8**) may be caused by any number of factors.

If a field does not produce the yields that could reasonably be expected based on all inputs and growing conditions, high numbers of root-feeding nematodes should be considered as a likely cause of yield loss. There is only one way to determine whether a nematode problem exists in a field: Sample the soil.

How to sample for nematodes. To do effective soil sampling, you must first decide the purpose of the sampling.

- For research purposes, sampling must be intensive, and each sample must represent a very small plot of land. A typical field research plot ranges from 1 to 50 square meters.
- For detection purposes—that is, to determine whether a particular nematode is present in high enough numbers to cause crop damage—each sample must represent no more than 10 acres. If a "hot spot" (an area with visible crop damage; see **Figure 15.9**) is present, the soil samples taken should include the edges of the hot spot but not the center. At the center, root damage may have been severe enough that the remaining roots are not able to support a nematode population.
- For monitoring purposes, that is, to assess the effects of nematode management practices over time, the size of the sampled area should be relatively small, perhaps an acre. This "sampling plot" area should be representative of the whole field in terms of soil type, topography, and treatments. The sampling plot should be marked, or the GPS coordinates recorded, so that the area can be resampled over a period of years.
- Because sampling purposes differ, the sampling area represented in **Figure 15.10** can range in size from 1 square meter to 10 acres.

Second, prepare a soil-sampling kit. The kit should contain the following items:

- a tool with which to take several samples of soil—preferably a soil tube that is 1 inch in diameter, or a shovel or trowel (**Figure 15.11**)
- a bucket (**Figure 15.11**)
- 1-quart-capacity plastic zipper-style bags (**Figure 15.12**)
- a permanent marker (**Figure 15.12**)
- a small cooler

Figure 15.9. A "hot spot" in a soybean cyst nematode–infested field, showing symptoms of nematode infection and potassium deficiency.

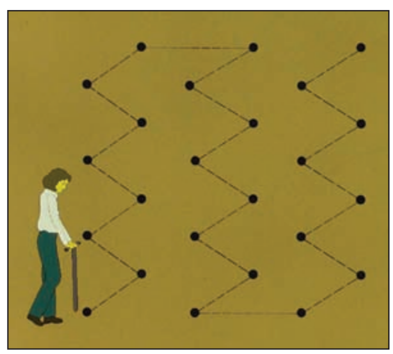

Figure 15.10. A zigzag sampling pattern for an area that can range in size from 1 square meter to 10 acres.

Figure 15.11. Tools recommended for soil sampling for soybean cyst nematode: soil-sampling probe, screwdriver to remove soil from the probe, and bucket to bulk individual cores.

Figure 15.12. Tools recommended for soil sampling for soybean cyst nematode: quart-size plastic bags and indelible marker.

Figure 15.13. After all cores are collected for a sample (left), the soil should be mixed gently but thoroughly (right).

Figure 15.14. Soil samples prepared for shipping or transport to the lab, in a cardboard box cushioned with newspaper to reduce drying, heating, and rough treatment, which can damage the nematodes and interfere with the lab's ability to recover them.

Third, sample the plot or field in the following manner:

- Take 20 to 30 subsamples (represented in **Figure 15.10** as black dots) in a zigzag pattern throughout the area to be sampled.
- Each subsample should be taken to a depth of 8 to 12 inches. The top inch may be discarded. (Sampling for certain nematodes, such as needle nematode, may have to be much deeper depending on the time of year and soil moisture.)
- Place all subsamples in a bucket as they are taken. After all subsamples are collected, mix the soil gently but thoroughly and break up clods (**Figure 15.13**).
- Lightly fill a 1-quart plastic bag with the mixed soil and discard leftover soil.
- Use a permanent marker to write an identifying label on the plastic bag. Use any words or numbers that will allow you to identify the source of the sample later (**Figure 15.12**).
- Place the sample in a cooler and keep it out of heat and sun until it can be sent to a lab for analysis.
- If the sample is to be shipped, pack it in a cardboard box cushioned with newspaper or some other insulating material (**Figure 15.14**). Drying, heating, or rough treatment of the sample can render it useless for analysis.

Soybean Parasitic Nematodes

Soybean Cyst Nematode

The soybean cyst nematode (SCN) is the most important soybean pathogen in Illinois, causing more than $200 million in losses to producers each year. SCN can be found in more than 80% of the soybean fields in Illinois; it is known to occur in every county.

SCN remains a problem year after year because, in most infested fields, yield loss occurs without any visible symptoms, such as stunting, chlorosis (yellowing), or "sick-looking" plants (**Figures 15.3, 15.8,** and **15.9**). If soybean yields are not what they should be in any given field, SCN should be the first suspected cause even if plants look healthy.

Life cycle. SCN survives from one year to the next in eggs that are contained within cysts in the soil. Each cyst may contain up to 200 eggs (**Figure 15.15**). If a nonhost crop, such as corn, is planted, only a few of the eggs will hatch, with the others remaining dormant until soybean (or another susceptible crop) is planted. Soybean yield reduction is dependent on the number of eggs in the soil because the eggs hatch into juvenile worms that invade the roots (**Figure 15.16**).

SCN juveniles, sometimes called "larvae" in old texts, enter soybean roots and migrate to the vascular tissue, where they inject saliva between and into cells. The saliva contains enzymes and other compounds (many still un-

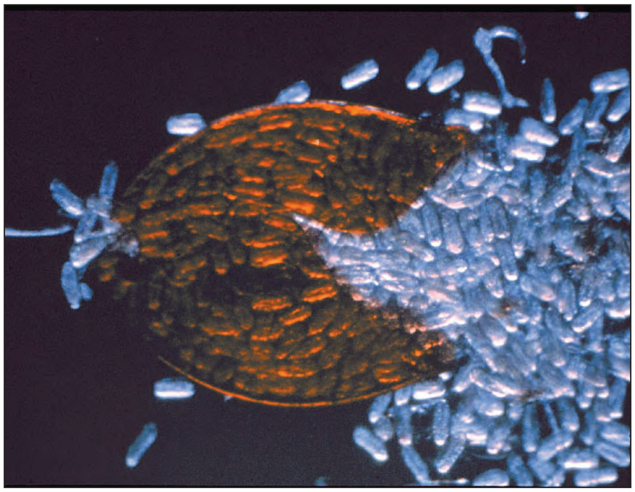

Figure 15.15. A cyst, broken open to expose the eggs and juveniles within. (Photo courtesy of E. Sikora.)

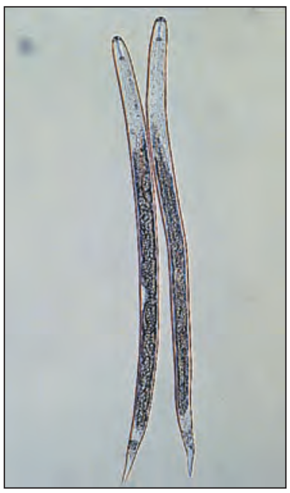

Figure 15.16. Soybean cyst nematode juveniles after hatching: the infective stage.

identified) that cause the injected cells and their neighbors to form a feeding site, a system of giant cells known as a synctium. Because of their location in the vascular tissue, syncytia interfere with normal root function. The syncytia also function as "transfer cells," transferring photosynthetic products from the leaves, much as normal transfer cells do in other metabolically active parts of the plant. In this way, the nematode can compete with the seeds for photosynthate and can reduce yields without causing the plants to look unhealthy. If SCN numbers are high, however, the nematodes can interfere with root function and outcompete normal plant parts so that plants become stunted and chlorotic.

While inducing and maintaining their syncytia, the juveniles do not move from the feeding site. Following several molts, the nematodes become adults. Half of the adults are male; they regain their original worm shape (although they are much larger) and exit the root system. The other

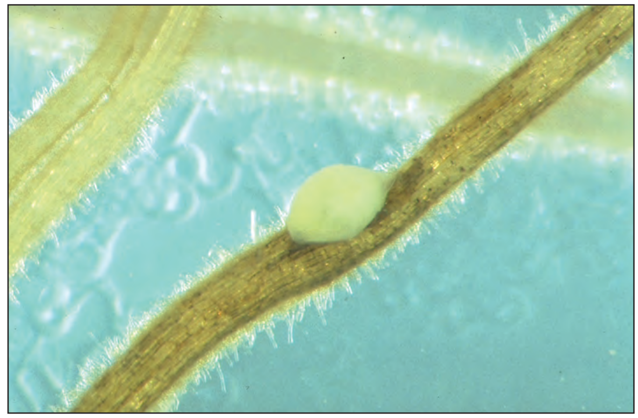

Figure 15.17. Young female soybean cyst nematode on soybean root. (Photo courtesy of G. Tylka.)

half become females (**Figure 15.17**); they are unable to move because of their large lemonlike shape and lack of muscle. Females become so large that they protrude from the root and can be seen, when they are young, as white spheres (**Figure 15.18**).

Females turn yellow and then brown (**Figure 15.19**) as they lay eggs, and they can no longer be seen without a microscope. Brown females are known as cysts, hence the name soybean cyst nematode. The whole life cycle takes only 28 days in a greenhouse under optimal conditions. In the field, it may take as long as 6 weeks.

Management. There are currently no recommended chemical control options for SCN in Illinois. Although some products are labeled for use, using them is not an economically viable approach.

You cannot get rid of SCN once it infests a field. Some of the eggs within cysts can remain viable for at least 12 years, even when a susceptible crop is never planted. However, yield losses caused by SCN can be reduced by the rotate-rotate-rotate system:

- Rotate with a nonhost crop, such as corn.
- Rotate with SCN-resistant varieties. In 2008, more than

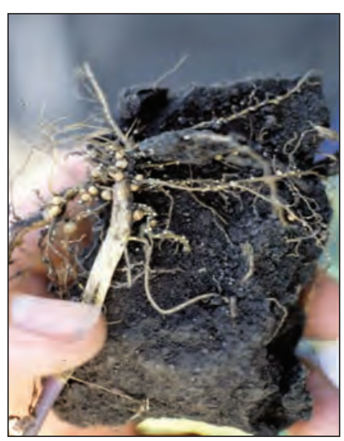

Figure 15.18. Soybean cyst nematode females (small white bodies) on the roots of a soybean plant.

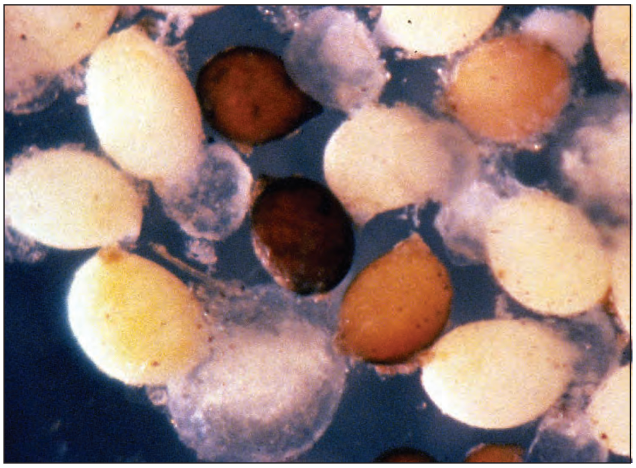

Figure 15.19. Color change of soybean cyst nematode cysts as they age. White females are young and actively producing eggs; brown cysts are dead females containing eggs that can remain viable for many years.

700 resistant varieties were available to soybean producers in Illinois. Their levels of resistance are verified and available at www.vipsoybeans.org.

- Rotate resistant varieties. Never grow the same SCN-resistant variety in the same field twice. No variety is completely resistant to SCN, and adaptation to resistance can occur quickly. Avoid this "race shift" problem by changing resistant varieties every time you plant soybean.

Monitor SCN-infested fields over time. Most fields do not need to be sampled more than once every 6 years (3 soybean years). In the fall before soybeans are planted the following spring, submit a soil sample from each field to a qualified lab for analysis. In Illinois, overwinter survival of SCN approaches 100%, so the number of nematodes present in the fall is highly predictive of the number that will be present at planting in the spring.

Race shifts. If SCN numbers appear to be increasing in a field that has been managed by rotation of resistance, it is likely that a so-called race shift has occurred. What this means is that the nematodes in the field have adapted to resistant cultivars that have been grown in that field, and they may be causing yield loss even though the cultivar is labeled "resistant." In this case, the best way to plan a management strategy is to have an "SCN type" test done by the Nematology Lab at the University of Illinois (Department of Crop Sciences, AW101 Turner Hall, Urbana IL 61801). This test will determine the extent of the shift and help the grower devise a management plan.

There are four SCN types of concern in Illinois. These are identified in a greenhouse bioassay in which the nematodes from a particular field are placed on each of the four sources of resistance available to Illinois soybean producers. (A "source of resistance" refers to the original resistant parent in a pedigree; sources include four plant introductions [PI] included in the USDA National Soybean Germplasm Collection, which happens to be located on the Urbana campus of the University of Illinois.) SCN types are determined by the nematodes' ability to parasitize a source:

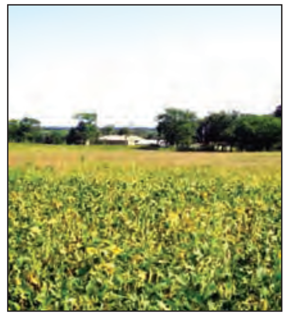

Figure 15.20. Soybean plants showing symptoms of sudden death syndrome in a field heavily infested with soybean cyst nematode. (Photo courtesy of T. Jackson.)

- SCN Type 0 cannot parasitize any of the sources of resistance; therefore, any resistant cultivar may be used to manage this type.
- SCN Type 1 can parasitize PI 548402, often referred to as "Peking." A cultivar with the Peking source of resistance should not be used in a field with this SCN type.
- SCN Type 2 can parasitize PI 88788, which is the most common source of resistance in cultivars available in Illinois. If the SCN population has shifted to Type 2, then a cultivar with resistance to Peking or PI 437654 (Hartwig or CystX, for example) should be used for one season.
- SCN Type 4 can parasitize PI 437654. None of this type have been identified in Illinois except in experimental locations, and they should not occur unless PI 437654 has been used repeatedly in the same location. Management of a Type 4 would require closely monitored tactics over time, and consultation with a nematologist would be advantageous.

Disease interactions. SCN infection stresses plants, which can increase a crop's susceptibility to nutrient deficiencies, water stress, and pathogens. Diagnosis of disease problems in Illinois should always include an assessment of SCN, because the nematode is common and is likely to be involved, at the very least as a stress factor. Take care of the SCN problem first to reduce crop stress.

SCN is known to be directly involved in the development of certain soybean diseases. Sudden death syndrome (SDS; **Figure 15.20**) and brown stem rot (BSR) are the most important of these diseases in Illinois. The exact nature of SCN involvement with SDS and BSR is not known, but when either disease occurs in a field, SCN is likely to be present. Seed varieties with resistance to BSR and SCN, or tolerance to SDS and resistance to SCN, are available, and these varieties should be used when appropriate.

Root-Knot Nematodes

Root-knot nematodes are currently a problem for some soybean producers in southern Illinois, and certain soybean-parasitic root-knot nematodes have been found as far north as Quincy. Life cycle and ability to reduce soybean yield are similar to that of SCN in that these nematodes are endoparasites that feed on giant cells within soybean roots. In addition, root-knot nematodes cause visible knotty-looking galls on soybean roots (hence, the name "root-knot"; **Figure 15.7**).

Management of root-knot nematodes requires identifying the nematode species, because several species can damage soybean. Collect soil samples as described "How to Sample for Nematodes" (p. 205) and submit them for analysis to the Nematology Lab (Department of Crop Sciences, AW101 Turner Hall, University of Illinois, Urbana IL 61801) or the Plant Clinic (plantclinic.cropsci.illinois.edu). Root-knot nematode–resistant varieties are available for southern Illinois.

Figure 15.21. Corn roots infected (left) and noninfected with lesion nematodes.

Figure 15.22. Soybean roots with symptoms of sting nematode damage. (Photo courtesy of the Society of Nematologists.)

Other Nematodes

Lesion nematode. After SCN, lesion nematode is probably the most common soybean-pathogenic nematode in Illinois. Diagnosis of a lesion nematode problem is very difficult because these nematodes cause no specific aboveground symptoms—only stunting and chlorosis, as other nematodes do—and no identifiable root symptoms. Several species of this nematode can be found across the state. Lesion nematodes are small (300 to 750 µm), migratory endoparasites; unlike SCN and root-knot nematodes, they retain a wormlike shape throughout their lives. Lesion nematodes devastate roots by migrating through them and feeding on root cells. The damage they cause looks very similar to the damage caused by several root-rotting fungi (**Figure 15.21**). These fungi may infect roots at the same time as lesion nematode, complicating diagnosis.

As with root-knot nematodes, management requires identification of the species. Collect soil samples as described in "How to Sample for Nematodes" (p. 205) and submit them for analysis to the Nematology Lab (Department of Crop Sciences, AW101 Turner Hall, University of Illinois, Urbana IL 61801) or Plant Clinic (plantclinic.cropsci.illinois.edu). No lesion-resistant soybean varieties are available at present, and rotation recommendations depend on the species present.

Sting, stunt, and pin nematodes. These nematodes are only mentioned here because some laboratories routinely assay soil samples for them. Stunt and pin nematodes are very common in Illinois soybean fields but rarely at population densities high enough to damage soybean. Sting nematodes can be found occasionally in soils with a very high sand content, and the damage looks like severe root rot (**Figure 15.22**). All three of these nematodes are ectoparasitic, but they can cause problems. The only way to diagnose a sting, stunt, or pin nematode problem is through analysis of a soil sample. Collect samples as described in "How to Sample for Nematodes" (p. 205) and submit them for analysis to the Nematology Lab (Department of Crop Sciences, AW101 Turner Hall, University of Illinois, Urbana IL 61801) or Plant Clinic (plantclinic.cropsci.illinois.edu).

Corn-Parasitic Nematodes

Nematodes are the most frequently overlooked cause of corn disease, even though they probably cause at least $80 million in corn yield losses each year. Just as with soybean, these tiny animals cause aboveground symptoms that could be attributed to other types of stress (for example, stunting or chlorosis), and they can intensify expression of specific symptoms due to nutrient deficiency, herbicide injury, and other causes. It is generally thought that nematodes are not important in corn production—that the injury they cause is rare, confined to sandy soils, and not worth the effort it takes to find the damage and diagnose the nematodes—but this conventional wisdom is wrong. Nematode injury to corn is not rare; it is simply difficult to identify. It is human nature to discount problems that are hard to see and hard to diagnose. Don't let nematodes be the last thing on your list of problems to look for in corn production.

Adding to the difficulty of diagnosis is the probability that few corn nematode species cause direct injury on their own. They interact with other problems to intensify symptoms. They also occur in polyspecific communities (that is, in combination with several other plant-pathogenic nematode species), and corn nematologists believe that corn injury due to nematodes is not frequently a one-nematode–one-disease situation. The practical implication of corn injury as an "interaction disease" is that it requires highly trained people to diagnose and supply management recommendations. There is no easy fix for the difficulty of diagnosing corn nematode problems.

Lance, needle, lesion, and dagger nematodes are the nematodes responsible for most of the suppression of corn yields in Illinois. Lance and lesion nematodes are endoparasitic **(Figure 15.5**) on corn, whereas needle and dagger nematodes are ectoparasitic (**Figure 15.4**). Management recommendations depend on species identification by a qualified laboratory. Collect soil samples as described in "How to Sample for Nematodes" (p. 205) and submit them for analysis to the Nematology Lab (Department of Crop Sciences, AW101 Turner Hall, University of Illinois, Urbana IL 61801) or Plant Clinic (plantclinic.cropsci.illinois.edu).

Lance and Lesion Nematodes

Of the four species of lance nematode that can parasitize corn, *Hoplolaimus galeatus* is the one that affects corn yields in Illinois. Although lance nematode is large for a nematode (around 1 mm or more in length), it is not unusual to find this nematode in silt loam soils. Lance nematodes are extremely common, with a very wide host range, including monocots and dicots. As few as 100 lance nematodes per 100 cm^3 of soil will damage young corn plants. Like lesion nematodes (described in the next paragraph), lance nematodes are endoparasites on corn (**Figure 15.23**). Plants that appear to grow out of early damage will yield significantly less than plants that appear healthy in the same field.

Lesion nematodes are probably the most economically important of the corn-pathogenic nematodes. At least 15 species parasitize corn; three—*P. brachyurus, P. hexincisus*, and *P. zeae*—are well-documented corn pathogens. Eight species are known or potential pathogens of corn in Illinois. The damage that lesion nematodes cause on corn is very similar to that described for soybean in the previous section. Resistance to lesion nematodes has been investigated very little, but it is known that some hybrids are less suitable hosts than others.

Control of lance and lesion nematodes, in the absence of suitable chemical controls, depends on species identification. Where polyspecific communities occur, rotation crop recommendations must be based on knowledge of host preference. Sanitation and natural-product-based soil amendments have provided lesion nematode control in some cases.

Needle and Dagger Nematodes

Needle and dagger nematodes are very large nematodes. Both are ectoparasites, remaining outside the roots while they use their long stylets to feed on cells deep within (**Figure 15.4**). Needle nematodes are limited to soils with a very high sand content, whereas dagger nematodes may be found in heavier soils.

The dagger nematode can be up to 2 mm long, but it is less sensitive to sand content than the needle nematode. Very little is known about the dagger nematode–corn relationship. Suppression may be possible with tillage because this nematode is highly sensitive to soil disturbance. Its long life cycle (perhaps a year) and its occurrence in the upper layers of the soil profile make it vulnerable to tillage operations.

Needle nematodes. Needle nematodes can cause spectacular losses—up to 62%—in infested fields (**Figure 15.2**). High rainfall and cool spring temperatures encourage needle nematode activity and the appearance of needle nematode damage. These nematodes feed on root tips, stunting the lateral roots and essentially destroying the fibrous root system (**Figure 15.24**). The root damage looks very similar to herbicide injury. Heavily parasitized seedlings may be killed. Infected corn plants can appear to grow out of early damage, but yield will be significantly reduced. Older infected plants appear to be under severe drought stress.

Two factors make needle nematode damage relatively easy to diagnose. First, their size (4 to 5 mm long) makes the nematodes relatively easy to see in a corn soil sample (although a microscope is still required). Second, their oc-

Figure 15.23. Corn roots infected with lance nematodes (stained pink; photo courtesy of G. Tylka).

Figure 15.24. Corn roots with severe (top) and slight (bottom) damage due to needle nematodes (photo courtesy of T. Jackson).

currence only in sandy soils means they do not have to be considered as the cause of problems in heavier soils.

In Illinois, very good threshold numbers have been established for needle nematode damage. One to five needle nematodes per 100 cubic centimeters of soil can cause a moderate level of damage, whereas more than 25 can cause very severe damage. Corn planting should be avoided in fields with high numbers of needle nematodes.

Although they are relatively easy to diagnose, needle nematodes are not easy to control without nematicides. Management of needle nematodes requires monocotyledonous weed control because the nematodes have a wide host range and can maintain and even increase their population densities on such weeds. Rotation to a nonhost crop, such as soybean, can reduce needle nematode populations if weed control is good.

Nematode Damage Thresholds

Decades of experience and research by nematologists in Illinois have given corn and soybean growers excellent guidelines for determining the risk of damage by nematodes **(Table 15.1).** As mentioned in the preceding sections, however, interpretation of these numbers depends on the unique situation from which the soil samples were taken. The quality of the information you get from soil samples depends on the quality of the samples!

Table 15.1. Generalized population thresholds for risk of damage by plant-parasitic nematodes in Illinois.[a]

Nematode common and generic names	Notes	Threshold numbers per 100 cubic cm of soil for degrees of severity[b]				
		Not significant[c]	Minor[d]	Moderate[e]	Severe[f]	Very severe[g]
Cyst (Heterodera)	cysts, soybeans only	—	—	1–5	6–25	>25
Cyst (Heterodera)	eggs, soybeans only	1–50	51–500	500–3,000	3,000–6,000	>6,000
Dagger (Xiphinema)		1–10	11–25	26–50	51–100	>100
Lance (Hoplolaimus)		1–10	11–40	41–75	76–150	>150
Lesion (Pratylenchus)	preplant only	1–10	11–25	26–50	51–100	>100
Needle (Longidorus)	corn only	—	1–5	6–20	21–75	>75
Pin (Paratylenchus)		1–50	51–100	101–500	501–1000	>1,000
Ring (Criconemoides)		1–75	76–150	151–300	301–600	>600
Root-knot (Meloidogyne)	juveniles	1–10	11–40	41–80	81–150	>150
Spiral (Helicotylenchus)		1–75	76–150	151–300	301–500	>500
Sting (Belonolaimus)		—	1–5	6–20	21–50	>50
Stubby-root (Paratrichodorus)		1–5	6–20	21–50	51–100	>100

Table compiled by D.I. Edwards (2003) and T.L. Niblack (2005).

[a]Figures are guidelines only; thresholds often must be increased or decreased substantially, depending on plant weather conditions, sampling and extraction methods, and other biotic and abiotic factors.

[b]Based on soil analysis unless otherwise indicated; figures in the columns underneath (left to right) subjectively correspond to trace, low, moderate, heavy, and very heavy nematode population levels.

[c]Population of no consequence during present growing season; potential for increase to damaging level remote in subsequent years.

[d]Population of little consequence at present; potential for increase to damaging level remote during present growing season but good on highly susceptible, monocultured hosts in subsequent years.

[e]Borderline situation with soil nematodes; measurable damage from nematodes alone highly dependent on present and future weather conditions and fertility level; nematodes possibly a contributing factor in a disease complex with fungi, bacteria, viruses, and/or other nematodes; control measures may not be economically practical; strip test recommended; continued monocultured may result a in severe problem. Eventual mortality of parts or all of plant can be expected with foliar and stem nematodes; treatment or destruction of plant recommended.

[f]Population sufficiently high to cause severe economic damage and some plant mortality; established planting may not be salvageable; control measure mandatory.

[g]Population sufficiently high to cause severe economic damage and some plant mortality; established planting may not be salvageable; control mandatory.