Cropping Systems and Alternative Crops

by Phillip Alberti, Talon Becker, Jennifer Jones, and Nathan Johanning; adapted from the previous version of this chapter written by Emerson Nafziger

Introduction

Two crops—corn and soybeans—have come to dominate the cultivated area of Illinois over the past 70 years (**Figure 5.1**), moving from around 60% of cropped acres in 1950 to more than 90% in recent years. This has been, in large part, due to increases in soybean acreage, which increased from around 20% of total harvested acres in 1950 to around 45% of total harvested acres in recent years.

In 2000, Illinois corn and soybean acreage were near equal, with approximately 11 million harvested acres and 10.5 million harvested acres, respectively. In the following decade corn acreage saw a large increase, peaking in 2007 at about 13 million acres (**Figure 5.1**). This increase in corn acreage and movement away from the relatively even split of corn and soybean acreage coincided with a large increase in domestic ethanol production due to increases in gasoline prices and the adoption of federal bioenergy policies (Wallander et al., 2011).

Over the past decade, corn acreage has receded back to pre-2000 acreage levels, with an average of 10.9 M acres harvested from 2016 through 2020. Because corn and soybean acreage have continuously accounted for more than 90% of Illinois' total acreage in recent years, this decrease in corn acres has been balanced by increased soybean acres. Illinois wheat acreage declined by over 60% during the past 70 years, from approximately 1.4 M harvested acres in 1950 to approximately 0.5 M harvested acres in 2020. While somewhat volatile, the decline in harvested wheat acres over the past several decades is apparent. This decline has been mirrored by an even larger decline in hay acreage, with approximately 2.8 M hay acres harvested in 1950 down to approximately 0.5 M acres in 2020. Harvested acres of oats for grain declined starkly in the 1950s and 1960s, from about 3.8 M acres to less than 1 M acres. Acreage continued to decline, although slower, with harvested acres falling below 100,000 in 1993 and reported acreage in recent years ranging from 10,000 – 15,000. Oats are used more widely as a companion crop for forage establishment or often as a cover crop that will winterkill, particularly in the state's northern and central regions.

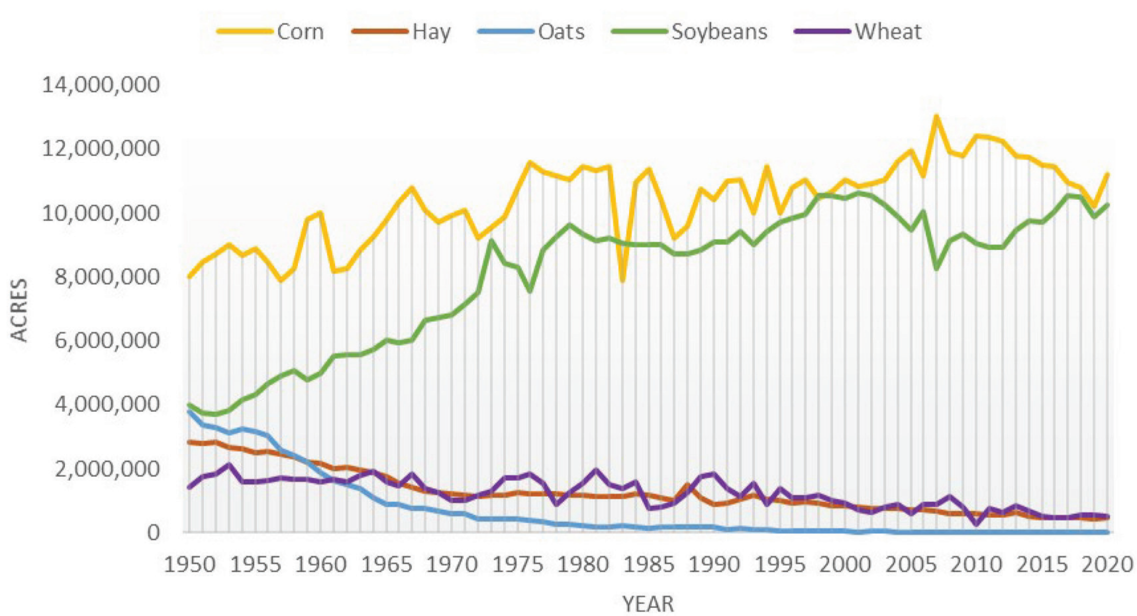

Fig 5.1. Harvested acres of five main crops in Illinois, 1950-2020. Data from the USDA National Agricultural Statistics Service.

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. Therefore, 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. The goal of this approach is usually to increase biodiversity in a given field, but it can also result 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 are obstacles to wider adoption of this approach. Increased consumer demand for locally produced foods, including meats, may have an influence on the diversity of production systems on some Illinois farms in the years to come.

Corn and Soybean in Rotation

The corn–soybean rotation (with no sequential years of one crop) is still by far the most common one in Illinois. **Figure 5.2** shows the frequency of corn planting over the past decade, with darker blue indicating more years of corn on corn, yellow indicating a relatively even split of corn and an alternative crop, presumably soybean, and darker red indicating fewer years of corn. From this, we can see that a true corn-soybean rotation is more common in central Illinois than it is in either southern or northern Illinois.

The corn-soybean rotation offers several advantages over growing either crop continuously. These advantages have been affected by the development of corn and soybeans with tolerance to a number of herbicides, including glyphosate, glufosinate, 2,4-D, and dicamba (which have

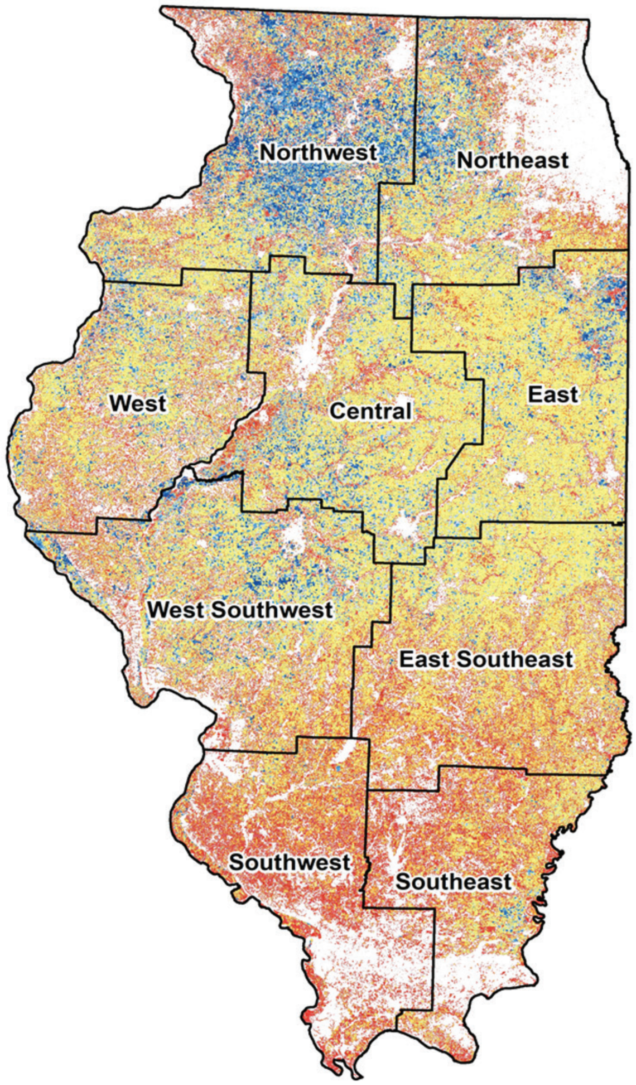

Fig 5.2. Frequency of corn planted 2010-2019 - USDA NASS Crop Frequency Layer: 1 pixel = 30 meters. Higher frequency of corn = blue and lower frequency of corn = red. The data can be viewed and downloaded at the CropScape web service at https://nassgeodata.gmu.edu/CropScape/. Map produced with ArcGIS by N. Dennis Bowman.

tended to lessen the advantages of rotation with regard to weed control). Additionally, the development of corn hybrids with corn rootworm resistance from the insertion of one or more genes from *Bacillus thuringiensis* (Bt) 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 as there are management strategies that can help mitigate some of the negative aspects of a corn monoculture.

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, resulting in a low C:N ratio. Less residue means 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. Disease carryover can also occur in continuous corn systems when the pathogens that cause the disease survive in the previous year's corn crop residue and infect the next year's crop (assuming the environment is favorable for disease development). Disease carryover is less likely to happen when corn is rotated with soybean.

Soybean is usually grown following corn in Illinois, but soybean is occasionally grown following soybean. This may be due to relatively better income expected from soybean in a given year; alternatively, unforeseen circumstances such as late planting or application of the wrong herbicide may favor a switch from an intended corn planting to soybean. As with continuous corn, continuous soybean can also lead to build-up of soybean disease and/or pest pressure. Soybean cyst nematode (SCN) is an ever-present pest in soybeans whose effects often go unnoticed due to a lack of readily visible above-ground symptoms when SCN populations are relatively low. Genetic resistance to SCN bred into most commercial soybean varieties has helped to keep the impact of this pest from being catastrophic in recent decades, but over-use of one or two genetic resistance sources in the commercially available varieties has led to increasing numbers of SCN populations that are overcoming that resistance. Rotating away from the SCN host crop of soybean with corn or other crops is one of the best methods we have to mitigate this pest while also slowing the speed at which SCN populations are able to evolve to overcome any genetic resistance mechanisms modern soybean varieties have been bred to contain.

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 term. 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.

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 study over six locations in Illinois from 2004 to 2016. The locations included DeKalb and Monmouth in Northern Illinois, Urbana and Perry in Central Illinois, and Brownstown and Dixon Springs in Southern Illinois. No difference was seen in yields between first- and second-year corn in the CCS rotation in the Central and Southern locations, but first-year corn yielded more than second-year corn in the Northern locations. Continuous corn yields were significantly lower than corn yields in all the other rotations. Soybean saw a yield boost following two years of corn instead of one at the Northern and Southern locations, but not in Central Illinois.

A study conducted in Illinois over the course of 12 years compared soil quality indicators under three common crop rotations: continuous corn (CCC), corn-soybean (CS), and corn-corn-soybean (CCS) (Hoss et al., 2017). The researchers found no differences in soil attributes when comparing the short corn rotations (CS and CCS) to continuous corn systems. Essentially, short corn rotations were not improving soil quality compared to a corn monoculture. This finding is especially interesting since monocultures are generally associated with low functioning ecosystems due to a decrease in biodiversity, so even a short rotation of CS or CCS would presumably cause a positive change in soil properties by adding some biodiversity into the system. The researchers highlighted the need to diversify cropping rotations both temporally and spatially in order to achieve sustainability goals. Cover crops are an example of a practice that could increase temporal and spatial diversification in a monoculture or short corn rotation system because they grow during typically fallow periods of the year and can attract animal, insect, and microorganism life that corn and soybean crops may not, thus increasing biodiversity of life present in the field.

Table 5.1. Yields of corn and soybean in a study comparing continuous corn with corn-soybean and corn-corn soybean rotations. The North locations include DeKalb (7 site-years) and Monmouth (13 site-years). The Central locations include Urbana (13 site-years) and Perry (11 site-years). The South locations include Brownstown (10 site-years for corn data; 11 site-years for soybean data) and Dixon Springs (10 site-years for corn data; 11 site-years for soybean data). Different letters within location columns for corn and soybean data indicate statistical significant difference among those yields. Data and analysis provided by Dr. Emerson Nafziger.

Corn Yields (BU/AC)			
Rotation	**North (20 site-years)**	**Central (24 site-years)**	**South (20 site-years)**
Continuous Corn	195 c	187 c	145 c
1st-yr corn in Corn-Corn-Soy	216 a	199 b	152 ab
Corn-Soybean	216 a	205 a	155 a
2nd-yr corn in Corn-Corn-Soy	203 b	196 b	150 b
Soybean Yields (BU/AC)			
Rotation	**North (20 site-years)**	**Central (24 site-years)**	**South (20 site-years)**
Corn-Corn-Soy	66 a	59 a	45 a
Corn-Soy	61 b	59 a	43 b

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 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

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, a study was conducted at four sites and a total of 14 site-years. This research study investigated the effect of two tillage treatments (chisel plow vs. strip-tillage), two fertility programs (high = 320 lb N/ac; normal = 220 lb N/ac), and an R1 foliar fungicide treatment on yield. The high fertility plots were also maintained with higher soil test phosphorus and potassium levels than the low fertility plots. **Figure 5.3** shows the results across all site-years from this study. In most cases, strip-tilling instead of using a chisel plow had little effect on yield (4 of 14 site-years with significant tillage treatment effect; analysis not shown). When looking across all site-years, statistically significant yield effects from tillage treatments were seen only when a fungicide was included under a “normal fertility” program or when no fungicide was included under a “high fertility” program, but not over the experiment as a whole. Overall, the “high” fertility program resulted in a 16 bu yield increase compared to the “normal” fertility program, but in many site-years it likely did not increase economic return, depending on cost of inputs and price of corn. Including a foliar fungicide application at R1 resulted in an 8 bu yield increase across the whole trial. However, when looking specifically at the tillage by fungicide interaction, the positive yield effect from an R1 fungicide application was not greater in the strip-tilled plots as compared to the chisel plowed plots (analysis

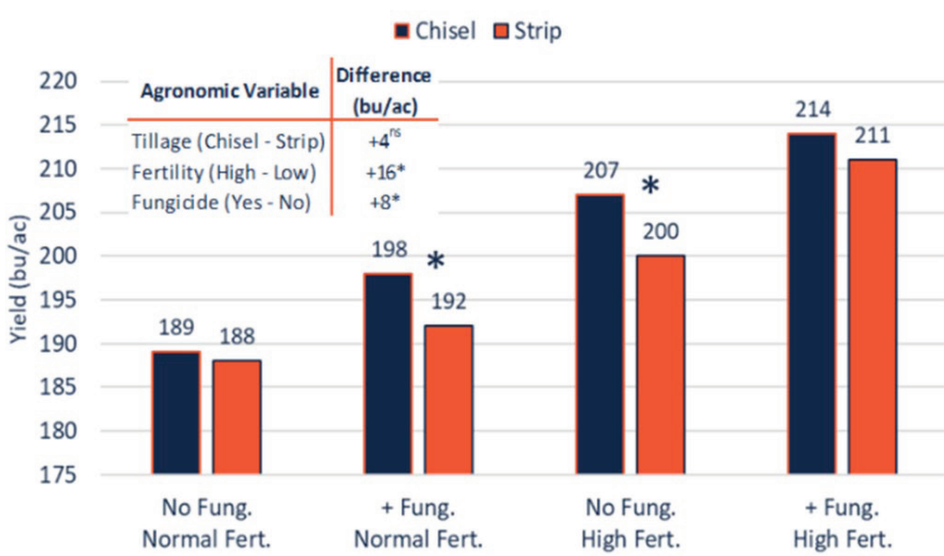

Fig 5.3. Average continuous corn yields and effects of agronomic variables over 14 site-years (2008-2013). Normal Fertility = 220 lb N/ac and High Fertility = 320 lb N/ac. Fungicide was applied at R1. Asterisk indicates a significant difference (α = 0.1). Data and analysis provided by Dr. Emerson Nafziger.

not shown), despite the larger amount of corn residue and potential for more carryover of fungal inoculum (spores) from previous seasons.

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** and **Table 5.2** show results averaged over 32 site-years in Illinois from 2006 to 2015. As residue was partially removed from no-till plots, the optimum N rate lowered about 14% while yield increased slightly (nine bushels per acre) compared to no residue removal. Removing all the residue in no-till plots lowered the optimum N rate by about 29% compared to no residue removal while yield increased by eight bushels per acre. Fully or partially removing residue from conventionally tilled plots had nearly no effect on yield compared to no removal, but partial residue removal reduced the optimum N rate by about 10% compared to no removal. Little additional benefit was seen from full removal or residue in the conventional tilled plots.

These data illustrate how residue removal can influence optimum N rate in a no-till system more than a conventional tillage system. Removal of all residue resulted in a decrease of 68.4 lb N/ac (29%) in no-till plots vs. decrease of 21.7 lb N/ac (11%) in conventional till plots. This is likely due in part to the use of fertilizer-supplied nitrate by soil microbes in the decomposition of corn residue. Even partial removal of residue from no-till plots resulted in a 14% reduction in optimum N rate and boosted yields to levels comparable to those seen in the conventional tilled plots. Although not tested in this study, no-till soils where cover crops have been incorporated could potentially see an increase in the rate of residue decomposition, possibly mimicking the partial residue removal tested in this experiment. This is because cover crops are commonly regarded as a tool to increase soil microbe population levels and diversity, which typically increases the rate of residue decomposition (Barel et al., 2019).

Fig 5.4. Effect of full and partial residue removal, tillage, and N rate on yields of continuous corn. Data are averaged over 32 site-years from 2006 to 2015. CT = conventional tillage and NT = no-till. Triangles represent the optimum yield for each treatment. Data and analysis provided by Dr. Emerson Nafziger.

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.

Table 5.2. Effect of residue removal, tillage, and N rate on continuous corn yields (also shown in Figure 5.7). Data are averaged over 32 site-years from 2006 to 2015. CT = conventional tillage and NT = no-till. Triangles represent the optimum yield for each treatment. Deltas (Δ) represent the difference between NT and CT of each treatment for optimum N rate and yield at optimum N. Data and analysis provided by Dr. Emerson Nafziger.

Residue/tillage	Optimum N rate		Yield at optimum N	
	lb/acre	Δ	bu/acre	Δ
No removal NT	236.9	43	180	-13
No removal CT	194.2		193	
Partial removal NT	204.8	30	189	-1
Partial removal CT	175.0		190	
All removed NT	168.5	-4	188	-6
All removed CT	172.5		194	

Experiments were conducted from 2006-2016 at three sites in Illinois to see how adding winter wheat into the corn–soybean rotation affects yields and profitability. These experiments included 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 was present in all possible phases each year. Double-crop soybean followed 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 these studies are presented in **Table 5.3**. Continuous corn yielded 1% to 12% less than corn following soybean and including wheat in the rotation improved corn yields by 4% to 6% at the Monmouth and Perry locations, respectively. At the Brownstown location, there was no change in corn yields when adding wheat into the rotation. The sequence of corn, soybean, and wheat had little impact on corn yield, though corn following soybean yielded slightly more than corn following wheat at both the Monmouth and Brownstown locations

Continuous soybean yielded 7% and 2% less than soybean rotated with corn at Monmouth and Perry, respectively. Adding wheat into the rotation increased soybean yields by 4% on average across all locations and stage in the rotation. Over 10 years of favorable double-crop conditions, double-crop soybean yielded about 75% 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 affected by crop sequence, with yields 4%-10% higher when wheat followed soybean compared to wheat following corn.

Incorporation of additional plant species (soybeans, wheat) into corn cropping systems has long been touted to improve soil quality compared to monocropping systems (continuous corn). Analysis of both the Brownstown and Perry locations indicate that implementation of continuous corn had similar soil quality parameters to those found under short (corn-soybean) rotations. Although these short rotations make economic sense, they behave more similarly to corn monocultures than longer, diversified rotations from a soil quality standpoint (Hoss et al., 2018 and Zuber et al., 2015).

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.

Table 5.3. Yields of corn, soybean, and wheat in cropping system trials at three Illinois sites. Data and analysis provided by Dr. Emerson Nafziger.

Crop and Sequence	Monmouth 2007-2016	Perry 2007-2016	Brownstown 2007-2016
	- bushels per acre -		
Corn			
Continuous Corn	198	183	150
Soybean-corn	222	196	152
Soy-wheat-corn	231	192	164
Wheat-soy-corn	234	200	158
Soybean			
Continuous soy	66	48	-
Corn-soybean	71	50	42
Wheat-corn-soy	74	52	42
Corn-wheat-soy	75	51	45
C-S-W/doublecrop	-	-	31
S-C-W/doublecrop	-	-	32
Wheat			
Corn-soy-wheat	73	67	57
Soy-corn-wheat	66	62	55

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.

Alternative Crops in Illinois

While corn, soybean, and small grains dominate the landscape, many other agronomic crops will grow quite well in Illinois, and many will grow quite well. 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. Alternative crops are often 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 first 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 grow well in similar areas for very good reasons, and in most of those 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. The value of production must be sufficient to justify these capital expenses for the crop to be viable. Seasonal labor is usually limited in terms of availability and/or expensive in the Corn Belt. Thus, crops that require intensive hand labor, such as hand harvest, must be high value crops to justify this expense and make the crop economically viable.

Web Resources on Alternative or New Crops

There are very good online resources on alternative crops. 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. Below are just a few examples of some good resources from the Midwest on alternative crops:

- Purdue University NewCROP™ - www.hort.purdue.edu/newcrop
- Iowa State University: Alternative Agriculture - https://www.extension.iastate.edu/alternativeag/
- University of Kentucky Center for Crop Diversification: Crop Profiles - https://www.uky.edu/ccd/production/crop-resources

Sunflower

Sunflower is an alternative crop that some Illinois farmers have produced profitably. Due to its susceptibility to several fungal diseases, sunflower usually grows in areas of low humidity. 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 non-ruminant 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, but an acceptable crop is possible using a wide range of planting dates. 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 a host of 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 pan-like 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. Research from the University of Illinois has shown that canola meal can be used as a feed substitute for both swine and sows with several products being commercially available.

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. Canola is widely adapted to temperate zones, but 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 medium soil textures and good surface drainage should be used, with good internal drainage improving 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. Seeding into a smooth, firm seedbed will be critical to maintaining a uniform seeding depth and emergence. The very small seeds need to be planted shallowly (½- 1 in.) 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.

Hemp

Hemp (*Cannabis sativa*) is an alternative crop that can be grown in Illinois for grain, fiber, or cannabinoid production. Hemp and marijuana are both types of plants within the *C. sativa* species that are classified based on their chemical composition. According to current USDA regulations, hemp is a *C. sativa* plant with less than 0.3% total tetrahydrocannabinol (THC) based on the dry weight of the plant. Total THC is primarily composed of delta-9-THC and the acid form of that compound, THCa. During combustion, THCa is decarboxylated to form delta-9-THC, which is one of many cannabinoids produced by the *C. sativa* plant and is noted for its intoxicating effects. For this reason, current USDA rules require hemp samples to be decarboxylated (mimicking combustion) before cannabinoid quantification so that results show the levels of all possible delta-9 THC, not only what was in the delta-9 THC form at harvest. For this reason, from this point on we will use ‘THC’ to refer to total THC following decarboxylation.

THC is found in much higher concentrations in plants classified as marijuana because marijuana plants have been bred to produce a high amount of THC on purpose. If the THC level is below 0.3%, the *C. sativa* plant can be classified as hemp. Conversely, if the THC level is above 0.3%, the *C. sativa* plant is classified as marijuana. The difference between industrial hemp and marijuana is analogous to the difference between sweet corn and field corn; both are corn (*Zea mays*) plants which have been bred for different purposes. The former is a high-sugar fresh-market vegetable and the latter is a dry grain high in starch that is used for animal feed, fuel/alcohol, and processed products for human consumption (e.g. corn flour/masa harina, oil, starch, sugar/syrup) or industrial uses (dextrins and starch).

Illinois legalized production of industrial hemp in August 2018, requiring growers and processors to obtain a license from the Illinois Department of Agriculture (https://www2.illinois.gov/sites/agr/Plants/Pages/Industrial-Hemp.aspx). Potential growers of industrial hemp should be aware of the testing, reporting, and recordkeeping involved in producing or processing industrial hemp as required by the IDOA. While these reports are not exhaustive, they are an extra requirement compared to more traditional crops. Interested parties are highly encouraged to read the rules and regulations prior to applying to grow or process industrial hemp. Given that state and tribal hemp production plans will vary, being up to date on the most current rules and regulations are essential to compliance. Variation among state hemp production plans largely concerns which of the component(s) of THC (THCa and/or delta-9-THC) that will be used when determining compliance.

Over the first two years of hemp production in Illinois (2019 and 2020), on average 699 producers planted ~7000 acres of industrial hemp, with the vast majority of that intended for cannabinoid production. A lack of large-scale processing and distribution availability for grain and fiber has limited the acreage grown for these purposes in Illinois so far. Despite limitations with industrial hemp grain and fiber, production of industrial hemp for flower has seen a fair amount of interest across the region as states have legalized production.

Preliminary information from 2018-2020 hemp growing seasons in Illinois and Wisconsin, in addition to support from other land grant institutions, indicates that weed pressure may be the greatest limiting factor in terms of yield. *Cannabis*, while germinating and emerging quickly, is considered to have two phases of vegetative growth following emergence: slow and rapid. It is critical to keep weed pressure to a minimum during this slow growth phase to prevent weeds from outcompeting a young hemp crop. There are currently no herbicide options available for hemp production in Illinois. As such, control measures are limited to cultural practices including cultivation, mowing, cover crops, etc.

The end use of the hemp plant (grain, fiber, and cannabinoids) will ultimately determine the production methods used. Regardless of production system, hemp performs best in well-drained soils and temperate climates with optimal growth and development occurring where soil has ample moisture without periods of prolonged soil saturation. Hemp plants with well-developed root systems may be able to tolerate prolonged dry periods but the information in this area is lacking. In short, we currently do not have enough information to make regional recommendations on moisture requirements for water use/irrigation.

Grain and Fiber (Industrial Hemp)

Historically, conventional farm equipment has been used to produce industrial hemp for grain and fiber with those production systems mirroring small grain and hay production systems, respectively. Hemp grain is high in protein, omega-3 and omega-6 fatty acids. Hemp seeds are safe and healthy for humans to eat but cannot be fed to livestock being raised for human consumption at this time. However, research is underway to verify the safety of hemp seed or seed byproducts as livestock feed. Hemp fiber is used to make a variety of commercial and industrial products including, but not limited to, rope, textiles (clothing), shoes, food, paper, bioplastics, insulation, and biofuel. Hemp flower is produced both as a smokable product and for the extraction of cannabinoids such as CBD, CBN, CBG, etc.

As it is photoperiod dependent, the goal in grain/fiber systems should be to plant as early as soils are fit to maximize growing days and increase vegetative growth (fiber production) prior to flowering. This is similar to the idea behind planting soybeans early to allow for more vegetative growth prior to flowering. Generally, research suggests hemp will germinate in soil temperatures above 50°F, thus likely coinciding with planting of corn and soybeans in the region.

Both grain and fiber varieties are dioecious and are usually planted with a grain drill at high seeding rates (25-35 lbs./acre [≈625K-875K seeds/acre] for grain and up to ≈60 lbs./acre [≈1.5M seeds/acre] for fiber). However, modified planters have been used as well, specifically those with sorghum/milo seed meters that can account for small seed. High seeding rates are used to help improve weed control via canopy closure; additionally, dense populations encourage tall, thin plants, which is of particular interest in producing high quality fiber. If direct seeding, the field should be planted after a rain event or when there is enough soil moisture without the potential of soil crusting. Shallow seeding depths (~1/2in.) are likely to increase the success of the germinating seeds. When direct seeding, seeding rates should be increased to account for seedling mortality and germination issues. It is highly recommended to check the germination rate of a seed lot prior to planting and to use test strips at the beginning of planting to allow time to make modifications if necessary.

Fertility recommendations of industrial hemp have yet to be developed in Illinois, but research out of the University of Kentucky has provided a baseline (Williams, 2018):

Grain
- 100-125 lbs./acre Nitrogen
- 40-70 lbs./acre Phosphorous
- 60-100 lbs./acre Potassium

Fiber
- 50 lbs./acre Nitrogen
- 40-70 lbs./acre Phosphorous
- 200 lbs./acre Potassium

Hemp grain is typically harvested by using a straight-cut method. However, in certain conditions swathing may be an option. When straight cutting, plants are clipped below the base of the seed head, to reduce the amount of fiber wrapping that may occur in the moving parts of machinery. Straight cutting leaves large amounts of fiber remaining in the field, giving producers the option to chop and bale (dual-purpose cropping) or utilize alternative residue management strategies that fit their system. However, the efficacy of dual-purpose production systems to produce sufficient quality and quantity of grain and fiber remain to be seen.

Hemp grown solely for fiber is harvested similarly to hay. The hemp plant is chopped at flowering and is typically raked over several times to allow even retting to occur before being baled up and sent for processing. Field retting employs moisture and bacteria to naturally break down cellular tissues to aid in the separation of fiber from the stem during the decortication process. The amount of time required for the hemp to ret in the field will depend on environmental conditions, such as temperature and rainfall, but has been shown to take ~7-21 days according to weather conditions. Proper field retting is an important step which contributes to overall fiber quality and profitability.

Cannabinoids

Cannabinoids are naturally occurring compounds found in the resinous flower of a C. sativa plant. There are currently over 100 cannabinoids that have been identified to date. Production of industrial hemp for various cannabinoids (CBD, CBN, CBG, etc.) typically uses a much more specialized system which mirrors that of a specialty crop operation more than traditional row cropping due to the end use: smokable flower or high-quality biomass for extraction. Information from the following section contains information shared from the Midwestern Hemp Database (MHD) and associated reports (Alberti, 2021).

High cannabinoid hemp is typically grown on small acreage (<5 acres) and is more akin to specialty crops than traditional row crops. Regional data has shown an increase in number of licensed growers while acreage has decreased indicating a downward shift in average operation size. Farmer ingenuity has led to the implementation of direct seeding strategies, but high cannabinoid hemp is still established primarily via transplants from seed (63%) followed by transplants from clones (31%). Low seedling vigor, poor seed quality, and high seed costs across the industry are likely the cause for these trends. Hemp grown for cannabinoid production is a high input specialty crop and must often be treated like one for success.

Transplanting of hemp into the field peaks in mid-June but extends into early July; delaying planting will result in less vegetative growth prior to flowering subsequently reducing biomass and floral yields but will still produce a viable crop. Seedlings/clones are usually established in greenhouse/nurseries for several weeks prior to transplanting into the field. Well-prepared seedbeds with good soil tilth will promote uniform growth and development. Hemp does not take well to cold, saturated soils, and 65% of all cultivar entries in the MHD were planted into either silt-loam or sandy-loam soils. Planting/transplanting may be delayed in cannabinoid production systems to prevent plants from getting too large and lodging due to excessive branching and bud formation.

Standing populations typically range from 1,200-2,700 plants per acre and are planted/transplanted in the field in June/July. Whereas direct seeding dominates grain/fiber production, most high cannabinoid hemp will be transferred into the field in the form of transplants or clones. Plant populations will ultimately depend on row spacing, which is typically between 3-5 feet. This type of row spacing can be hard to achieve with conventional seeding equipment and in many cases, plants are started in a greenhouse and transplanted using a vegetable transplanter or by hand. Innovative farmers and private industry have been developing direct-seeding technologies with varying degrees of success. Several conventional growers have modified corn planters by raising row units, plugging holes, buying new seed meters, and calibrating the equipment prior to planting. However, success with these tactics has been extremely variable. At such low populations, hemp plants exhibit more lateral branching in response to the decreased competition and stress resulting in plants that look more like vegetable crops than row crops. Upon flower initiation in August/September, female plants will begin to develop flowering structures ("buds") at each node which will continue to develop through the flowering. It is during this time that fields must be scouted to cull males and reduce potential for pollination and yield loss.

Cannabinoids are found in the highest concentrations in the unpollinated flower of the female plant and generally increase in concentration as the flowering period proceeds. The tightrope that producers must walk is maximizing production of desirable cannabinoids while still producing a crop which fails to exceed the threshold of 0.3% THC. Due to differences regarding which components of THC will be used to determine compliance (delta-9-THC and/or THCa), growers must be aware of state regulations and how it may impact their production system. Production of cannabinoids are significantly limited upon pollination and subsequent grain formation. It is for this reason that most hemp grown for cannabinoids utilizes feminized seed to reduce the number of male plants in the field that will likely need to be culled during flowering. The end use of the harvested plant material for cannabinoid production will determine the harvesting method, i.e. high-quality smokable flower or biomass for extraction. Current harvest methods are extremely variable and changing rapidly as new technologies emerge.

High cannabinoid hemp is often harvested in early October; plants grown for quality flower are typically harvested by hand before undergoing the drying, trimming, and curing processes. Growers can expect yields of ~1 lbs./plant of dried floral material, but there is a great deal of variability due to genetics and production skill. Hemp grown for cannabinoid extraction is harvested by chopping down plant material (methods vary) and is subsequently dried to ~10% moisture. The amount of post-harvest processing (drying, bucking, milling etc.) required prior to delivery to extraction facilities will depend on the specifications of the extraction facility. Growers are strongly encouraged to have contracts in place prior to the growing season and to know the required specifications for the delivered product of the extraction facilities. The material you grow must be deemed compliant via laboratory analysis before it is harvested or transported. The harvested material must test below 0.3% THC by an Illinois Department of Agriculture (IDOA)-approved laboratory. Submitting plant samples for analysis throughout flowering is the best way to ensure compliance of selected varieties at the end of the season.

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. As a result. there are not many varieties available. Mancan and Manor are the most common varieties available; you can also find ‘common’ buckwheat which is often a blend of varieties.

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 and industrial products, although some offer feeding advantages for livestock as well.

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 (https://www.ams.usda.gov/rules-regulations/organic). 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 non-organic 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. The feasibility of organic production often depends on the availability of manure as a non-synthetic fertilizer source.

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 (genetically modified organism) corn and soybean. A non-GMO corn hybrid or soybean variety is called such because it does not contain any ‘transgenes’ (a gene from another organism inserted with the use of molecular biology techniques instead of traditional breeding methods; aka ‘traits’) that confer herbicide or insect resistance. These “traits” or “trait packages” are prevalent in much of the available commercial corn hybrids and soybean varieties. While non-GMO corn and soybean have not been “genetically modified” in the sense that they contain inserted transgenes from other organisms, their genetics have been modified through the use of selective breeding techniques. This means that non-GMO corn and/or soybean seed released from a company today is likely to have more genetic yield potential than that of the pre-GMO row crop era.

Production of non-GMO corn and soybean relies on the more traditional row-crop farming techniques that were used prior to the emergence of GMO crops in the 1990s. One exception to this may be the increased use of cover crops for weed suppression in non-GMO production systems as compared to the early 1990s. Use of cover crops can create a “mat” of biomass once terminated, particularly if they are also flattened with a “roller-crimper” prior to or during planting. This mat of biomass can reduce weed emergence and survival/vigor by shading much of the soil surface prior to canopy closure of the cash crop. Integration of strip-tillage with cover crops may provide the benefits of a warmer seed bed within the row while maintaining biomass cover between the rows. Potentially, similar effects could also be achieved with the use of precision planting techniques when seeding the cover crop, so that the specie(s) seeded into the cash crop row will winter-kill, leaving a blank row for the cash crop to be seeded into.

Other than needing to manage weeds and insects using more traditional techniques, keeping harvested grain separate from that produced using GMO seed is perhaps the most difficult aspect of non-GMO corn and soybean production. Several GMO traits have USDA-verified 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 (https://www.ams.usda.gov/services/fgis/standardization/biotechnology).

Beyond the non-GMO category, most other specialty types of field corn differ from commodity corn by having altered profiles of protein, oil, starch, or other nutritional components in their grain, while some food grade types may also have altered pigment profiles in their outer cell layers (pericarp and/or aleurone) (Paulsmeyer et al., 2017 and Scott et al., 2019). Some of these are described in Chapter 2. Many of the specialty soybeans are characterized by their altered types or ratios of fatty acids in their oil, as compared to a normal commodity soybean. Some demand for these products stems from the current health concerns and labeling requirements regarding trans-fats. Soybean oils with altered fatty acid profiles have the potential to reduce saturated and trans-fats in the foods that contain them while maintaining favorable flavor, texture, and shelf-life qualities (Wilkes 2008, Medic et al., 2014, and Hagely et al., 2021). Certain types of alterations of the fatty acid profiles that can be achieved through genetic modification techniques have the potential to improve the quality of soybean oils for specific industrial uses, although the economic feasibility of these products is often uncertain considering the high costs of regulatory approval of genetically modified crops (Cahoon, 2003).

Biofuel Sources and Crops

According to the U.S. Energy Information Administration (USEIA) in their 2021 Annual Energy Outlook, demand for all liquid fuels was decreased as a result of the COVID-19 pandemic. However, biofuel consumption decreased by a lower percentage than petroleum-based fuels (https://www.eia.gov/outlooks/aeo/). In this report, the USEIA projects that, bolstered by regulatory support, biofuel demand will recover slightly faster than that of petroleum-based fuels, thereby leading to an increased share of the domestic fuel supply coming from biofuels over the next several years. According to their models, future increases in the share that biofuels demand of the domestic fuel supply will largely depend on the price of oil. In their high oil price scenario ($173/barrel Brent crude oil price in 2020 dollars), biofuel's proportion of the domestic fuel supply is projected to almost double, from ≈7.5% in 2020 to ≈14% in 2050. However, in their reference ($95/barrel) and low oil price ($48/barrel) scenarios, projected gains in market share of biofuels by 2050 are much more limited. The reference scenario projects the market share of biofuels will increase at a slow, steady rate, reaching ≈10% by 2050, while the low oil price scenario projects a modest increase over the next decade, a leveling out over the following decade, and a possible decline in the 2040s, resulting in a market share of ≈9% by 2050.

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 recent years, the U.S. has used about 35-40% of the corn crop to produce approximately 16 billion gallons of fuel ethanol (https://www.ers.usda.gov/data-products/us-bioenergy-statistics/). The Biofuels Atlas produced by the National Renewable Energy Laboratory (NREL) lists 14 ethanol biorefineries in Illinois and more than 200 in the U.S. In terms of the number of ethanol biorefineries in each state, Iowa leads the nation with 44. Most of the ethanol biorefineries listed by the NREL utilize corn as their feedstock, but a growing number are also accepting sorghum, waste alcohol and sugars, and cellulosic biomass. At this time, none of the 14 Illinois ethanol biorefineries are listed as accepting alternative feedstocks, including cellulosic biomass, but this feedstock is accepted by four Iowa ethanol biorefineries and one in Wisconsin.

Increasing demands for ethanol and eventual limitations imposed by 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; however, 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 sludge-like material that could present a disposal challenge. However, research has shown some promise for optimizing procedures to create valuable industrial biproducts from the waste products of cellulosic ethanol production, potentially decreasing the cost to the consumer for cellulosic ethanol and making it more economically viable (Rosales-Calderon & Arantes, 2019).

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. Therefore, 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 potentially waste disposal costs will be high. 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.

If sufficient commercial processing becomes available, the crop residue and other sources of cellulose could 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 even roadsides, interstate highway medians, waterways, and other unfarmed areas might become viable sources, so long as 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 also take on value as feedstock.

Biodiesel is another biofuel with growing interest and production in the U.S. This biofuel is produced from vegetable oils (primarily soybean oil in the Midwest), yellow grease (i.e. used/recycled cooking oils), and animal fats through a process called "transesterification". This is a chemical process that produces fatty acid methyl esters (FAME) through the reaction of fats/oils with a short-chain alcohol (often methanol) and a catalyst (https://www.eia.gov/energyexplained/biofuels/biodiesel.php). Domestic production of biodiesel still pales in comparison to ethanol, averaging 1.7 to 1.8 billion gallons annually over the past several years (https://www.eia.gov/biofuels/biodiesel/production/). However, domestic production of this biofuel has seen steady increases over the past decade, with less than a half billion gallons produced in 2010, increasing at an average rate of about 140 million gallons per year. Illinois currently has 5 biodiesel refineries with a total annual production capacity of 162 million gallons. Iowa again leads the U.S. with 10 biodiesel refineries and a total annual production capacity of 445 million gallons.

While production of liquid biofuel (ethanol, biodiesel, and a couple 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 biofuel. It also means less waste, though ash—mineral content that does not 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

A great deal of effort is under way to find and develop crops that produce large quantities of harvestable dry matter that could be used as a source of cellulose for ethanol production. We call these "dedicated" biofuel crops because from a human-use perspective, they are most useful as a biofuel source rather than as a source of food. Some of these crops might have additional purposes, including forage, but harvest timing and other cultural factors may affect their utility for these purposes.

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

Fig 5.5. Switchgrass (foreground, left) and Miscanthus x giganteus (right).

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 per acre (Casler et al., 2018 and Zumpf et al., 2019). 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. 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. There is no established market and not enough seed stock to plant large acreages, so most plantings over the next several years will likely be for research and demonstration.

One of the major drawbacks to growing *Miscanthus x giganteus* 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 usually takes place in late fall or winter, after the leaf material has dried up and blown away and stems have dried. Recent research has shown that biomass yields may be higher in the first year or two by harvesting in late fall or early winter, before the plant fully senesces (dries down). However, early harvest also increases the amount of fertilizer nitrogen that must be applied to maximize yield in the following years and compromises long-term productivity (Parrish et al., 2021). This is probably because more nitrogen is removed from the field when the biomass is harvested early before it has had time to remobilize much of the nitrogen and other mobile nutrients in above-ground tissues to its rhizomes, thereby reducing the energy stored for regrowth the following spring. *Miscanthus* 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

Cover crops are annual plants grown in agricultural fields during typically fallow periods in order to provide ground cover protection and many other possible benefits for otherwise bare soil. Cereal rye, wheat, annual ryegrass, oats, crimson clover, hairy vetch, and other grasses and broadleaves are sometimes used as cover crops in the Midwest. Cover crops are used for many different reasons including:

- protecting and holding soil in place during winter and spring

- scavenging nutrients like nitrogen and phosphorus from the soil to keep them for future crops by preventing runoff or leaching into water bodies
- acting as a nitrogen source in the case of legumes
- building soil health and improving soil tilth by adding organic matter through plant biomass, or residue, into the system both above ground and below ground
- improving water infiltration by creating root channels and increasing soil aggregate stability
- suppressing weed growth
- providing a habitat for beneficial insects and soil microbes
- building the soil and suppressing weeds in prevent-plant fields
- serving as a source of grazing material for livestock

Cover Crop Benefits

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 (Korucu et al., 2018). 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 practices will generally reduce soil loss. Additionally, cover crops are cited in the Illinois Nutrient Loss Reduction Strategy as one of the most promising conservation practices to help the state reach its water quality goals. They positively affect water quality by growing during fallow periods and taking up excess nutrients, which are susceptible to loss via surface runoff, leaching through tile drainage, or soil erosion.

A recent meta-analysis of data (Kim et al., 2020) evaluated the effect of cover crops on soil microbial properties. The researchers found that soil microbial abundance, activity, and diversity were all increased by cover crops compared to bare fallow. The biomass produced by cover crops both above ground (leafy tissue) and below ground (roots) provides multiple benefits, one of which is to act as a food source for soil microbes during periods of the year when cash crops are not growing.

In addition, cover crop biomass helps hold soil in place and prevents it from eroding. Cover crops achieve this in part because they aid in increasing soil aggregate stability. Aggregates form when soil particles bind together in clumps ranging from micro to macro levels in size. Roots, earthworms, fungi, and other microorganisms play a part in the formation of soil aggregates through physically holding aggregates together and/or secreting organic compounds that act as natural glue to hold the aggregates together. Soils are able to hold more water and air when aggregates are present and stable because they form pores and give the soil a stable structure. Cover crops encourage aggregate formation by increasing soil biological activity and adding roots and biomass into the system. The stability of a soil aggregate refers to its ability to resist destruction from outside forces such as water. A soil with higher aggregate stability is more likely to withstand erosion and avoid compaction issues. In a conventional system, a cash crop of corn or soybeans may grow for four to five months, and soil remains bare for the remaining months of the year. Depending on if a species that survives winter is selected, cover crops can allow soils to have protection for an additional four to eight months of the year. A cover crop's ability to contribute to greater soil aggregate stability and a larger and often more diverse soil microbiome can also lead to increased water infiltration and water holding capacity in the soil. Root channels under the soil surface left by cover crops can act as guides for the following cash crop's roots and aid them in breaking through compacted layers as they seek water and nutrients.

One resource available to help farmers, landowners, agronomists, and conservation professionals select appropriate cover crop species and manage them is the Midwest Cover Crops Council (MCCC) (www.mccc.msu.edu). The MCCC website has many factsheets and resources on all aspects of cover crop use. One very useful resource is the Cover Crop Decision Tool, which includes cover crop management information from species selection and planting to termination and cash crop planting. A user of the Cover Crop Decision Tool can select their state, county, soil drainage class, and cash crop to get specific recommendations for several different cover crop species and mixes.

Recommendations include planting and termination dates and methods, seeding rates by planting method, performance and roles of each species, and potential advantages and disadvantages. The user can also select up to three goals they hope to achieve by utilizing cover crops, and the system will rank the species to address the selected goals. Another useful publication developed by the Illinois Nutrient Research and Education Council (NREC) is available at https://www.illinoisnrec.org/cover-crop-guide-2-0/. It includes cover crop recommendations based on research funded by NREC around the state of Illinois. For general cover cropping information, the book "Managing Cover Crops Profitably" published by the Sustainable Agriculture Research and Education (SARE) program is a good resource. It describes most of our common, cover crop species, citing on-farm uses, research and general plant characteristics. It can be purchased as a printed book or downloaded as a free PDF at https://www.sare.org/resources/managing-cover-crops-profitably-3rd-edition/.

Cover Crop Challenges

Many of the challenges associated with cover crops are addressed throughout the cover crop section. Here are a few common challenges farmers can face when adopting cover crops:

- Soil temperatures – cover crops may keep soils cooler in the spring during planting time, which is generally undesirable. However, those cooler temperatures may linger into the summer months, which can be an advantage.
- Moisture management – actively growing cover crops will help to pull moisture from the soil in the spring which can help in a wet year; however, in a dry spring this can deplete water needed for the crop. Cover crop residue will also help to preserve moisture, reducing evaporative losses from the soil later into the summer when the growing crop needs water compared to fields without cover crop residue.
- Nutrient Management - Residue from grass cover crops, such as cereal rye, can have a high carbon-to-nitrogen (C:N) ratio, so nitrogen from the soil is tied up by microbes as they break down the residue. Terminating the cover crop at a minimum of two weeks before planting corn OR before it exceeds about 8-12 inches in height (whichever comes first) may help alleviate some of the nitrogen tie up issues as microbes digest the residue because the biomass will generally have a lower C:N ratio and there will be less of it. Additionally, applying about 50 pounds of nitrogen at planting or using starter fertilizer with the planter can help the corn get off to a better start by offsetting the nitrogen that microbes may use while decomposing the cover crop residue.
- Herbicide compatibility – some soil residual herbicides applied in the crop prior to cover crop planting can carryover in the soil for months after application, so thought needs to go into the herbicide plan to ensure the cover crop will not receive detrimental impacts from an herbicide utilized earlier in the season. The carryover concerns vary, based on the cover crop to be planted, specific herbicide used, the amount of time passed, and precipitation since application.
- Equipment – planting a cash crop into heavy cover crop residue can potentially be challenging without the proper equipment that has been adjusted to handle these conditions. Make sure planting depth is adjusted in-field to account for the thickness of the residue, and the planter is adjusted and equipped to open and close the seed slot, achieving the desired seed placement.

Grass Cover Crops

The advantages of grass cover crops such as cereal rye include low seed costs, rapid establishment of ground cover in the fall, vigorous growth, weed suppression, recovery of residual nitrogen from the soil, and good winter survival. Additional winter, small grains that have been used as a cover crop include wheat, barley, and triticale. While cereal rye is among the most cold-hardy, and best nitrogen scavenger and weed suppressor, these additional overwintering small grains are also effective cover crops with many similar benefits.

Cereal rye is one of the most widely used cover crops ahead of soybean. In a cover crop study in Piatt County Illinois study, cereal rye was allowed 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, led by Lowell Gentry of the University of Illinois and Dan Schaefer of the Illinois Fertilizer and Chemical Association, the cereal rye accumulated nearly 50 pounds of N per acre. In another recent study, conducted in Douglas County, Illinois, on replicated tile drainage plots, researchers measured a reduction in tile nitrate load of >40% when using cereal rye after corn and ahead of soybean. The study evaluated tile nitrate concentrations and loads as influenced by nitrogen application timing and use of a cereal rye cover crop in a corn-soybean rotation. **Figure 5.6** shows tile nitrate concentrations from three treatments at the Douglas County field site from December 2014 to August 2016. The three treatments shown include (1) all nitrogen applied spring pre-plant, no cover crop, (2) half of the nitrogen applied spring pre-plant and half at side-dress, no cover crop, and (3) half of the nitrogen applied pre-plant and half at side-dress, with a cereal rye cover crop. The cereal rye cover crop was aerially seeded on September 16, 2015, and was terminated on May 6, 2016, when it reached a biomass accumulation of 1.25 tons/acre containing 35 lbs of N/acre. Soybean was no-till planted on May 29, approximately 3 weeks after cover crop termination. Tile nitrate loads for the treatments without cereal rye were 25 and 22 lbs/acre for 100% Spring N and 50:50 split N, respectively. In the cover crop treatment (green line), tile nitrate concentrations declined throughout the spring to <4 mg/L (or parts per million), reducing the tile nitrate load to 13 lbs/acre without reducing soybean yield (all three treatments yielded approximately 80 bu/acre). This study demonstrates proof of concept that overwintering cover crops can effectively act as an N catch crop, reducing tile nitrate contributions to surface waters.

At the same study site, researchers concluded that mineralized N during the non-growing season (especially following soybean) is an important source of tile nitrate, and therefore, river nitrate. They estimate that the leaching of mineralized N may contribute as much as 50% of the total annual nitrate tile load when averaged across both corn and soybean phases of the rotation in a given year. In 2019, researchers found that tile nitrate loads following soybean crop were greater than following corn. This was due in part to greater net N mineralization following soybean (formerly considered a soybean N credit), highlighting the potential benefit of planting a cover crop following soybean in order to capture and retain nitrate in the field. Another option is to consider a corn-soybean-winter wheat rotation. Winter wheat occupies the place of a cover crop and can absorb nitrate that is liberated from N mineralization following soybean. Before the predominant corn and soybean rotation of today, a corn-soybean-wheat rotation was often employed. The position of winter wheat after soybean in the rotation suggests that there was a reason for the order of the crop rotation in that the winter wheat can take advantage of greater net mineralization following

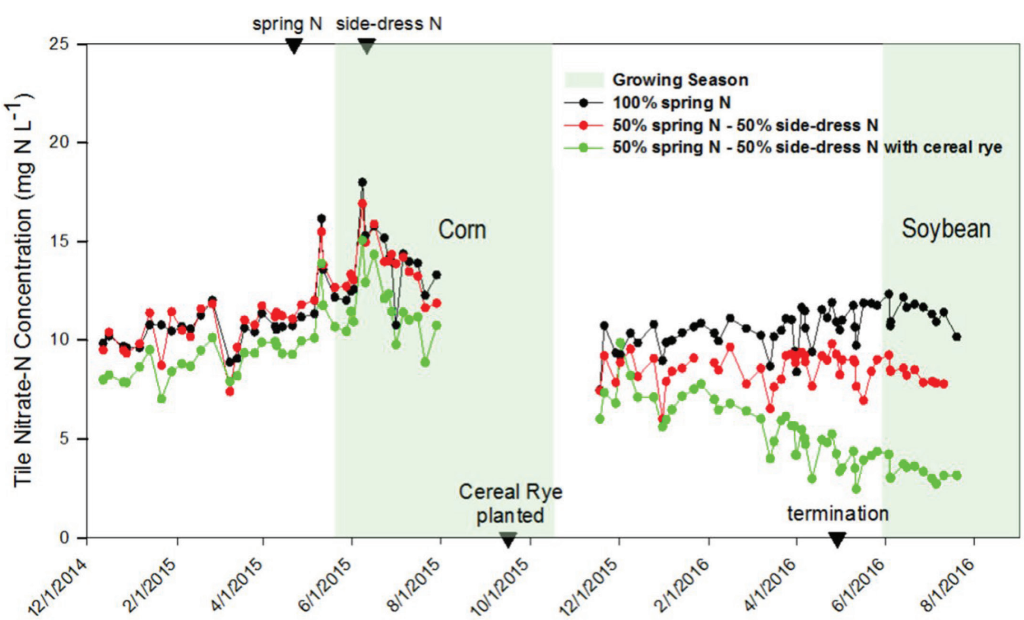

Fig 5.6. Tile nitrate concentrations as influenced by nitrogen application timing and use of a cereal rye cover crop in a corn-soybean rotation. Data shown is from a site in Douglas County from December 2014 to August 2016. Data courtesy of Lowell Gentry.

soybean before possibly losing nitrate to the tile. (L. Gentry, personal communication).

Aggregating data from four independent studies using cereal rye in corn and soybean systems in central Illinois, researchers estimated that 0.5 tons/acre of above ground cereal rye biomass (good stand with 6-8 inch stem height) can accumulate enough N to reduce tile nitrate concentrations (**Figure 5.7**). The researchers noted that cereal rye ahead of soybean can be allowed to accumulate as much as 2.5 tons of biomass/acre (this biomass would be equivalent to 3-5 feet high cereal rye with a uniform stand at heading growth stage) without a decrease in yield. Timing of cereal rye termination ahead of soybean is not critical and soybean can be directly planted into standing cereal rye (i.e. "planting green"). It has also been shown that cereal rye can suppress weed germination and competition, potentially reducing herbicide passes (partially offsetting the cost of the cover crop). (L. Gentry, personal communication).

In an experiment designed to test the efficacy of growing a cereal rye cover crop ahead of corn, researchers found that timely termination is important and that too much cereal rye biomass can reduce corn yield. In this experiment, four cover crop treatments were split with three N treatments to evaluate the impact on soil inorganic N (**Figure 5.8**), V7 corn biomass accumulation (**Figure 5.9**), and corn yield (**Figure 5.10**). The four cover crop treatments were: (1) termination 4 weeks before corn planting, (2) termination two weeks before corn planting, (3) termination the day before corn planting, and (4) no cover crop. The three

Fig 5.7. Cereal rye cover crop at 0.5 tons/acre. Picture courtesy of Lowell Gentry.

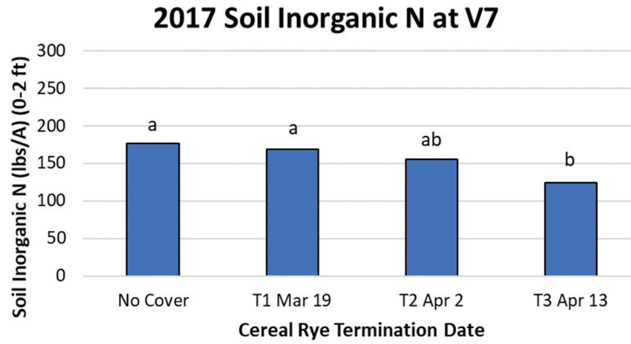

Fig 5.8. Impact of cereal rye termination time on soil inorganic N (lbs/acre) at V7 in corn. The results are averaged across three nitrogen treatments. Terminating the cereal rye the day before planting corn significantly reduced soil inorganic N at V7 compared to the two earlier termination timings and a no cover crop control. Data courtesy of Lowell Gentry.

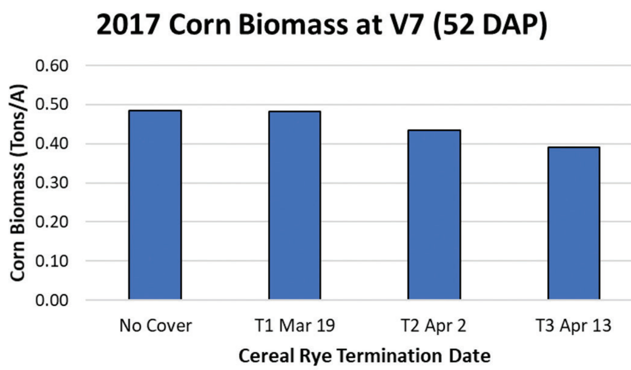

Fig 5.9. Corn biomass (tons/acre) at V7 as influenced by cereal rye termination timing. Terminating cereal rye the day before corn planting decreased corn biomass at V7. Data courtesy of Lowell Gentry.

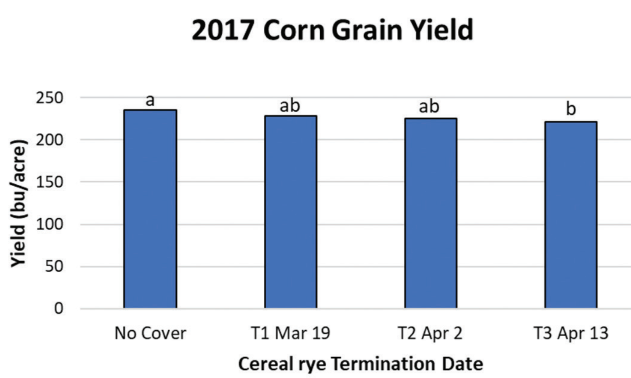

Fig 5.10. Corn yields (bu/acre) as influenced by cereal rye termination timing. The data are averaged across three nitrogen treatments. Terminating the cereal rye the day before planting corn significantly decreased corn yields. Data courtesy of Lowell Gentry.

N treatments were: (1) 100% spring pre-plant, (2) 50% in the fall, 25% at planting and 25% side-dress, and (3) 25% at planting and 75% side-dress. Greater cereal rye biomass accumulation decreased soil inorganic N, early corn growth, and significantly decreased corn yield. Researchers found no interference from the cereal rye cover crop if biomass was not greater than 0.5 tons/acre and termination occurred at least two weeks before corn planting (**Figure 5.11**). Additionally, this study found that when using cereal rye ahead of corn it is best to frontload the N application, as 100% spring N application produced the greatest corn yields (L. Gentry, personal communication). A similar study conducted in Monmouth from 2018 to 2020 also showed that cereal rye before corn should not negatively impact yields if the cover crop is terminated at least two weeks before planting.

Another common grass cover crop is annual ryegrass. It grows deep roots, which can improve soil structure as they decay. In southern Illinois and Kentucky, some farmers and researchers have been exploring using an annual ryegrass cover crop to penetrate fragipans in soil. Fragipans are a brittle subsoil horizon that water and roots have difficulty penetrating and moving through. The average depth to the pan is generally 12-24 inches, which can limit the amount of available water and nutrients for cash crops to pull from the soil in a drought, or cause saturated soil conditions during a wet season when water fails to drain through the soil profile quickly. Cash crop yields are often negatively impacted in soils that contain a fragipan layer compared to those that do not. Research conducted at the University of Kentucky has shown that root exudates from annual ryegrass can help to break down fragipan layers (Matocha et al., 2018), thus creating the potential for increased water holding capacity and infiltration, as well as deeper root penetration of a cash crop.

Research from Ewing, Illinois, investigated the effect of three grass cover crops on yield full-season soybean under a no-till system across four years in a corn, soybean, wheat rotation. Treatments included cereal rye (70 lbs/A), triticale (70 lbs/A), annual ryegrass (15 lbs/A), and no cover crop. Results (**Table 5.4**) show no significant effect of cover crop on yield in the first three years of the experiment, but a significant yield decrease was seen in annual ryegrass plots in 2017. This result is also seen when yield data from all years are combined, as well as when data from 2014-2016 are combined, indicating this effect is persistent although not statistically apparent in every growing season alone. The negative yield effect associated with this cover crop in 2017 was mainly due to increased vole activity (possibly because of mild winter an ample habitat) and subsequent stand losses (visual estimates of >75% loss by harvest), as this grass appears to be a preferred habitat for this rodent. This may also explain the significant yield reduction following annual ryegrass seen in the 2014-2016 combined analysis. Although the stand losses were not as noticeable in those years,

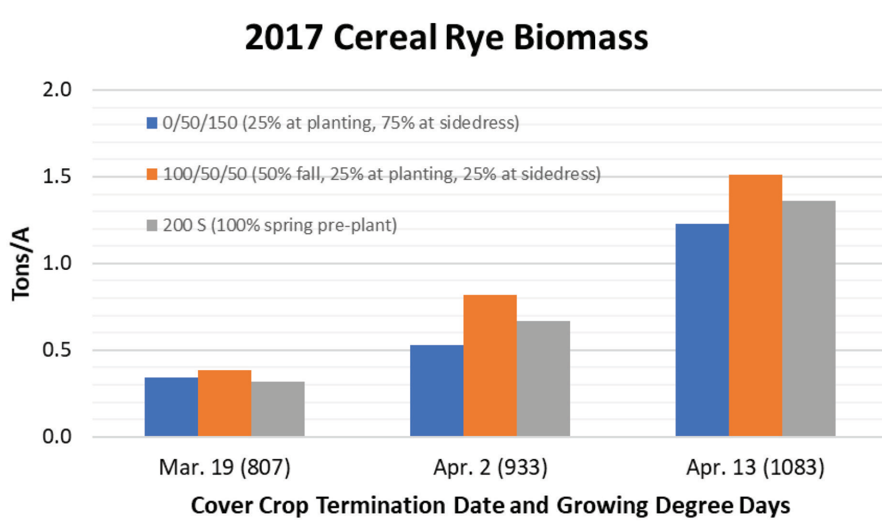

Fig 5.11. Cereal rye biomass (tons/acre) as influenced by three nitrogen treatments and by termination timing. Data courtesy of Lowell Gentry.

Table 5.4. Effects of fall planted grass cover crops on no-till soybean across 4 years (2014-2017) at the Ewing Demonstration Center, Ewing, IL. (N. Johanning & T. Becker, 2017, data not published).

	Soybean Yields (bu/A)											
Treatment	**2014**		**2015**		**2016**		**2017**		**All Years**		**2014-2016**	
No Cover	52.5	A	48.1	A	51.4	A	47.9	A	50.0	A	50.7	A
Triticale	51.8	A	46.1	A	51.4	A	49.3	A	49.6	A	49.8	A
Annual Ryegrass	50.2	A	42.9	A	44.2	A	29.9	B	41.8	B	45.8	B
Cereal Rye	53.2	A	48.9	A	49.9	A	49.4	A	50.3	A	50.6	A

scattered stand loss throughout the plots would not be as apparent but would likely still affect plot yield. Farmers have found that rolling down residue is one tool that can reduce vole habitat. (N. Johanning & T. Becker, 2017, data not published)

Spring oats are a common cover crop planted in the fall. They usually die off in the winter in Illinois, however, if planted early in the fall they can provide a lot of biomass and will continue to grow until temperatures down into the 20s (°F). Spring oats are commonly used with legume or other broadleaf cover crops in mixtures. It is a good nitrogen scavenger and the root system helps to hold the soil even after it winterkills. Given time over the winter to break down, spring oats provide a loose seedbed to plant into and reduce the nitrogen immobilization issues that some of the over-wintering grass cover crops can have. This makes it a good grass cover crop for ahead of corn. The biggest limitation of oats is the need to plant them early enough (generally late August to September) to get any substantial growth before winter.

Legume and Broadleaf Cover Crops

Legume and other broadleaf cover crops can also be beneficial in our cropping systems. There are several reasons why legumes might be better cover crops than grasses in some situations. 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 C:N ratio than those from grasses, so breakdown of their residue ties up little or no soil nitrogen. On the negative side, early fall growth by most legumes is usually slower than that of grass cover crops, and many of the legumes are not as winter-hardy as grasses such as cereal rye. Most overwintering legumes need to be seeded early in the fall for best establishment. Depending on harvest date, planting after the harvest of a corn or soybean crop might lead to little growth 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. Finding ways for timely planting will maximize the success and benefits these cover crops can provide.

Common legume, winter cover crops include crimson clover, balansa clover, berseem clover, hairy vetch, and mammoth and medium red clovers. Crimson clover is a winter annual clover known for its ability to fix large amounts of nitrogen. As a winter annual, it can be easier to terminate than some perennial clovers because it will naturally mature and die by late May or early June. Balansa clover has more recently been used as a cover crop and some new varieties perform well, especially in the southern half of Illinois. It is also an annual clover, noted for its tolerance of more poorly drained soils than many of the other legume cover crops. It is slow to establish and its fall, above ground growth is often limited, but in the spring, it produces more biomass than many other clover species. Berseem clover is also an annual clover. It is similar to balansa in some respects; its biomass potential is less than balansa clover, but more than crimson clover. **Table 5.5** shows data from the Ewing, Illinois, illustrating the differences in biomass of these species along with winter survivability and date of full bloom. Note the balansa clover variety had the lowest biomass in the fall yet the highest biomass at termination. Red clover is a perennial and very common legume cover crop. Like many other legumes, they establish slowly in the fall, but do have the capacity to produce large amounts of nitrogen if given time to grow in the spring.

Table 5.5. Biomass production of clover cover crop species and varieties from the Ewing Demonstration Center - 2016. (N. Johanning, 2016, data not published)

Treatments (planted 9/24/2015)	% Winter Survival	Spring Biomass (DW; lbs/A)	Date of Full Bloom
Fixation Balansa Clover	98 a	8,401 a	5/10/2016
Kentucky Pride Crimson Clover	94 a	4,150 c	4/25/2016
Frosty Berseem Clover	95 a	6,093 b	N/A*
Dixie Crimson Clover	69 b	911 d	4/25/2016
LSD (0.05)	*8*	*1,802*	
Data Collection Date	*4/7/2016*	*5/13/2016*	

*Did not bloom prior to termination (5/13/2016)

Hairy vetch, at least in the southern Midwest, has often worked well as a winter cover crop. It offers the advantages of relatively 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 reached at least 4 to 6 inches of growth in the fall. 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. **Figure 5.12** 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 cereal rye or the combination of cereal rye and vetch, at least at lower N rates.

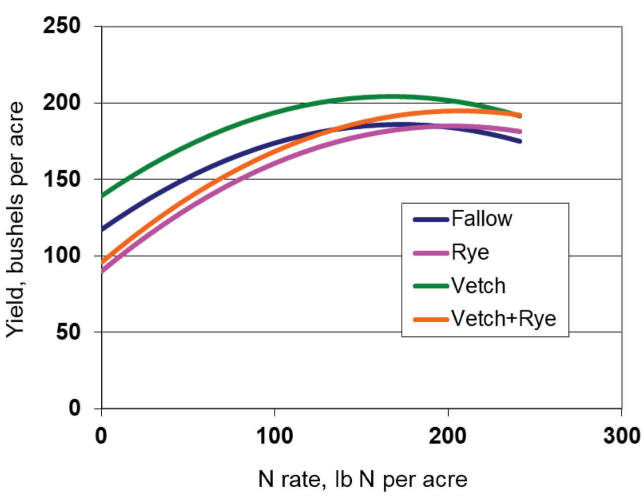

Fig 5.12. Effects of no cover crop, hairy vetch, rye, or hairy vetch plus rye on yield and N response of no-till corn grown following soybean. Data are from a 2-year study at Urbana, published by Fernando Miquez and Germán Bollero in Crop Science 46:1536–1545 (2006).

Winter survival of legumes depends on the amount of fall growth they have to establish themselves, winter temperatures, and snow cover to protect them. To get the maximum survivability of legumes, they must be planted early enough to grow for 6 to 8 weeks before the onset of cold weather in the late fall. If poorly established, they will not have enough of a root system to prevent frost heaving of the roots in freeze/thaw cycles and then the plants desiccate in the cold, dry winter winds. Snow cover will provide a great deal of protection from the cold and winds. Also, the residue from planting a grass such as oats or cereal rye at a low seeding rate with legumes will help to provide some winter protection and help to catch any snowfall.

Other non-legume broadleaves also are common, such as daikon radish, mustards, rapeseed, and turnip. These are all in the *Brassica* family and are known for their ability to scavenge nutrients, reduce compaction, and loosen the soil. Most are winter-killed, similar to oats. However, there are some varieties of rapeseed that may survive the winter, and some of the others may have limited survival in mild winters in parts of southern Illinois.

Summer Annuals

Most of the cover crops we have discussed are primarily for fall planting. In fallow or prevent plant fields, or even after wheat harvest, there are many warm season cover crops that can be used for spring or summer planting. These include sorghum-sudangrass, pearl millet, buckwheat, sunnhemp, and cowpeas. These may also be used as good late-summer forage for operations with livestock. Most of these spring/summer cover crops are frost sensitive and therefore not suitable as a fall-planted cover crop.

Fall Cover Crop Establishment

Timely planting is beneficial especially with winter-killed cover crops, legumes, and select grasses like annual ryegrass. Again, for county specific optimal planting windows for various cover crops, utilize the MCCC Cover Crop Selector Tool (www.midwestcovercrops.org). Achieving timely planting for successful establishment and optimal growth can be more challenging in the northern part of Illinois. The last half of August into September is probably the best time for planting winter-killed and legume crops. With timely harvest, this can be achieved, especially in central and southern Illinois. Farmers may also investigate shorter maturity crop varieties and hybrids that are still competitive in yield potential for their area, but offer more timely harvest to allow for cover crop planting. Cover crops can be seeded with high-clearance ground equipment or aerially into a standing crop of corn or soybean, although dry weather after seeding may result in poor stands. Research has been done in other parts of the Midwest to investigate the utility of interseeding a cover crop into corn at the time of the last cultivation (V5-6). 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 poorly or die during periods of heat and dry weather. This practice has not been as consistently effective for our field conditions in Illinois. For all cover crops, the timing of rainfall can play a large role in the success of establishment.

Spring Cover Crop Termination

The best management of cover crops before planting field crops in the spring varies based on many factors specific to the field conditions, weather, and crop to be planted. Generally, for farmers new to using cover crops, it is recommended that cover crops be terminated two weeks before planting, or when the cover crops are 6 to 12 inches tall, whichever occurs first. Terminating at least 2 weeks prior to planting can eliminate the challenge of trying to plant into a partially dead cover crop residue, which can be difficult to cut with coulters and openers. Residue will often cut best when it is either fully dead or still green, rather than while it is in the process of dying. With experience, farmers may find they can maximize benefits by terminating later, either a day or two before or soon after planting. A trade-off of benefits usually exists. Delaying termination of cover crops until closer to planting will maximize some of the benefits the cover crop can provide including building soil organic matter, suppressing weeds, and producing nitrogen (legumes). However, especially in corn, terminating cover crops at planting can take more management, particularly nutrient management, and is usually only recommended for those who have more experience with cover crops. Soybeans are more adapted to planting into a more mature cover crop. Cereal rye is the most commonly used cover crop ahead of soybeans and many farmers, with experience, will plant into a green or freshly sprayed cover crop. The concerns around delaying termination are that it can immobilize more nitrogen (ahead of corn), soil under a heavy mat of residue can stay wetter in a year with a lot of precipitation following termination, and cover crop growth can deplete soil moisture in a dry spring. However, if the cover crop is still actively growing it can help to pull moisture from the soil in a wet year. Check the weather before terminating a cover crop to make sure a major rain event will not significantly delay cash crop planting and allow the dead cover crop biomass to form a mat. If a cover crop has grown past the vegetative stage in a wet year, it might be better to wait until planting to terminate versus terminating it early and risk having a mat of dead residue which slows soil drying.

Herbicide termination coupled with no-till planting is the most common method of cover crop termination in Illinois. For optimal termination, make sure the cover crop is actively growing for best herbicide uptake. Also, make sure to follow any labeled recommendations, including those for water conditioners, adjuvants, and spray carrier volume. If cover crop biomass is tall, farmers might consider using some form of roller to lay down the cover crop, especially in corn. This optimizes the access of young seedlings to sunlight. Also, rolling residue reduces the habitat for small rodents, such as voles, which can become localized issues in long-term no-till/cover crop fields. Roller crimpers can also be used to lay down cover crops and terminate; however, for optimal termination most cover crops need to reach flowering to prevent regrowth, and some species are more suited to roller crimping termination than others. Tillage is also a termination option for cover crops, though the use of tillage reduces some of the benefits of cover crops compared with a no-till system. Incorporation of cover crop residue using tillage 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 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.

Fertilizer Considerations with Cover Crops

Although the amount of nitrogen contained in some legume cover crops 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 5.12**, 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. While legumes such as hairy vetch do fix added nitrogen, often this nitrogen is not broken down and available to the corn crop when needed. Use of legume cover crops ahead of corn does reduce the issues with nitrogen immobilization and tie up we can see with grass cover crops. The greatest potential for increased and sustained nitrogen supplying power comes with long-term cover crop use and the building of soil health and organic matter.

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 identified as a probable leading cause of climate change, there has recently been a lot of interest in quantifying “carbon credits” 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 performed by the actively-growing plant life removes it from the air (https://www.esrl.noaa.gov/gmd/ccgg/trends/global.html)

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 undergoes respiration to release its energy and is released back to the environment as exhaled CO_2. 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 (David et al., 2009). Measurements from the Morrow Plots show that fertilized continuous corn, corn-oat/soy, and corn-oat-hay rotations lost about 0.9, 1.2, and 0.7 tons of soil organic matter per acre, respectively, per decade over the past century, but it appears that the rate of soil organic matter loss has slowed or stopped in recent decades (**Figure 5.13)**. 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 shows that roots break down more slowly and contribute considerably more to soil organic matter than do crop residues from above ground.

Although crop residues decompose relatively quickly (within one to several growing seasons), stabilization and turnover of organic carbon from residue into stable soil organic carbon. Changes in total soil organic carbon are typically not detectable with high confidence at timescales of < 5 years due to a combination of: 1) in-field variability of soil carbon, 2) accuracy of measurements, and 3) gradual nature of carbon accrual in soils. It may therefore take up to 10 or more years to detect a change in total soil organic carbon following a change in management.

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

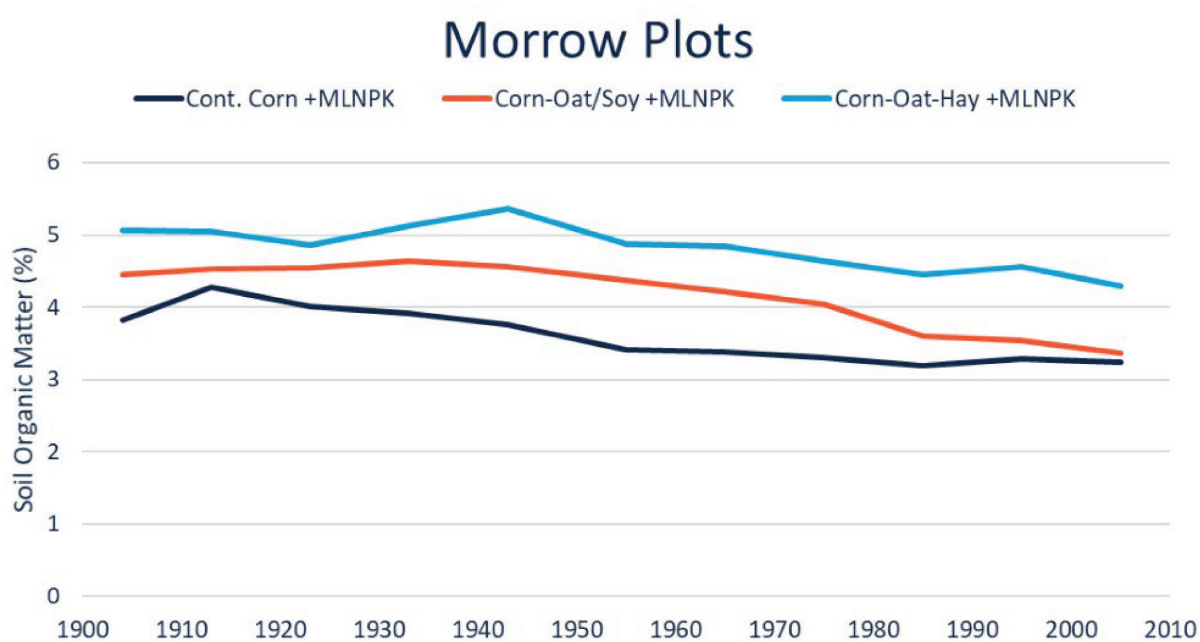

Fig 5.13. Soil organic matter content of Morrow Plots under continuous corn, corn-oat/soy, and corn-oat-hay rotations. The corn-oat/soy rotation was a corn-oat rotation from 1876-1966 and a corn-soy rotation from 1967-present. Plots were amended with manure, lime, nitrogen, phosphorus, and potassium as needed. MLNPK = manure + lime + N-P-K fertilizer. Data redrawn from Nafziger and Dunker in Agronomy Journal 103:261-267 (2011). After 1943, all data for a given decade were aggregated and an average value is shown.

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.

Recently, the agriculture industry has embraced the idea of ecosystem markets, or carbon markets, where farmers are paid to adopt conservation practices that can help slow climate change by reducing amounts of gases in the atmosphere known to contribute to climate change, such as carbon dioxide, methane, and nitrous oxide. In exchange, outside organizations are able to buy carbon credits in order to help them achieve theoretical carbon neutrality, or at least reduced carbon outputs, by paying for the carbon that farmers sequestered. Some of the conservation practices farmers are paid to adopt include no-tillage, cover crops, and regenerative grazing practices for livestock. Soil is one of the largest carbon sinks on the planet, meaning it can absorb carbon from the atmosphere. Plants play a huge role in sequestering carbon into soil through the process of photosynthesis. By planting cover crops on agricultural fields, the window to sequester carbon in soil significantly increases compared to a typical corn-soybean rotation, when plants are only growing for four to five months of the year and the soil is left bare the remaining months. Additionally, tilling soil produces a temporary increase in microbial respiration, which releases carbon as CO_2 that has been stored in the top inches of the profile. Thus, limiting tillage as much as possible allows the carbon to remain sequestered for longer and may increase the amount of plant-sequestered carbon that becomes part of the stable organic matter pool.

At the time this was written, several companies and firms are offering pilot programs to farmers in order to work out their objectives and logistics of this new ecosystem market frontier. It is difficult to say what this ever-evolving market will look like in the next five to ten years: which companies will survive the initial rush to secure a spot in the marketplace, the price farmers might receive per carbon credit, or even how success will be measured (e.g. in soil carbon changes, or in successful implementation of the conservation practice). However, it is unlikely this effort will go away any time soon as consumers demand a more sustainably grown product.

Water Quality

The agriculture community has faced the grand challenge of protecting water quality for many years. Recently, efforts to educate the public, increase adoption rates of conservation practices, and monitor conservation practices' impacts on water quality have become more coordinated and impactful, thanks in part to the development of the Illinois Nutrient Loss Reduction Strategy (NLRS) in 2015. The NLRS aims to reduce nitrate-N and total phosphorus (P) losses from Illinois by 15% and 25%, respectively, by 2025. The overall goal is to reduce both nitrate-N and total P losses by 45%. Losses of N and P from nonpoint sources of pollution, like agriculture, point sources of pollution, like wastewater treatment plants, and urban stormwater are primary drivers of water quality issues locally in Illinois, but also downstream to the Gulf of Mexico. The amount of soil lost as runoff into surface water and the amount of plant nutrients and pesticides that reach surface waters impact water quality. 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. 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. Edge-of-field practices such as woodchip bioreactors, saturated buffers, constructed wetlands, and drainage water management can be useful to help reduce nutrient loss at the edge of fields utilizing tile drainage. Additionally, in-field agricultural conservation practices such as reduced or no-tillage, cover crops, following best practices for nutrient management (the "4R" principles), and routine soil testing can help reduce soil and nutrient losses. Grass waterways and buffers can be viable options to prevent in-field soil erosion and protect waterways that border agricultural fields. 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. However, with proper care, it is possible to produce crops with minimal effects on water quality. Further elaboration and discussion on agricultural water quality challenges and solutions can be found in Chapter 11.

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. 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 less favorable weather conditions that lead to more plant 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—growing a corn crop means losing up to 20 inches of water per acre per season, which is more than 15 gallons of water per plant that is lost through leaves during a growing season. 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 widely depending on wind speed 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.

A study conducted in Urbana, Illinois, from 2014 to 2017 found that a good stand of cover crops (at least 0.22 tons/acre of above ground biomass in the spring) could reduce emissions of nitrous oxide (N_2O), a gas commonly associated with climate change, from the soil. The researchers used several different species of cover crops during a corn-soybean rotation in the study including rapeseed, cereal rye, hairy vetch, radish, annual ryegrass, spring oats, and clover. During the first two years of the study, N_2O emissions were about five times greater than during the last two years of the study. The researchers contributed this finding to poor cover crop stand establishment during the first two years, which meant the cover crops were not able to take up as much nitrate (NO_3^-) from the soil as compared to the last two years of the study. When the cover crops took up more NO_3^- from the soil, it reduced N_2O emissions because less NO_3^- was available in the soil to go through the denitrification process (Behnke and Villamil, 2019).

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 through the use of extensive inputs such as new seed, methods of weed control, and nitrogen.

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." Incorporating more complex crop rotations or even cover crops into our simple corn-soybean rotations can increase the biodiversity of life present in our soils and improve the overall functionality of the soil to produce crops.

References

Alberti, P. Midwestern Hemp Database 2020 Report. University of Illinois Extension Service Publication. https://extension.illinois.edu/sites/default/files/mhd_fact_sheet_1.pdf (2021).

Barel, J. M. et al. Winter cover crop legacy effects on litter decomposition act through litter quality and microbial community changes. J. Appl. Ecol. 56, 132–143 (2019).

Behnke, G.D., & M.B. Villamil. Cover crop rotations affect greenhouse gas emissions and crop production in Illinois, USA. Field Crops Research 241, 1-9 (2019).

Cahoon, E. B. Genetic Enhancement of Soybean Oil for Industrial Uses: Prospects and Challenges. J. Agrobiotechnology 6, (2003).

Casler, M. D. et al. 30 Years of Progress toward Increased Biomass Yield of Switchgrass and Big Bluestem. Crop Sci. 58, 1242–1254 (2018).

David, M. B., McIsaac, G. F., Darmody, R. G. & Omonode, R. A. Long-Term Changes in Mollisol Organic Carbon and Nitrogen. J. Environ. Qual. 38, 200–211 (2009).

Gentry, Lowell. Principal Research Specialist in Agriculture, University of Illinois Department of Natural Resources and Environmental Sciences. Lgentry@illinois.edu.

Hagely, K., Konda, A. R., Kim, J.-H., Cahoon, E. B. & Bilyeu, K. Molecular-assisted breeding for soybean with high oleic/low linolenic acid and elevated vitamin E in the seed oil. Mol. Breed. 41, 3 (2021).

Hoss, M., Behnke, G. D., Davis, A. S., Nafziger, E. D. & Villamil, M. B. Short Corn Rotations Do Not Improve Soil Quality, Compared with Corn Monocultures. Agron. J. 110, 1274–1288 (2018).

Johanning, Nathan and Talon Becker. Extension Commercial Agriculture Educators, University of Illinois. Njohann@illinois.edu; tbecker2@illinois.edu.

Kim, N., M.C. Zabaloy, K. Guan, & M.B. Villamil. Do cover crops benefit soil microbiome? A meta-analysis of current research. Soil Biol and Biochem 142, 1-14 (2020).

Korucu, T., Shipitalo, M.J., & Kaspar, T.C. Rye cover crop increases earthworm populations and reduces losses of broadcast, fall-applied, fertilizers in surface runoff. Soil and Tillage Research 180, 99-106 (2018).

Matocha, C. J. et al. Influence of ryegrass on physico-chemical properties of a fragipan soil. Geoderma 317, 32–38 (2018).

Medic, J., Atkinson, C. & Hurburgh, C. R. Current Knowledge in Soybean Composition. Journal of the American Chemists' Society. 91: 363-384 (2014) doi: 10.1007/s11746-013-2407-9.

Parrish, A. S., Lee, M.-S., Voigt, T. B. & Lee, D. K. Miscanthus × giganteus Responses to Nitrogen Fertilization and Harvest Timing in Illinois, USA. BioEnergy Res. (2021) doi:10.1007/s12155-021-10244-w.

Paulsmeyer, M. et al. Survey of Anthocyanin Composition and Concentration in Diverse Maize Germplasms. J. Agric. Food Chem. 65, 4341–4350 (2017).

Rosales-Calderon, O. & Arantes, V. A review on commercial-scale high-value products that can be produced alongside cellulosic ethanol. Biotechnol. Biofuels 12, 240 (2019).

Scott, P., Pratt, R. C., Hoffman, N. & Montgomery, R. Chapter 10 - Specialty Corns. in Corn (Third Edition) (ed. Serna-Saldivar, S. O.) 289–303 (AACC International Press, 2019). doi:10.1016/B978-0-12-811971-6.00010-3.

Wallander, S., Claassen, R. & Nickerson, C. The Ethanol Decade: An Expansion of U.S. Corn Production, 2000-09. SSRN Electron. J. (2011) doi:10.2139/ssrn.2131399.

Wilkes, R. S. Low linolenic soybeans and beyond. Lipid Technol. 20, 277–279 (2008).

Williams, D.W. An Introduction to Industrial Hemp and Hemp Agronomy. University of Kentucky Cooperative Extension Service Publication. ID-250. http://www2.ca.uky.edu/agcomm/pubs/ID/ID250/ID250.pdf (2018).

Zuber, S., Behnke, G., Nafziger, E. & Villamil, M. Crop Rotation and Tillage Effects on Soil Physical and Chemical Properties in Illinois, Agron.J. 107, 971-978 (2015). doi:10.2134/agronj14.0465

Zumpf, C. et al. Impact of warm-season grass management on feedstock production on marginal farmland in Central Illinois. GCB Bioenergy 11, 1202–1214 (2019).