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Concepts in Crop Rotations

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1. Introduction

1.1 Crop rotations – A historical perspective

Crop rotation is the production of different economically important plant species in recurrent succession on a particular field or group of fields. It is an agricultural practice that has been followed at least since the Middle Ages. During the rule of Charlemagne crop rotation was vital to much of Europe which at that time followed a two-field rotation of seeding one field one year with a crop and leaving another fallow. The following year the fields were reversed (Butt, 2002). Sometime during the Carolingian period the three-field rotation system was introduced. It consisted of planting one field, usually with a winter cereal, a second with a summer annual legume, and leaving a third field fallow. The following year a switch would occur. Sometime during the 17th and /or 18th centuries it was discovered that planting a legume in the field coming out of fallow of the three-field rotation would increase fodder for livestock and improve land quality, which was later found to be due to increased levels of available soil nitrogen (N). During the 16th century Charles Townshend 2nd Viscount Townshend (aka Turnip Townshend) introduced the four-field concept of crop rotation to the Waasland region of England (Ashton, 1948). This system, which consisted of a root crop (turnips (*Brassica rapa* var. *rapa*)), wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), and clover (*Trifolium* spp.) followed by fallow. Every third year introduced a fodder crop and grazing crop into the system, allowing livestock production the year-round and thus increased overall agriculture production. Our present day systems of crop rotation have their beginnings traceable to the Norfolk four-year system, developed in Norfolk County England around 1730 (Martin, et al., 1976). This system was similar to that developed by Townshend except barley followed turnips, clover was seeded for the third year and finally wheat on the fourth year. The field would then be seeded to turnips again with no fallow year being part of the rotation.

In the new world, prior to the arrival of European settlers, the indigenous people in what is now the Northeastern United States, practiced slash-and-burn agriculture combined with fishing, hunting, and gathering (Lyng, 2011). Fields were moved often as the soil would become depleted and despite the tale of Native Americans teaching the European settlers to put a fish into the corn hills at planting, there is little or no evidence of the aboriginal people fertilizing their crops. Maize would be planted in hills using crude wooden hoes with gourds and beans (*Phaseolus* spp. L.) being planting alongside and allowed to climb the

maize stalks. When an area would become depleted of plant nutrients, it would be abandoned and over time, would recover its natural fertility. Lyng (2011), describes the Native Americans of the northeast as not so much conscience ecologist but rather people with a strong sense of dependences on nature minus the pressure to provide for consumer demands. Plains Indians on the other hand are classified as being of two cultures. There were the nomadic nations that followed the herds of bison that roamed the region and lived mainly on a diet of bison meat and what they might gather in the way of wild berries, fruits, and nuts with very little farming except for some maize and tobacco (*Nicotiana tabacum* L.). There were then the nations that lived on a combination of meat and crops they would raise. These peoples tended to live in established villages and would fish, hunt, and gather wild fruit and berries. The crop farming they practiced again, were maize, beans, and squash (*Cucubina* spp. L.), sometimes referred to as “The Three Sisters” in Native American society (Vivian, 2001). As with the nations in what would become the northeastern United States, the Plains Indians that practiced crop farming would usually clear their garden areas by slash and burn, grow their crops, and then allow a two-year fallow before planting again. Just prior to planting, some villages would carry in brush and other plant debris to burn along with the refuge that grew in the field during fallow to “enrich” the soil for the crops about to be planted.

The early European settlers attempted to raise those crops (wheat, and rye (*Secale cereal* L.)) which they were accustom to, using cultivation methods they had used in the old country. They also, introduced livestock, (cattle, swine, and sheep) which were not found in the New World but that had been a major source of food for them in their native homeland. They soon discovered that clearing fields for planting and pasturing was an arduous task and in order to survive adopted some of the crop production techniques practiced by the indigenous peoples and allowed their livestock to forage open-range (Lyng, 2011). As colonization expanded and available labor increased along with the demand for food, the permanent clearing of arable land increased along with the introduction of more Old World crops and, unfortunately, their pests that continue to demand time and financial resources to contain today.

The first export from the American colonies to England was tobacco. Though not a food crop, tobacco played a pivotal role in helping sustain the Jamestown colony and gave the settlers something to exchange for necessary items to survive. Tobacco is a high cash value, very labor intensive crop. Even as of 2002, with only about 57,000 total farms in the United States being classed as tobacco farms producing an average of 3 hectares of the crop per farm, the average cash value of those 3 hectares was nearly \$42,000 (Capehart, 2004). Though tobacco preserved the Virginia colony, within seven years of its cultivation and export, its continued production in the New World would usher in the African slave trade, the darkest part of America’s past, and would culminate 200 years later into the American Civil War.

Prior to colonization, a species of cotton, *Gossypium barbadense*, was being grown by the indigenous people of the New World (West, 2004). Columbus received gifts from the Arawaks of balls of cotton thread upon making landfall in 1492. Egyptian cotton (*G. hirsutum* L.) was introduced to the colonies as early as 1607 by the Virginia Company in an attempt to encourage its production and help satisfy the European appetite for the fiber that was currently being exported from India. However, tobacco production and the lucrative

prices being paid for it along with the belief that cotton depleted the soil and required too much hand labor, dissuaded the colonist from planting the crop. Even encouragement from the colonial Governors, William Berkley and Edmund Andors could not convince the settlers to switch to cotton. Small hectares of *G. hirsutum* L. though were grown along the Mid Atlantic colonies for individual household use. The Revolutionary War halted imports of large quantities of cotton to the former colonies from Britain and forced the Americans to grow their own supply. By the mid 1780's production had expanded and the newly formed United States became a net exporter of cotton to Britain.

After the development of the cotton gin by Eli Whitney in 1793 the key to financial success in the southern states was acquiring large hectares of land for cotton production and large numbers of slaves to tend to the crop. Maize, small grains, forages, and food crops were grown only in sufficient quantities to sustain the plantations that had developed. These crops were not grown for the purpose of commerce and were often relegated to some of the marginal lands on the plantation or near the homestead for convenient harvest. The bulk of all cleared fields were devoted to production of tobacco or "King Cotton" as it would become known. From 1800 to 1830 cotton went from making up 7% (\$5 million) of exports from the United States to 41% (\$30 million) (West, 2004). Tobacco production went from 45.4 million kg at the outbreak of the Revolutionary War to 175.8 million kg prior to the Civil War (Jacobstein, 1907). Crop rotation was not even considered an option with respect to these crops due to the cash value paid for them. By 1835 the top soil of eastern Georgia had eroded away with the remaining clay unsuitable for cotton production. As soils became depleted of nutrients necessary for the crops' production, more wilderness, particularly further west would be cleared and farmed. This resulted in conflicts with the native peoples that resulted in their forced resettlement onto reservations and the spread of slavery westward into newly chartered states in the south. This further deepened political and economic conflicts that would explode into the American Civil War.

1.2 Advent of agricultural education and research

The Morrill Act of 1862 and again 1892 established the American Land-Grant colleges in each state and charged them with the responsibility of teaching the agricultural and mechanical disciplines, along with other responsibilities necessary to an advanced education. The Hatch Act of 1887 then established the Agriculture Experiment Station system which, in most states, is administered by the Land-Grant Universities and was to provide further enhancement of agricultural teaching through experimentation. In 1914 the Smith-Lever Act established the State Cooperative Extension Service which disseminates information to the public of advances in agriculture production discovered by the state agricultural experiment stations. All three of these legislative acts came about because of a need to better understand sound farm management practices, including crop rotations, to improve the nation's farm economy.

The concept of agriculture research stations was not an American idea. The Rothamsted Experiment Station in the United Kingdom is said to be the world's oldest, being established in 1843, while Möcken station in Germany, established in 1850, is said to be the world's oldest state supported agricultural research station. Agricultural research stations can now be found in most all developed countries and even many less developed nations. Research on crop rotations has been and continues to be conducted at virtually all of these stations,

with specialization towards the environment and crop species indigenous to their location. Some of these studies have been in existence since the late 19th century (Rothamsted, 2011).

Some of the more famous experiments in the United States that continue to be performed at some of the Land-Grant Universities, and are now designated on the National Register of Historic Places, include The Old Rotation experiment on the Auburn University campus in Alabama, The Morrow Plots on the campus of the University of Illinois, and Sanborn Field at the University of Missouri. Mitchell et al., (2008) published that the Old Rotation experiment in Alabama has shown over the long-term, seeding winter legumes were as effective as fertilizer N in producing high cotton lint yields and increasing soil organic C levels. Rotation schemes with corn or with corn-winter wheat- and soybean (*Glycine max* L. Merr.) produced no yield advantage beyond that associated with soil organic C (Table 1). However, winter legumes and crop rotations contributed to increased soil organic matter and did result in higher lint yields.

| Cotton Lint Yield (kg ha ⁻¹) | | | |
|--|------------------------|------------------------|------------------------|
| Continous Cotton | 1986-1995 [†] | 1996-2002 [†] | Soil OM % [‡] |
| 0 N/no winter legumes | 392d | 403b | 0.8e |
| winter legumes | 952ab | 1131a | 1.8c |
| 134 kg N ha ⁻¹ | 792c | 1154a | 1.6d |
| Cotton-Corn Rotation | | | |
| winter legumes | 870ab | 1120a | 1.8c |
| legumes + 134 kg N ha ⁻¹ | 970a | 1276a | 2.1b |
| 3-Year Rotation (common- | | | |
| winter legumes | | | |
| corn-small grain-soybean | 850ab | 1109a | 2.3a |

[†]Values followed by the same letter are not significantly different at P<0.05
[‡]Recent data show the effect of increasing soil organic matter on cotton productivity.

Table 1. Long-term effects of crop rotations, winter legumes and nitrogen fertilizer on cotton lint yields at the “Old Rotation Experiment” of Auburn University in Alabama. (Mitchell, 2004).

Data from the Morrow Plots in Illinois have shown that yields from continuous corn have always been much less than corn yields from a of corn-oats (*Avena sativa* L.) rotation or a or corn-oats-and hay (clover (*Trifolium* spp.) or alfalfa (*Medicago sativa* L.)) rotation (Aref and Wander, 1998). After the introduction of hybrid corn varieties in 1937, the first plots to show an increase in corn yields due to these varieties were the corn-oats-hay rotation. Yield increases due to hybrids were not noticed in the corn-oat plots until the late 1940’s and in the continuous corn plots until the early 1950’s. These lower corn yields of the continuous corn and the slower response to corn hybridization in the corn-oat rotation appear to coincide with long-term average levels of soil organic matter and nitrogen observed in the various plots (Table 2).

| Rotation | C (g kg ⁻¹) | N (g kg ⁻¹) | C-N ratio |
|-----------------|-------------------------|-------------------------|-----------|
| Continuous corn | 19.2a | 1.55a | 12.36a |
| Corn-oats | 23.0b | 1.84b | 12.46a |
| Corn-oats-hay | 26.5c | 2.12c | 12.48a |

Table 2. Soil carbon C, nitrogen N, and C-N ration from a crop rotation experiment on the Morrow Plots of the University of Illinois.

Means of samples taken in 1904, 1911, 1913, 1923, 1933, 1943, 1953, 1961, 1973, 1974, 1980, 1986, and 1992. (Aref and Wander, 1998). Values within a column followed different letters are significantly different $P \leq 0.05$.

Corn and wheat yields at Sanborn Field at the University of Missouri have been consistently higher when grown in rotation with each other along with red clover (*Trifolium pratense* L.) inter-seeded into the wheat in late winter for forage the following year (Miles, 1999). Plots of both corn and wheat have been grown continuously since the site’s establishment in 1888, some receiving animal manure, some commercial fertilizer, and some no fertility treatment. All have had reduced grain yields compared to those grown in rotation, even with the added manure and/or fertilizer.

Thirty years after Sanborn Field’s establishment, its focus began to shift to the study of cropping systems as related to soil erosion and the resulting loss of productivity. An experiment conducted in 1917 by F.L. Duley and M.F. Miller on the campus of the University of Missouri used seven test plots to measure soil erosion resulting from rainfall (Duley and Miller, 1923). This research led to creation of the Soil Conservation Service of the USDA, which is now a component of NRCS-USDA. It led to the establishment of experiment stations throughout the United States dedicated to the study of crop rotations on soil erosion and developing cropping systems to minimize erosion’s impact (Weaver and Noll, 1935). Experiments at these stations in Iowa, Missouri, Ohio, Oklahoma, and Texas all showed plots planted to a continuous cropping system had higher surface soil losses and losses of rainfall than plots planted to a forage or in a three or four year rotation (Uhland, 1948).

2. Crop rotations vs. continuous cropping

Crop rotation schemes are, by and large, regional in nature and a specific rotation in one environment may not be applicable in another. Continuous cropping schemes or monocultures for the most part, have fallen out of favor in many farming regions. Roth (1996) published mean corn yields from a 20 year crop rotation experiment in Pennsylvania that included rotation with both soybean and alfalfa showing higher yields with all rotation schemes than continuous corn (Table 3). The extensive use of commercial fertilizers and pesticides has helped mask most of the beneficial effects of crop rotation. But Karlen et al. (1994) has stated “no amount of chemical fertilizer or pesticide can be fully compensated for crop rotation effects”. However, economics continues to be the large determining factor into how a field is managed.

| Crop Rotation | Yield Mg ha ⁻¹ |
|------------------------------|---------------------------|
| Continuous corn | 8.7 |
| Corn/soybean | 9.1 |
| Corn/two-year alfalfa | 9.6 |
| Corn/corn/three-year alfalfa | 9.6† |
| Corn/corn/three-year alfalfa | 9.3‡ |

†First year corn yield

‡Second year corn yield

Table 3. Mean corn grain yields as influence by crop rotation from 1969 to1989 at Rock Springs, PA. (Roth, 1996).

One primary benefit to crop rotation is the breaking of crop pest cycles. Roth (1996) states that in Pennsylvania, crop rotations help control several of the crop-disease problems common to the area such as gray leaf spot in corn (*Cercospora zeae-maydis*) take-all in wheat (*Gaeumannomyces graminis* var. *tritici*), and sclerotinia in soybean (*Sclerotinia sclerotiorum*). In corn, corn rootworms (*Diabrotica virgifera* spp.) can be a devastating pest and crop rotation was considered to be the most effect method of control. However, beginning in the late 1980's there was a variant of the Western corn root worm (*D. virgifera virgifera* LeConte) that began egg laying in soybean fields, making larvae present to feed upon first year corn in a soybean-corn rotation (Hammond et al., 2009). Prior to this time the standard method to avoiding rootworm damage was to rotate. However, during the mid-1960's in the Cornbelt there was a movement to engage in growing corn continuously on highly productive soils. Atrazine [2-chloro-4-(ethylamino)-6-(isopropylamino)-s-triazine] was being readily adopted for weed control in corn and a number of insecticides were becoming available for of control corn rootworm and other corn insects. Also sources of nitrogen fertilizer were readily available and relatively inexpensive. Competitive profits for other crops, particularly soybean, and continued research showing tangible benefits to rotations though returned most fields to some sort of rotation scheme. However, there are some producers today who are profitable at growing continuous corn. But, such a system appears to require strict adherence to sound management practices.

Cotton is probably the principle crop that has been grown continuously on many fields, some for over 100 years. The crop was profitable and well suited for production in areas prone to hot summer temperatures and limited rainfall. There was also an infrastructure available in these production regions for processing the lint and seed as well as a social bond that connected the crop to the people who grew it. Corn, hay, and small grains were the “step children” of agronomic crops for generations of southern planters. Corn and winter oats were grown in the Cottonbelt solely as feed grains for the draft animals used to grow cotton and the meat and dairy animals grown for home consumption. There were basically no markets available or facilities to handle some of these crops for commercial trade. Despite being introduced in the 1930's, it wasn't until the early 1950's that soybean became an important crop in the lower Mississippi River Valley (Bowman, 1986). Rice (*Oryza sativa* L.) was introduced to the Mississippi River Delta in 1948 and together these crops provided alternative sources of agronomic income to cotton but did little to encourage crop rotation. Both rice and soybean were relegated to the heavier clay soils of the Mississippi Delta with the sandy loams, silts, and silty clays remaining in cotton. It wasn't

until changes in government support programs in the mid-1990’s that planters in the Mid South became interested in alternatives to continuous cotton and began to produce corn for commercial sale and rotate it with cotton. Corn hectareage in the states of Arkansas, Louisiana, and Mississippi increased from 161,000 ha in 1990, to 382,000 ha in 2000, to 630,000 ha in 2010 (USDA-NASS, 2011).

Until 2007 research information about corn-cotton rotations were limited. An extensive study on various corn-cotton rotation schemes yielded data on the effects of rotation on yields and reniform nematode (*Rotylenchulus reniformis*) a serious pest to cotton. Bruns, et al. (2007), reported corn grain yields were greater following cotton than in plots of continuous corn. Pettigrew, et al. (2007), noted that cotton plant height increased 10% in plots following one year of corn and 13% following two years of corn when compared to continuous cotton (Table 4). Lint yields increased 13% following two years of corn primarily due to a 13% in bolls per m². No other increases were noted however. Stetina, et al., (2007) found that following two years of corn production, reniform nematode populations remained below damaging levels to the cotton plants. However, cotton following just one year of corn would have reniform nematode populations rebound to damaging levels towards the end of the growing season.

| Crop | Rotation sequence† | Yield(kg ha ⁻¹) | | | |
|--------|-------------------------|-----------------------------|---------|-------|--------|
| | | 2000 | 2001 | 2002 | 2003 |
| Cotton | continuous cotton | 1101a | 1036a | 1257 | 1266b |
| | corn-cotton-corn-cotton | xxx | 1068a | xxx | 1353ab |
| | cotton-corn-corn-cotton | 1117a | xxx | xxx | 1460a |
| Corn | continuous corn | 10,364a | 10,107b | 7587a | 9032 |
| | corn-cotton-corn-cotton | 10,297a | xxx | 8157a | xxx |
| | cotton-corn-corn-cotton | xxx | 10,675a | 7730a | xxx |

†Lint yield for cotton; grain yield at 155 g kg⁻¹ seed moisture; all values are means of eight reps averaged across four genotypes.
‡Within each crop and year, means followed by the same letter are not significantly different by lsd (P≤0.05)

Table 4. Effect of crop rotation sequence on crop yield of corn and cotton from 2000 to 2003 in Stoneville, MS. (Stetina et al., 2007).

3. Rice production and crop rotation

Rice ranks third behind corn and wheat in total tons of grain produced in the world but it is the primary dietary staple for more people than any other cereal (Raun and Johnson, 1999). It is grown on every continent except Antarctica. By the 1990’s rice was providing 35% to 59% of the total calories consumed by nearly 2.7 billion people in Asia (Neue, 1993). Peng et al. (1999) quoted that world rice production would need to be at least 600 million tons by 2025, an increase of 266 million tons above 1995 production just to maintain current nutrition levels. This increase will likely not be sufficient to alleviate current malnutrition in many of the rice dependent cultures (Neue, 1993). In areas where it is virtually the sole source of calories it is seldom grown in rotation with other crops. Anders, et al., (2004)

stated that producers growing continuous rice will likely experience lower grain yields than those using a rice-soybean rotation.

A common rotation with rice in southern and eastern Asia is a rice-wheat rotation system that occupies an estimated 24 to 27 million hectares (Wassmann, et al., 2004). Lattimore (1994) reviewed the literature pertaining to rice-pasture rotations in southeastern Australia. Annual pastures based on subterranean clover (*Trifolium subterraneum* L.) are well adapted to this part of the world and the rice cropping system. It provides considerable fixed N to the rice crop thus reducing the need level of supplemental N fertilizer as well as breaking weed cycles. It helps sustain a complimentary animal agriculture to use crop residues and provides opportunities for improved farm income. With respect to disease control in rice, both false smut (*Ustilaginoidea virens* (Cooke) Takah) and kernel smut (*Neovossia horrida* (Takah.) Padwick & A. Khan, syn. *Tilletia barclayana* (Bref.) Sacc. & P. Syd.) two serious fungal pests in rice production areas of the United States, appear to be best controlled when rice is grown in three year rotations with soybean and corn between rice crops (Brooks, 2011). Traditional rotations of rice-soybean, with winter wheat grown between the two summer annuals, were observed to have the highest levels of these diseases especially with high N- fertility levels.

4. The corn-soybean rotation

One of the more widely practiced rotations in the United States involves the corn-soybean rotation scheme used extensively in the North Central and Mid-Atlantic States. Within the 20 year period between 1988 and 2008 nearly 30 publications were known to have been published that compared corn-soybean rotations to continuous corn (Erickson, 2008). Virtually all of this research showed increases in corn grain yields from plots that had been planted to soybean the previous year. A few of these experiments followed soybean with two years of corn and in those studies yields from the second year corn crop were equal to or still greater than those from plots of continuous corn but less than the first year corn crop. One of these studies (Porter et al., 1997) examined the effects of various corn-soybean rotation schemes at three locations in the northern Corn Belt. Data from these studies showed that not only were both corn and soybean yields higher in rotation compared to monocultures of the two crops (Table 5), but that differences between rotations and monocultures were greater in low-yielding environments than in high-yielding conditions.

| Crop [†] | Yield (Mg ha ⁻¹) | | | | | | S-C rotation |
|-------------------|------------------------------|--------|--------|--------|--------|-------|--------------|
| | 1st-yr | 2nd-yr | 3rd-yr | 4th-yr | 5th-yr | Cont. | |
| Corn | 9.00a | 8.04b | 7.90b | 7.90b | 7.88b | 7.81b | 8.83a |
| Soybean | 3.26a | 2.99b | 2.84c | 2.82cd | 2.8cd | 2.77d | 3.05b |

[†]Crops were grown under corn or soybean monoculture of the respective crop in the following sequence: 1st-yr, 2nd-yr, 3rd-yr, 4th-yr and 5th-yr corn or soybean after 5 yr of corn or soybean; Cont. (continuous corn or soybean); and S-C (alternating soybean and corn). Values followed by the same letter or letters within each crop species are not significantly different at (P≤0.05).

Table 5. Corn and soybean yields from 3 locations in Minnesota and Wisconsin representing 29 environments. (Porter, et al., 1997)

Studying the net returns of various crop rotation schemes involving corn, Singer and Cox (1998) calculated a greater net return (\$250 US ha⁻¹) with a corn-soybean rotation than a continuous corn (\$193 US ha⁻¹) or a three year soybean-wheat/red clover rotation (\$133 US ha⁻¹). A recent study reported though, that yield comparisons are not the appropriate basis for decision making on cropping systems but rather economics is most important (Stanger et al., 2008). This report showed that, with the exception of continuous corn grown with 224 kg N ha⁻¹, a corn-soybean rotation was the most stochastically efficient cropping system across a range of N fertility treatments and other rotation schemes.

4.1 Other soybean rotations

Though soybean is one of humankind’s oldest crops, it did not really become of significance in the United States until the late 1940’s. The species was introduced in Europe from China in the mid 18th century and into the new world in the early 19th century where it was used primarily as a hay crop. The combination of the destruction in China from World War II and the Cultural Revolution removed it as the world’s primary supplier of soybeans and opened an opportunity for the United States to develop the crop as a major oil seed (North Carolina Soybean Producers Assn. , 2011). Currently the United States produces about 40% of the world’s soybeans followed by Brazil and Argentina combining to produce 50%. Besides corn, soybean is being rotated with rice or cotton in the Mid South and Southeastern States (Anders et al., 2004; Stallcup, 2009). In the eastern Great Plains soybean is often rotated with wheat or grain sorghum (*Sorghum bicolor* L. Moench) as well as corn (Kelley et al., 2003). Kelley et al. (2003), found that in general soybean yields grown in rotations with wheat or grain sorghum produced a 16% greater seed yield than when grown in a monoculture (Table 6). One of these rotations was soybean double-cropped behind winter wheat which is frequently practiced in areas of the United States south of 39° N latitude. This practice does risk failure from drought either causing poor emergence or poor seed set. Above 39° N there is also the risk of early frost terminating growth and above 40° N the practice of double-crop soybean after wheat is not advisable.

| Rotation† | | | |
|-----------------------------|---------|------|---------|
| W-S/S | W-Fal/S | GS/S | Cont. S |
| Yield Mg ha ⁻¹ ‡ | | | |
| 1.91 | 2.09 | 1.99 | 1.68 |

†W-S/S=Wheat-double crop soybean/soybean; W-F/S= Wheat-fallow/ soybean; GS/S= Grain sorghum/soybean; Cont. S= continuous soybean.
‡All means are significantly different by LSD (P≤0.05).

Table 6. 10 Year average 2nd year soybean yields in a two year rotation scheme at Columbus, KS from1980 to1998. (Kelley et al., 2003)

5. Rotations for forage crops

Prior to the extensive production of soybean for seed in the United States, and important rotation scheme in much of the New England, Mid-Atlantic and North Central states was corn-winter wheat-red clover. Frequently the red clover would be over seeded in late winter or early spring in the developing wheat crop. Many times timothy (*Phleum pretense* L.) a cool-season perennial grass would be seeded along with the red clover. The mixture

would provide some pasture or hay the first year after the wheat was harvested but was most productive the following year. The two species combined will provide more forage production together than each species separately (Martin and Leonard, 1967). These fields would frequently then be plowed in fall or spring of the second year with the sward providing a green manure crop for the following season. Sometimes only red clover would be over seeded in the wheat solely for the purpose of being used as a green manure crop. Other grass species would occasionally be seeded with the red clover and sometimes the field would remain in red clover-grass for two or more years to provide hay and grazing. Though this rotation is comparatively old, it is still practiced, especially where there are numerous beef cow-calf, dairy, or horse enterprises.

Both beef and dairy cattle farming involves crop management challenges that many tend to overlook when thinking about crop rotations. Many people do not think of pasture swards as being a “crop”. But to the cattleman it is a very important source of income and deserves as much attention to management as any other economic plant life. Dairy farms are very dependent on careful management of feed and forage resources in order to be sustainable. Not only is the quantity of feed and forage important to the dairy animal but quality as well, to insure maximum milk production during lactation. Roth et al., (1997), list a number of suggestions to aid dairy farmers in developing long term crop rotation plans that address production issues, such as feed quantities, forage quality, fertility, and pest control issues as it relates to corn silage production. Greater restrictions on pesticide use, are often placed on dairy operations due to concerns over traces of some chemicals carrying over into milk that is consumed by children. Continuous corn silage production carries the risk of corn rootworm damage, and as pointed out earlier, the western corn rootworm has adapted to egg laying in soybean fields and can damage corn following soybean. Roth (1996) points out that western corn rootworm larvae cannot tolerate a rotation to alfalfa. Therefore, seeding alfalfa after corn for silage will not only provide a good source of quality hay but also eliminate the need for a soil insecticide for rootworm control in the following corn crop.

Temporary meadows, which are seeded into a forage species for one to three years and then cultivated for a grain crop are sometimes included in discussions regarding crop rotations. However, a number of dairy farms and beef cow-calf operations occur in areas that include land unsuitable for tillage of any kind and are often used as permanent pastures that should be managed with the same intensity as any other cropland. Without proper attention these areas will often revert to a high proportion of weedy or woody species that are not useable by livestock and low yielding forage that reduces the pasture's carrying capacity or places greater demands on tillable cropland to provide necessary feed to maintain the animal enterprise. Johnson et al., (2007) states that periodic renovation or “renewing” of a pasture is the best way to improve forage yield and animal performance. Pasture renovation is in a way a form of crop rotation if you consider crop rotation as a means of maintaining land productivity. In temperate climates renovation usually begins in the fall by overgrazing the pasture to be renovated to remove excess vegetative material that might interfere with seeding and germination of the new pasture mix (Johnson et al., 2007; Lacefield and Smith, 2009). Seeding usually occurs in mid-winter while the soil is frozen in the first few centimeters. The thawing and refreezing of the soil surface is usually sufficient to allow good contact of the forage seed with the soil for germination. Sometimes a light cultivation with a disk or spike-toothed harrow is done to improve the chances of a good soil-seed contact.

Soil tests are usually acquired prior to seeding to determine nutrient availability. Applications of pulverized limestone are often required to supply Ca and adjust pH levels to facilitate establishment of a forage legume. Many soils in temperate climates tend to be acidic (pH 4.5 to 5.5) and require liming to elevate soil pH levels to 5.7 or higher to be more suitable for legume establishment. Virtually all recommendations for pasture renovation in temperate climates call for the establishment of one or two legumes in the sward (Wheaton and Roberts, 1993; Johnson et al., 2007; Lacefield and Smith, 2009; Teusch and Fike, 2009). Wheaton and Roberts (1993) listed 10 benefits of including a forage legume in a pasture mix. Among them were an increase in animal gain, decrease in herd health problems, an increased conception rate by cows, an increased protein yield per hectare, N being furnished by the legume to the grass, and reduced pasture production costs. Johnson et al., (2007) stated some of the same benefits along with a better seasonal distribution of forage because legumes are generally more productive in mid-summer than cool-season grasses which are the more common grass types grown in temperate climates. Lacefield and Smith (2009), reported that tall fescue (*Festuca arundinacea* Schreb.) growing in conjunction with red clover seeded at 6.7 kg ha⁻¹ yielded more dry matter (12,400 kg ha⁻¹) than fescue alone fertilized with 202 kg N ha⁻¹ (11,100 kg ha⁻¹). Teusch and Fike (2009) list several legume species to be considered for seeding in pasture renovation. The more common legume species recommended are red clover, ladino clover (*Trifolium repens* L.), annual lespedeza (*Lespedeza striata* Maxim.), alfalfa, and birdsfoot trefoil (*Lotus corniculatus* Cav.). As stated previously, in temperate climates cool season grass species are frequently selected to be seeded along with the legume when renovating pastures. For permanent pastures the species of choice are often tall fescue, orchard grass (*Dactylis glomerata* L.), or smooth brome (*Bromus inermis* L.). Pasture management is an on-going operation and additional seedings may be necessary to maintain a profitable sward. Birdsfoot trefoil has the ability to reseed itself even under grazing and alfalfa is a long-lived legume with individual plants able to survive up to five years. Red clover, though a perennial, will usually last only about three years and will need to be reseeded. Some forage specialists have found that over-seeding the pasture annually with 4.5 kg ha⁻¹ of red clover seed in mid-winter will maintain the sward at about 30% legume which is recommended as the proper mix of grass and legume (H.N. Wheaton, 1975, personal communication). Even with good management, most pastures will need renovation about every four to five years due to weed growth.

Pasture renovation in sub-tropical climates usually involves complete destruction of the old sward and reseeding or sprigging to reestablish the grass. The reasons for renovation in the sub-tropics are usually for weed control, or to reestablish swards lost to insects, over grazing, prolonged drought and in some cases multiple freezes during late winter that kill off the grasses. Renovation may also be done to replace an older grass cultivar with a newer more productive one (Woodruff et al., 2010). One basic difference between temperate pasture renovation and sub-tropical pastures is that in the sub-tropics the old sward is essentially destroyed and a new one established (Verdramini et al., 2010). Sub-tropical pastures are not as apt to include a forage legume due to most of those species being cool-season and may not survive well in hot humid summer months. Also, many of the grass species used are aggressive in nature and effective at crowding out less aggressive species. The more common species grown as pasture grasses in the subtropics are hybrid bermudagrass (*Cynodon dactylon* (L.) Pers.), bahiagrass (*Paspalum notatum*), atrapaspalum (*Paspalum atratum* Swallen), digitgrass (*Digitaria decumbens*) (En), limpograss (*Hemarthria*

altissima), and Rhodes grass (*Chloris gayana* (Kunth)) (Verdrimini et al., 2010). All of these grasses except *atra paspalum*, bahiagrass and Rhodes grass require vegetative propagation in order to be established. As with temperate pastures, the pasture must first be properly prepared by controlling weeds, insects, removing old or dead vegetative material and fertilizing to soil test recommendations. Burning is often used in preparing bermudagrass pastures for renovation (Stichler and Bade, 2005). Tillage operations are often performed during dry periods in the spring to further control weeds and old sward growth as well as better prepare the land for vegetative propagation with the onset of summer rains (Stichler and Bade, 2005; Verdrimini et al., 2010). In both the subtropical and temperate climates warm season annual forages may be included into crop rotations on land used primarily for cultivated crops. This is to provide additional pasture, hay or silage for livestock operations. Species such as pearl millet (*Pennisetum glaucum* (L.) R.Br.), sudangrass (*Sorghum bicolor* subsp. *Drummondii* (Steud.) de Wet ex Davidse), and other forage sorghum and sorghum x sudangrass crosses often fill this role (Hancock, 2009).

6. Summer fallow

Summer fallow, the practice of growing a crop every other year and in most systems, controlling weed growth during the off-year, has been used almost exclusively in semi-arid regions for the production of wheat or other small grains. Its purpose is to accumulate sufficient limited rainfall during the fallow year to grow a crop the following year and to break crop disease cycles. Most of the world's drylands are in developing countries where water resources are usually limited by a lack of rainfall and potential irrigation (Ryan et al., 2008). Stewart et al. (2006) has stated that dry regions worldwide supply about 60% of human food stuffs. Areas where this is a common practice are the Mediterranean, semiarid regions of Africa, Asia, Australia, the Pacific Northwestern United States, and the western regions of the Canadian and United States Great Plains. Many of these areas practice a "clean" summer fallow where the land is kept weed free during the fallow year, usually by cultivation or herbicides. However, in northern Africa a weedy fallow is often employed where palatable weeds and volunteer crop plants are allowed to grow and then be grazed by livestock (Ryan et al., 2008). This allows for an animal agriculture to exist that provides needed calories and returns manure to the land to provide nutrients for the following crop.

In semiarid areas of the Pacific Northwestern United States summer fallow wheat production has been practiced nearly 130 years (Schillinger et al., 2007). In recent years though, studies have been conducted in semiarid regions of the United States and Canada to adapt a continuous cropping system to replace summer fallow. Water storage efficiency in most summer fallow-wheat rotations is usually less than 25% of the rainfall received during a 14 month period using conventional tillage (McGee et al., 1997). Research from Colorado and Nebraska demonstrated that precipitation storage efficiency could be improved to 40% to 60% through minimum or no-till which allows crop residue to remain on the soil surface and soil disturbance is held to a minimum or eliminated (Croissant et al., 2008). However, such practices added little or no increase in wheat yields and it was concluded that the resultant water savings could only be converted to profit by employing intensive cropping systems where fallow time is decreased and summer crops such as maize, grain sorghum, or annual forages and included in the rotation. Under no-till it was determined that it cost more to save the additional water than the value of the added grain yield. Lyon et al. (2004)

reported that winter wheat yields in the central Great Plains were negatively affected by eliminating the 11 to 14 month summer fallow by spring planting a transitional crop before wheat in the fall. However, a spring planted forage crop that was harvested early had a minimum negative impact on wheat yields and that the value of the forage combined with the following wheat yields resulted in greater income than the traditional winter wheat-fallow rotation. Research from the Horse Heaven Hills region of Washington looked at a continuous no-till hard red spring wheat system verses a winter wheat-fallow rotation and found the hard red spring no-till system did not match the winter wheat-fallow system of production in yield or income. However, the continuous no-till system did offer a benefit of providing ground cover that reduced wind erosion and air pollution by dust particles (Young et al., 2000).

Summer fallow is also practiced on fields used to produce castor bean (*Ricinus communis* L.) the previous year. This is not done for accumulating moisture but to rid the field of any volunteer plants. Castor bean contains a very deadly toxin, ricin, which in very small quantities can kill humans and livestock. Summer fallow in this case allows volunteer plants to be destroyed and the field cleaned for future feed and food crops.

7. Organic farming and crop rotations

Organic farming has embraced crop rotations as its backbone to success. Crop rotation is practiced with what appears to be, much more intensity than most conventional farming systems with particular emphasis on sustainability. A crop rotation plan and accompanying records for a field and/or farm are required for certification as an organic farming operation (Johnson and Toensmeier, 2009). Organic farming and its use of crop rotations could be summed up in part, as the employment of proven crop management practices prior to the advent of pesticides and processed fertilizers. This is not to say that improvements on those rotation systems have not occurred. Most have been modified to accommodate mechanization and most other time saving ideas. But, yields may be lower. Maeder et al., (2002) reported on a 21 year study in Europe that crop yields on organic farms were generally 20% lower. However, there was an offsetting decrease of 34% in fertilizer expense, a 53% reduction in energy costs, and a 97% decrease in pesticides. Reganold et al., (1987) reported a comparison of the long-term effects (40 years) of conventional farming to organic systems found that organic farms had significantly higher levels of soil organic matter than conventional systems, greater top soil depth, higher polysaccharide content, and less soil erosion. Clark et al., (1998) reported that over an eight year period of applying organic crop rotation practices that soil organic matter had increased 2% over a comparable field that used conventional practices in a two-year rotation scheme.

A major challenge to organic crop production is control of weeds. Weed management has been identified by producers as the principle problem in organic farming (Walz, 1999). The advent and subsequent extensive use of herbicides after World War II altered crop production practices, especially crop rotations. Conventional crop farming today usually involves two- or three-crop crop rotations as have been previously mentioned with a heavy reliance on herbicides to at least reduce or eliminate weed problems. Regardless of the type of farming system used, conventional or organic, weeds are a constant annual drag on achieving maximum yields of high quality produce. Nave and Wax (1971) reported a reduction in soybean seed yields of between 25% to 30% compared to weed free plots due to

the presence of one smooth pigweed (*Amaranthus hybridus* L.) per 30 cm of row and that yield losses from stubble, lodging and stalks were more than double in pigweed and giant foxtail (*Setaria fabric* Herrm.) infested plots compared to weed free plots. Weeds compete with a crop for water, light, and soil nutrients directly reduce yields. Some species have alleopathogenic effects upon certain crops, reducing their growth and yield or in extreme cases causing their death. Weeds can harbor insect pests or serve as alternate hosts to plant diseases that further reduce yields and produce quality. They can add off-flavors to crop products or in some cases provide toxins to produce, rendering it unhealthy to consume. Weeds present during harvest can also damage the crop being harvested. Ellis et al., (1998) reported increases in damaged soybean seeds by 8.2% to 11.1% with the presences of a plant per m of row of any of five common weed species found in the Mid South. In organic farming, crop rotations are vital to controlling weed growth. Teasdale et al., (2004) evaluated the weed seed dynamics of three organic crop rotations and found that seedbanks of smooth pigweed and common lambsquarter (*Chenopodium album* L.) were usually lower following a hay sward in a four-year rotation or wheat in a three-year rotation than following soybean in a two-year rotation prior to being planted to corn. However, annual grassy weed seedbanks prior to corn planting were generally higher following the hay sward of the four-year rotation than the wheat of three-year rotation or the soybean of the two-year rotation. Porter et al., (2003) also found that weed control in organic corn and soybean were better when they were part of a four-year rotation of corn-soybean-oat-alfalfa compared to a two-year corn-soybean scheme.

Nitrogen is probably the most important of the macro-nutrients in crop production. Libraries at all major agricultural universities have a seemingly endless supply of research articles and texts pointing out the importance of adequate N-fertility in the growth and development of every crop important to humankind. In organic crop farming, and increasingly in conventional cropping systems, the use of crop rotations that supply ample supplies of N to non-leguminous cereals is an important management strategy. Prior to the escalating energy prices and the increasing cost of manufactured N-fertilizer sources, the use of legumes that fix atmospheric N by *Rhizobium*-legume symbiosis, especially clover species, as green manures or cover crops had diminished sharply. Even prior to World War I legumes would almost always be seeded for a green manure crop preceding corn (Heichel and Barnes, 1984). In organic farming, where the emphasis is to refrain from using manufactured N-fertilizer, green manure crops or cover crops are a vital source of N for much of their production. Lupwayi et al., (1998) reported that microbial diversity was greater under wheat preceded by red clover manure or field peas (*Pisum sativum* L.) than under continuous wheat. Long-term crop rotation research in Iowa has shown very little or no increase in corn yields from plots receiving N-fertilizer compared to those following one or two years of an alfalfa- brome grass- red clover meadow (Voss and Shrader, 1984).

Species selection for organic crop rotations is probably more thought out than for conventional crop rotations. As explained earlier, conventional crop rotations are heavily influenced by market price of the various commodities available to be grown. Though commodity price is important to practitioners of organic farming it is not the primary driving force in making species selections. Baldwin (2006) states that organic farmers face the challenge of practicing crop rotations by defining systems that maintain farm profits while improving soil quality and preserving the environment. Frequently organic farmers

will develop rotation schemes and select species based upon the crop's ability to extract nutrients and water from the soil. Some organic producers include vegetable crops into their operations due to these species tendency to extract nutrients and water from shallow depths then follow with a cereal that generally feeds to greater soil depths. Species selection is also made on the basis of weed, insect, and disease control. Delate and Hartzler (2003), states that rye has allelopathic properties and is often used as a winter cover crop following corn to aid in weed control in preceding soybean or oat crops. Sustainability through the natural preservation of soil fertility is paramount to the organic farmer and makes the selection of species an important part of the operation. Organic crop production makes as much use of natural pest control, including crop rotations, as is possible.

8. Biofuels production and crop rotations

Interest in using lignocellulosic biomass to produce ethanol is gaining in popularity. Lignocellulosic biomass production mainly involves growing and harvesting plants generally not used for food or feed. Woody species such as willow (*Salix*. spp.) and poplars (*Populus* spp.) (Matthew et al., 2010) and grasses such as switchgrass (*Panicum virgatum*), big bluestem (*Andropogon gerardii*), reed canarygrass (*Phalaris arundinacea*) are several sources of lignocellulosic biomass that have shown to be useful in ethanol production (Hill, 2007). Rotation schemes for growing lignocellulosic crops are, for the most part, still in development. Production of these materials for biofuels though is being done mostly on land not suitable for extensive corn and soybean production thus relieving pressure to grow more hectares of these crops to satisfy the conventional and biofuels markets. Worldwide it is estimated that about 1% of crop land or about 11-12 million hectares are being used to grow biofuels (de Fraiture et al., 2008). Raghu et al., (2006) points out that some of the traits favorable to producing a lignocellulosic crop such as being a C₄ photosynthetically, lacking pests, rapid early season growth, and long canopy duration can also tend towards them being invasive. This would not work well in a rotation scheme with most conventional crops. Currently lignocellulosic crops contribute little to current U.S. transportation biofuel suppliers but will likely provide the great share of ethanol in the near future.

In the United States, debate is underway concerning the use of corn as a primary source of fuel ethanol. Also, soybean oil is being blended with diesel to extend it. Diversion of these crops for biofuels is believed to increase food prices for consumers as the competing interest of food and fuel vie for the available supply. There is also concern that the increased demands for these grains will negatively impact crop rotations, particularly those that help conserve soil, water, and plant nutrients. One of the primary reasons corn and soybean are currently popular for biofuels over lignocellulosic crops is the comparatively short time to harvest maturity. Most of the lignocellulosic crops require three to five years to reach harvest maturity (Hill, 2007), compared to one year for corn or soybean. Though corn and soybean are regularly rotated with one another, history has shown that a substantial increase in the price received for any crop can encourage monocultures at the expense of proven rotations and their accompanying benefits. The expanded use of corn and soybean as biofuel could diminish the inclusion of small grains and/or forage crops in rotation schemes and the tillage of soils that are not well suited for cultivation.

Besides lignocellulosic crops, the harvesting of crop residues for ethanol production has been considered. Perlack et al., (2006) has reported that nearly 7.0×10^{10} kg of corn stover

could be harvested in the U.S. for ethanol production. Worldwide other crops that produce sufficient quantities of residue that could be used to produce ethanol include rice, barley, oat, wheat, sorghum, and sugar cane (*Saccharum officinarum* L.). The use of crop residues for lignocellulosic ethanol production has however run into opposition due to the negative impacts such removals have on C sequestration, soil properties, and nutrient availability for subsequent crops. Wilhelm et al., (2007) reported that between 5.25 and 12.50 Mg ha⁻¹ of corn stover are required to maintain soil C at productive levels for subsequent crops. Lal (2004) states that even though the energy acquired from the world's crop residue would be equivalent to 7.5 billion barrels of diesel, a 30% to 40% removal of crop residue would increase soil erosion and its subsequent pollution hazards, deplete soil organic C, and increase CO₂ and other greenhouse gas emissions from the soil. He suggests establishing biofuel plantations of adapted species on marginal lands rather than remove crop residues from land used to grow food and feed grains. Development of such plantations will require more aggressive research into developing crop rotation schemes specific for growing lignocellulosic crops for biofuel.

9. Conservation tillage

Conservation tillage continues to grow in importance in crop production since its inception over 40 years ago. C.M. Woodruff in 1970 was conducting research on strip-planting corn into tall fescue sod on Missouri hillsides with the idea of producing a cash grain/feed crop along with a forage crop for livestock production while maximizing conservation of the soil and rain water (Anonymous, 1970). Anders et al., (2004) found that phosphorus (P) concentrations in run-off water were higher for no-till rice than conventional tilled paddies, most likely due to the P being surface applied. However, total-P concentrations in run-off were lower in no-till because of the reduced loss of soil in no-till and its bound P. Conservation tillage which includes both minimum tillage and no-till practices, are used to grow an array of crops from corn, soybean, cotton, grain sorghum, and several small grain species almost always in some rotation scheme. It is popular not only for the conservation of natural resources as just mentioned, but also for the savings in fuel, time, wear and tear on farm equipment, and the environmentally sustainable attributes of the various practices. Minimum tillage, by reduced soil disturbance, promotes a complex decomposition subsystem that enhances soil system stability and efficiency of nutrient cycling. Basically minimum tillage more closely mimics natural ecosystems than conventional cropping systems (Francis and Clegg, 1990). Tillage has been reported to reduce the diversity of bacteria in the soil by reducing both the substrate richness and evenness (Lupwayi et al., 1998). They found that the influence of tillage on microbial diversity in fields planted to wheat was more prominent at the flag-leaf stage of growth than at seeding and more prominent in bulk soil than in the rhizosphere at the flag-leaf stage.

Kladivko et al., (1986), studied the production of corn and soybean using an array of tillage systems ranging from conventional moldboard plowing and seedbed preparation to no-till on a range of soils differing in organic matter, texture, and slope for seven-year and six-year periods. At one location on a Chalmers silty clay loam (fine-silty, mixed, superactive, mesic *Typic Endoaquolls*) comparisons of a corn-soybean rotation to continuous crops of these two species using various tillage systems was conducted for 10 years (Table 7). Yields of rotated crops tended to be greater than those of the monocultures regardless of tillage. Kladivko et

al. (1986) also reported from this research at other locations that conservation tillage systems resulted in increased soil water contents, lower soil temperatures, increased soil organic matter, and more water-stable aggregates near the soil surface with higher bulk densities than conventional tillage. Corn yields were found to be equal to or better than conventional tillage practices when grown on the better drained soils using conservation tillage. Only on the poorly drained soils did corn yields on conservation tilled fields fail to exceed conventional tillage, most likely due to low temperatures and excess wetness in the spring as depicted with the Chalmers silty clay in Table 7.

| Tillage System | Previous crop Crop | Corn Corn | Soybean Corn | Soybean Soybean | Corn Soybean |
|----------------|-----------------------|--------------|-----------------|--------------------|-----------------|
| Fall plow | | 10.7 | 11.6 | 3.6 | 3.8 |
| Fall chisel | | 10.3 | 11.4 | 3.3 | 3.6 |
| Ridge till | | 10.4 | 11.6 | 3.4 | 3.6 |
| No-till | | 9.1 | 11.2 | 3.2 | 3.3 |

Table 7. Mean corn and soybean yields (Mg ha⁻¹) in response to tillage system and crop rotation on a Chalmers silty clay loam in Indiana in 1980-1984 (data is from 6th to 10th year of the study). (Kladivko et al., 1986).

Roth (1996) presents several crop rotation schemes to use in no-till farming on Pennsylvania dairy farms. One of the more popular is an alfalfa-grass sward for hay followed by no-till corn. This involves killing the sod in the fall with herbicides to control weeds and reduce residue by early spring to facilitate corn planting. This rotation seems to work best where hay production is limited to three years. Alfalfa is also successfully no-tilled into fields that have just been harvested for corn silage or following the harvest of a spring seeded sorghum sudangrass. Lafond et al., (1992), evaluated no-till, minimum till (one pre-seeding tillage operation) and conventional till (fall and spring pre-seeding tillage operations) on a four-year crop rotation study. The rotations were fallow-spring wheat- spring wheat-winter wheat, spring wheat-spring wheat-flax (*Linum usitartissimum* L.)-winter wheat, and spring wheat-flax-winter wheat- field pea. Tillage systems did not affect the amount of water conserved during fallow. However, no-till and minimum till did result in an increase in soil water from the surface to 120 cm in depth over conventional till. All three crops in the study had greater yields in the no-till and minimum till treatments than in the conventional till. In an experiment using conservation tillage practices (strip-till or no-till) in combination with a corn-soybean rotation, both full-season soybean or double-crop soybean following wheat had the most consistent increase in seed yields (Edwards et al., 1987).

In recent years there has been considerable interest in various tillage practices and their influence on the sequestration of atmospheric CO₂ as a partial means of mitigating its current increase and subsequent impact on climate change. Sampson and Scholes (2000), state that the optimization of crop management to facilitate accumulation of soil organic matter could help sequester atmospheric CO₂ and lower the rate of its increase. West and Post (2002), found that, excluding a change to no-till in wheat-fallow rotations, a change from conventional tillage to no-till can sequester between 43 to 71 g C m⁻² yr⁻¹. These values are within the upper range (10 to 60 g C m² yr⁻¹) of those reported in a review by Follet (2001). West and Post (2002) also stated that enhanced crop rotation complexity can sequester an average of 8 to 32 g C m⁻² yr⁻¹ which is similar to an average of 20 g C m⁻² yr⁻¹

estimated by Lal et al. (1998; 1999) resulting from an improvement in rotation management.

Conservation tillage can present pest control problems that are different from those found in conventional systems, particularly weeds. Weed species composition and abundance often change in response to crop and soil management practices (Cardina et al., 2002). Buhler (1995), wrote that most conservation tillage practices rely heavily on increased herbicide use and that reduced herbicide efficacy has slowed the adoption of conservation tillage practices. Weed populations have tended to shift more towards perennials, summer annual grasses, biennials and winter annual species in conservation tillage systems. Moyer et al., (1994) stated that successful conservation tillage systems usually involve crop rotations of three or more species and several different herbicides. Legere et al., 1997 concluded that conservation tillage has the potential to produce sustained yields of spring barley in Quebec, provided attention is given to critical aspects such as crop establishment and weed management. With respect to plant diseases, Peters et al., (2003) determined that soil agroecosystems can be modified by crop rotation and conservation tillage to increase disease suppression by enhanced antibiosis abilities of endophytic and root zone bacteria in spring barley and potato (*Solanum tuberosum* L.).

10. Conclusions

Crop rotation is very likely to continue to be an important management practice, especially in the developed part of the world. However, economics is always going to have a major say in the decision making process of what gets planted where and by how much. Our ever increasing world population is going to place greater pressure on getting more production from our shrinking areas of arable land and potable water needed for drinking, personal use, and growing crops. Climate change is, despite all of the predictive computer models, a great unknown, not from the standpoint of whether or not it is occurring but as to just what can be realistically done, if anything, to curb it.

Lands that include a fallow period and/or irrigation to produce crops may eventually be taken out of the food and fiber production equation because of both shifts in the climate and the loss of water for irrigation. Production areas of various crop species may shift due to climate change. Changes in crop genetics through biotech and genetic engineering may contribute some relief but improvements in water use efficiency are not going to eliminate the need for irrigation. Also, genetically engineered crops in many areas of the world are not being well received based on fears, real or imaginary, and increased costs of such seed stocks are often prohibitive to many producers. A nearly 500% increase in energy prices and a shift from food, feed, and fiber crops to renewable energy crops will have an increasing impact on the land available to grow all crops and the rotations to produce them. Given the history of crop rotations and the overall benefits that appear to be gained from them, it is virtually assured that they will continue to be an important practice in food production. Despite the difficulties associated with conducting crop rotation research, it will be beneficial to society as a whole to support efforts in this area and to adequately reward scientists willing to dedicate their professional efforts in such endeavors.

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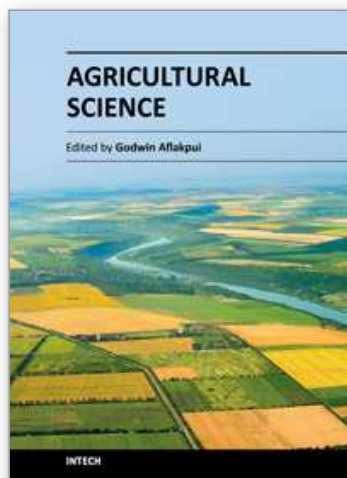
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This book covers key areas in agricultural science, namely crop improvement, production, response to water, nutrients, and temperature, crop protection, agriculture and human health, and animal nutrition. The contributions by the authors include manipulation of the variables and genetic resources of inheritance of quantitative genes, crop rotation, soil water and nitrogen, and effect of temperature on flowering. The rest are protecting crops against insect pests and diseases, linking agriculture landscape to recreation by humans, and small ruminant nutrition. This book is a valuable addition to the existing knowledge and is especially intended for university students and all professionals in the field of agriculture.

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