Cover Crops and Rotations

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I. Introduction

Recent requirements imposed by government farm policies, shifts in the economics of farming practices, and the public's concern in protecting the environment and conserving our natural resources have created a resurgence of interest in two of the oldest agricultural practices known. These two practices, using cover crops and crop rotations, have been recognized as good management practices since ancient times.

The value of rotations with legumes was recognized by the Chinese over 2,000 years ago (Pieters, 1927). Virgil, in pre-Christian Rome, proclaimed in verse the virtues of fallowing the land from continuous cropping and of rotating small grains with legumes (Gladstones, 1976). Although green manure crops, especially lupin (*Lupinus* spp.), were common in southern Europe long before

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the birth of Christ, crop rotations were unknown in northern Europe until about the 16th century (Pearson, 1967).

Sometime during the 1730's, Lord Townsend of Norfolk County, introduced the Norfolk rotation to England (Pearson, 1967). The Norfolk rotation is a 4-year rotation of wheat (*Triticum aestivum* L.)-turnip (*Brassica rapa* L.)-barley (*Hordeum vulgare* L.)- and red clover (*Trifolium pratense* L.). This rotation was responsible for raising average wheat yields in England from 540 kg ha^{-1} to 1350 kg ha^{-1} by the early 19th century. The Norfolk rotation, or some modification of it, is still in use in northern Europe today.

English settlers carried the knowledge of green manuring to America. A rotation of corn (*Zea mays* L.), wheat, and red clover was described by Thomas Cooper in 1794 as being practiced by the "best" farmers in Pennsylvania (Pieters, 1917). Partridge pea (*Chamaecrista fasciculata* Greene) and cowpea [*Vigna unguiculata* (L.) Walp subsp. *unguiculata*] were grown in rotations in Virginia and Maryland by the end of the 18th century (Pieters, 1927).

Modern farm practices are largely dictated by economics and government policies that affect those economics. As a consequence of these factors, farming has generally become more specialized. Highly capitalized mechanized systems do not lend themselves well to diversified farming practices (Pearson, 1967). As a result of this specialization, cover crops and rotations are not utilized to the extent they once were. Although the current focus on farming practices to "sustain" natural resources and productivity has created a resurgence of interest in these two practices, the interest has not progressed to large scale adoption of the practices. This chapter will review the general principles of crop rotation and cover crops, discuss their advantages and disadvantages in the context of their coordination into current agricultural systems, and outline future research that will facilitate wider adoption of these practices.

II. Principles of Crop Rotation

A systematic or recurrent sequence of crops grown over a number of cropping seasons is a common definition of crop rotation. Cropping season should be considered the unit of time rather than years since in some areas the length of the growing season allows for more than one crop per year. The choice of crops used in rotations is determined by ecology and economics (Pearson, 1967). Ecological limitations are generally not determined by the farmer. They include such things as the crop's suitability to edaphic, biotic and climatic factors. To some degree, however, researchers and farmers have learned to extend the natural ecological niche of crops. Examples of this include growing alfalfa on acid soils modified by liming, irrigating arid regions, chemical control of soil-borne and foliar diseases in warm, humid regions, and northward expansion of the Cotton Belt (*Gossypium hirsutum* L.) through the development and use of "short-season" germplasm and management schemes.

Certain crops, however, have an economic advantage over other crops within a particular area. This economic advantage may be related to environmental adaptation, variations in regional inputs necessary to produce the crop, and government policies and market influences. Pearson (1967) coined the term "comparative advantage" for this edge given by one or more of the above factors to one crop in a particular situation. If the comparative economic advantage of a crop is strong enough, the crop dominates to the extent that it is generally grown in monoculture. If the comparative advantage of one crop is not excessively greater than some others, the farmer is more likely to use crop rotations.

A basic premise to any successful crop rotation is the use of a "hub" crop, i.e., the crop which offers the greatest comparative advantage (Pearson, 1967). The hub crop varies by geographical area and is determined by ecological and economic principles as discussed previously.

The comparative advantage or choice of hub crop is, within limits imposed by climate and soil factors, mainly a function of economic principles. Other principles of crop rotation are based more on agronomic principles than economic principles *per se*. Pearson (1967) summarized these principles to include: i) utilization of both row crops and sod crops; ii) alternation of diverse crop species; iii) fertilizer management based on differential crop nutrient use response and efficiency; iv) a logical sequence and duration of crops; and v) flexibility for risk aversion. From a practical standpoint, crop rotation is best established by dividing the farm into a number of fields of equal size; the number of fields corresponding to the number of growing seasons necessary to complete the rotation cycle (Parker, 1915; Pearson, 1967).

III. Current Rotation Practices in the United States

Ecology and economics not only determine the choice of crops in rotations, but also influence the choice of soil management, i.e., tillage and residue management systems. Allmaras et al. (1991) outlined eleven different tillage management regions (TMR) within the contiguous United States (Figure 1). Two factors, climate and major crops grown, were the factors used to delineate the tillage management regions. Thus, the basic principles that determine the selection of crops grown in a geographical area form not only the basis for grouping regions as to their problems and potential benefits resulting from various residue management systems, but also form the criteria for selection of rotations and cover crops.

Corn (*Zea mays* L.) is the predominant hub crop in the Northern and Southern Corn Belts and Central Great Plains (Allmaras et al., 1991). Approximately 25% of the corn produced in these states is grown continuously, i.e., not rotated with another crop species (Daberkow and Gill, 1989; Gill and Daberkow, 1991). The most common rotation crop for corn is soybean [*Glycine max* (L.) Merr.], comprising about 50% of the acreage planted (Daberkow and

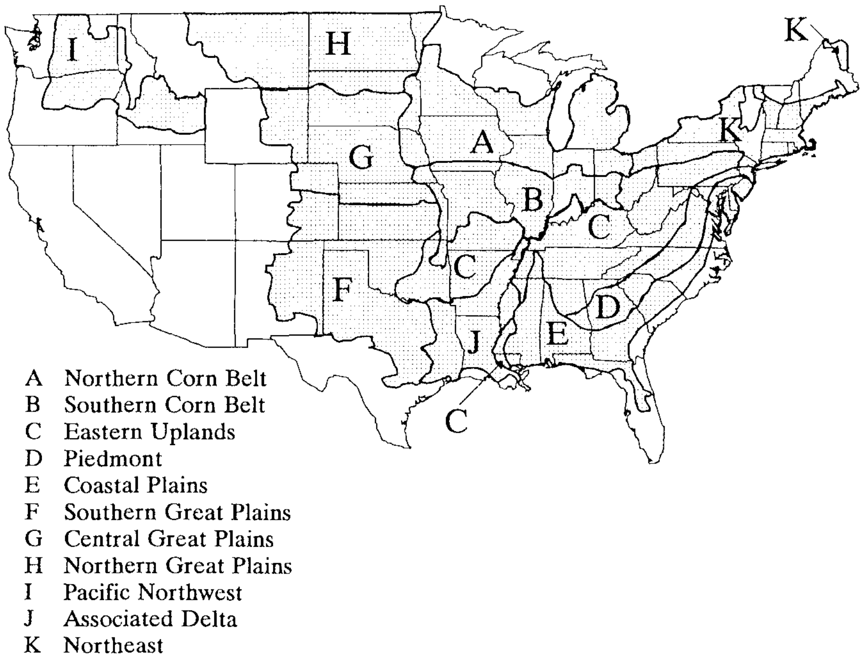

Figure 1. Eleven tillage management regions in the contiguous United States. (From Allmaras et al., 1991.)

Gill, 1989; Gill and Daberkow, 1991). Alfalfa (*Medicago sativa* L.) and small grain rotations generally comprise the remaining acreage of rotation crops in these areas.

Soybean can also be considered a major hub crop in the Southern Corn Belt tillage management region. In 1990, over 80% of the soybean grown in this area was rotated with corn, 58% in a soybean-corn-soybean rotation; 4% was not rotated, and 3% was grown following a fallow period (Gill and Daberkow, 1991).

In the area where corn and soybean are hub crops, approximately 30% of the corn and 35% of the soybean are planted with conservation-tillage, i.e., where 30% or more residue remains after planting (Taylor and Bull, 1992). The predominant conservation-tillage system in the Southern Corn Belt is mulch-tillage (primary tillage with chisels, disks, or other implements over the entire area of the field before planting to leave at least 30% residue cover)(CTIC, 1991). In certain areas of the Associated Delta, Coastal Plain, Piedmont and Eastern Upland tillage management regions (Figure 1), soybean is also the hub crop; however, in these areas soybean is often rotated in a double-cropping system with wheat. Approximately 30% of the wheat grown in the Southeast in 1990 was double-cropped with soybean (Gill and Daberkow, 1991). Conservation-tillage systems are used on 17% of the land planted to soybean in this area, with no-tillage being the predominant conservation-tillage system used (Taylor and Bull, 1992).

The example of soybean as the hub crop illustrates the interactive relationship between choice of crop rotation, climate, and tillage system utilized. In the northern area of soybean production, corn is the common rotation and mulch tillage is the conservation-tillage system of choice. In the southern area of soybean production, wheat is the rotation crop, and no-tillage is the preferred conservation-tillage technique.

Wheat is a hub crop grown in the Southern and Northern Great Plains tillage management regions (Figure 1) (Allmaras et al., 1991). These areas have mean annual evaporation rates that greatly exceed their annual precipitation (Kilmer, 1982; Allmaras et al., 1991). The role of climate in choosing both the hub crop and rotation is indicated by the fact that approximately 40 to 50% of the wheat grown in this area involves a fallow rotation in order to conserve soil water (Daberkow and Gill, 1989; Gill and Daberkow, 1991). Mulch tillage and reduced tillage (one-pass full-width tillage done at same time as planting/seeding operation) are the conservation-tillage systems used most for wheat in these dry areas (Allmaras et al., 1991; Taylor and Bull, 1992).

Rice (*Oryza sativa* L.) enjoys a comparative advantage on heavy soils in California to the extent that it is grown in continuous monoculture (Daberkow and Gill, 1989). In Arkansas and Louisiana, however, soybean is a rotation crop for rice on about 75% of the planted acreage (Gill and Daberkow, 1991). Because rice is generally planted on flat heavy soils and flooded, conservation-tillage systems are not required to control erosion. Ninety-five percent of the rice in the states in the Associated Delta tillage management region is planted with conventional tillage without the moldboard plow (Taylor and Bull, 1992).

Pest management dictates rotations be used in potato (*Solanum tuberosum* L.) production. In 1990, only 3% of the potatoes grown in the United States were grown following 2 years of potato (Gill and Daberkow, 1991). Small grain preceded potato in about 40% of the acreage planted in 1990. The variety of rotation crops used with potato is greater than for any of the major crops surveyed by Daberkow and Gill (1989) and Gill and Daberkow (1991). This is likely due to the wide distribution of potato production within states in a number of tillage management regions, and to the fact that potato production occurs in areas where livestock and forages are also produced. Traditionally, farms with livestock components most favor integration of crop rotation.

Cotton is the dominant crop in the Southern Great Plains and Associated Delta tillage management regions, and also represents a good portion of the cropland planted in California, Arizona, and the Eastern Upland and Coastal Plain Regions (Figure 1) (Allmaras et al., 1991). The potential profitability of cotton results in a strong comparative advantage, to the point that it is generally grown in continuous monoculture. Daberkow and Gill (1989) cite continuous cotton as the most economic cropping practice in the United States. The role of government farm programs in creating comparative advantage for a crop to the point of discouraging crop rotation is illustrated by the fact that on farms

Table 1. Average wheat yield at Rothamsted, England (1851-1919)

Treatment	Yield (kg ha^{-1})
Continuous wheat unfertilized	829
Continuous wheat fertilized	1589
Wheat in a Norfolk rotation (turnip, barley, clover, wheat)	1616
Wheat in a Norfolk rotation fertilized	2183

(From Martin et al., 1976.)

enrolled only in the cotton commodity program, over 75% of the cotton is grown continuously (Gill and Daberkow, 1991). Overall, 61% of the cotton grown in 1990 was grown continuously, 6% used corn in rotation, 4% used soybean in rotation, 8% used a fallow period, 2% used a vegetable crop in rotation, and 11% used sorghum (*Sorghum bicolor* L. Moench) in rotation (Gill and Daberkow, 1991).

Not only is cotton the crop grown most continuously, but 97% of cotton is tilled using conventional-tillage systems (Taylor and Bull, 1992). This reliance on conventional-tillage systems is due in part to requirements by some states to destroy cotton plant residues that can serve as food sources for boll weevils (*Anthonomus grandis* Boheman) and bollworms (*Heliothis* spp.). Twenty-two percent of the acreage planted to cotton in 1991 was on land designated as Highly Erodible Land (HEL) (Taylor and Bull, 1992). The combination of reliance on conventional-tillage on 2.36 million acres of HEL (Taylor and Bull, 1992), and lack of crop rotation indicates a critical area for research that needs to be addressed for this major crop.

With the exception of cotton and irrigated corn in Nebraska, continuous cropping is not the prevalent practice for the major crops grown in the United States (Daberkow and Gill, 1989; Gill and Daberkow, 1991). However, the types of rotations are limited, with only 5 to 10 rotations being used on over 80% of the cropland (Daberkow and Gill, 1989).

IV. Advantages of Crop Rotation

Yield increases were the earliest recognized advantage to crop rotations. Long-term wheat yields from the Norfolk rotation at Rothamsted, England illustrate the positive effect of rotation on crop yield (Table 1) (Martin et al., 1976). This "rotation effect" can be attributed to a number of factors, including a reduction in diseases and pests, more efficient weed control, improved water and nutrient use efficiencies, and improved soil physical properties. The underlying effects of crop rotations to improve yield have long been studied; however, it is only recently that research integrating rotations and residue management strategies has sought to better understand the interactive effects of tillage and residue management with rotations. Benefits from rotations have been attributed in part to the following factors:

A. Disease and Pest Control

Crop rotation has long been advised as a means of control of plant diseases (Leighty, 1938). Disease cycles are disrupted when diverse crop species are grown in sequence. For example, in Australia, a single crop of narrow-leaf or blue lupin (*Lupinus angustifolius* L.) reduced the infection rate of common root rot (*Fusarium* and *Bipolaris* spp.) in wheat compared to wheat in monoculture by approximately half (Reeves, 1984). Likewise, wheat in rotation with lupin reduced *Fusarium* spp. and leaf brown spot [*Pleiochaeta setosa* (Kirchn.) Hughes] infection in lupin (Reeves, 1984). Rotations are an effective method for control of a number of wheat diseases in the Pacific Northwest tillage management region (Cook, 1986).

Nematode control through crop rotation is especially effective. As more chemicals for control of nematodes are removed from the market due to environmental concerns, reliance on crop rotation for nematode control will increase. Kinloch (1983) found that yields of soybean varieties both resistant and susceptible to southern root-knot nematode [*Meloidogyne incognita* (Kofoid and White) Chitwood] were increased when grown in rotation with corn; however, only yields of susceptible varieties declined with reduced length in rotation. Inclusion of bahiagrass (*Paspalum notatum* Flügge) sod in rotation with peanut (*Arachis hypogaea* L.) is an effective control for root-knot [*Meloidogyne arenaria* (Neal) Chitwood] and lance (*Hoplolaimus coronatus* Cobb) nematode (Norden et al., 1977; Rodríguez-Kábana et al.,1988; Dickson and Hewlett, 1989). A 2-year rotation of bahiagrass reduced populations of *M. arenaria* and soybean cyst nematode (*Heterodera glycines* Ichinohe) to undetectable levels in Alabama and increased yield of soybean up to 114% (Rodríquez-Kábana et al., 1991).

Crop rotation is effective in controlling insect pests with narrow host compatibility and short migration distances (Francis and Clegg, 1990). Insects like corn rootworm (*Diabrotica* sp.), corn root aphid (*Anuraphis maidiradicis* Forbes), billbugs (*Sphenophorus* spp.) and wireworms (*Agriotes mancus* Say, *Horistonotus uhlerii* Horn, *Melanotus* spp., and *Aeolus mellillus*) can be controlled using crop rotations (Dicke and Guthrie, 1988; Luna and House, 1990).

Although the benefits of rotation *per se* are well represented in the literature, the interactive effects of rotations and tillage systems is not as well researched. In Alabama, conservation tillage systems (no-tillage and strip-tillage) in combination with a rotation with corn resulted in a consistent soybean yield increase compared to conventional tillage and continuous cropping (Edwards et al., 1988). The increase was due to a build up of soybean cyst nematode under conventional tillage and continuous soybean. In Indiana, sudden death syndrome of soybean (SDS) as a result of *Diaporthe* and *Phialophora* spp. occurred at the rate of 11% in continuous soybean, 6% in a corn-soybean rotation, and 2% in a wheat-corn-soybean rotation (von Qualen et al., 1989). Yield reductions were commensurate with SDS occurrence. In continuous soybean, SDS occurred more frequently with no-tillage than with conventional or chisel tillage. In contrast to these findings, other reports show reductions of some disease organisms with conservation-tillage (Rothrock, 1987; Herman, 1990). In Herman's study, infestation of wheat with take-all [*Gaeumannomyces graminis* (Sacc.) von Arx & Olivier var. *tritici* (Walker)] was greatest following alfalfa under conventional-tillage compared to minimal tillage. However, Herman concluded that tillage as a means of control for take-all was less effective in a crop rotation than in monoculture.

B. Weed Management

Leighty (1938) summarized the impact of crop rotation on weed control when he said "No other method of weed control, mechanical, chemical, or biological, is so economical or so easily practiced as a well-arranged sequence of tillage and cropping." Given an expanded definition of the words "sequence of tillage" as was known in 1938 to include practices involved in residue management known today, these words still ring true. Specific weeds are generally associated with specific crops (Froud-Williams, 1988). Rotation of crops breaks the life cycles of weeds adapted to the narrow ecological niche imposed by continuous cropping. Selective pressures on weeds, including crop competition, pathogens and pests, herbicide tolerance, fertility factors, and tillage, are reduced when rotation is not practiced. Rotation prevents dominance of a relatively narrow range of difficult to control weed species. Rotations are especially effective in controlling crop mimics like shattercane (wild x cultivated *Sorghum bicolor* crosses) in corn and grain sorghum (Francis and Clegg, 1990) and weed beet [*Beta vulgaris* L. ssp. *maritima* (L.) Arc./Thell] in sugarbeet (*Beta vulgaris* L.) (Froud-Williams, 1988).

Reduced tillage and consequent reliance on herbicides for weed control results in reduced weed species diversity but denser populations of highly specialized species, especially annual and perennial grasses (Peterson and Russ, 1982; Froud-Williams, 1988). Thus, the importance of crop rotation as a means of weed control is even greater in reduced tillage systems than in conventional systems.

C. Erosion Control

The development and wide scale use of herbicides and inorganic sources of N during the 1940's moved agriculture away from sod-based or meadow rotations to continuous cropping of row crops. These sod-based or hay-crop rotations are very effective in reducing soil erosion (Leighty, 1938; Mannering et al., 1968; Carreker et al., 1977; Langdale et al., 1991). Obviously, a key factor in residue management strategies is the type of residue left by a preceding crop. Previous crop residues are a major component of the cover and management factor (*C*) of the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978). As an example, the *C* factor for corn mulch, with 40% soil coverage and no-tillage is 0.21 while for soybean mulch under the same conditions it is 0.26 (Wischmeier and Smith, 1978). van Doren, Jr. et al. (1984) found that erosivity of corn-soybean rotation averaged over 18 years was 45% greater than with continuous corn. At equal residue cover, however, no-tillage was as effective in reducing erosion following soybean as following corn. On the Texas High Plains, reduced tillage operations resulted in greater yields of cotton and sorghum (Lacewell et al., 1989). Monoculture cotton and sorghum cropping systems produced the greatest wind erosion and 2- or 3-year rotations with wheat reduced average wind erosion to less than 13.5 Mg ha^{-1} per year.

The interactions of crop residue quantity, quality (C:N ratio), crop sequence, and tillage practices are complex, but conservation-tillage with intensive cropping sequences can dramatically reduce erosion losses (Mills et al., 1986; Langdale and Wilson, 1987). The most intensive cropping systems, i.e., those that maintain a crop year round, involve winter cover crops, either small grain cash crops or winter annual legumes.

D. Soil Physical Conditions

Yield increases arising from crop rotation are often a direct result of increased soil productivity from improvement of soil physical properties. The overall effect of rotation on soil physical properties is influenced by the interactive nature of the quantity and quality of residue produced both above- and below-ground and the management of these residues.

Crop species vary considerably in their ability to modify soil physical and chemical properties. Plant roots exert strong influences on soil conditions and crop species vary considerably in their rooting distribution (Table 2). Uhland (1949) reported that deep-rooted crops such as kudzu [*Pueraria lobata* (Willd.) Ohwi] and alfalfa increased the infiltration rate to a depth of 45 cm compared to cropping with cotton. More recently, Meek et al. (1990) reported that cotton planted with no-tillage and minimum tillage maintained macropores produced by alfalfa, producing high infiltration rates. In Australia, a wheat yield response to rotation with narrow-leaf or blue lupin of 100 kg ha^{-1} was attributed to lupin roots acting as "biological plows" in a compacted soil (Henderson, 1989). Elkins et al. (1977) reported that cotton yields doubled following bahiagrass due to an eight-fold increase in pores greater than 1.0 mm diameter within a compacted soil layer. These examples indicate that rotations have the ability, in some instances, to eliminate tillage operations.

Table 2. Rooting depth and lateral spread of roots for some important agronomic crops

Plant	Maximum rooting depth	Effective rooting depth	Lateral spread
	-----------------	cm	-----------------
Oat (*Avena sativa* L.)	200	150	25
Sugar beet	180	120	45
Turnip	168	150	75
Bermudagrass (*Cynodon dactylon* L.)	245	200	--
Soybean	225	200	50
Barley	195	135	30
Alfalfa	610	300	15
Bahiagrass	245	200	--
Garden pea	90	90	60
Rye	230	150	25
Potato	150	90	40
Sorghum	180	180	60
Wheat	200	150	15
Corn	188	180	100

(From Hanson, 1990.)

Roots affect soil structure by their influence on aggregation. Roots and associated fungal hypae bind large aggregates and root exudates stabilize microaggregates (Monroe and Kladivko, 1987; Habib et al., 1990; Dexter, 1991). Differences in aggregate formation and stability have been reported for different crops. The often reported increase in aggregation following sod crops has been attributed to the high density of roots and consequent water extraction cycles under these crops (Dexter, 1991). In some instances, as with corn, roots have been reported to reduce aggregate stability (Reid and Goss, 1982; Reid et al., 1982). In Kansas, sorghum cropping produced smaller, less dry-stable but more wet-stable aggregates than cropping with wheat (Skidmore et al., 1986). In that study, differences were also noted in other physical properties. Saturated hydraulic conductivity was from five to ten times greater following sorghum than wheat. Although sorghum cropping improved soil tilth characteristics, it also resulted in a high wind erodibility index compared to wheat. Bulk density and soil strength are also affected by cropping sequence and residue management (Carreker et al., 1968; Bruce et al., 1990; McFarland et al., 1990).

Maintenance of soil organic matter is the key to improved soil physical properties. Residue management strategies that increase cropping intensity and reduce incorporation of residues have the greatest impact on soil organic matter (Havlin et al., 1990; Langdale et al., 1990; Wood et al., 1990; Wood et al., 1991; Edwards et al., 1992). Increased soil C is associated with better aggregation, infiltration, and other soil properties that result in a more productive soil.

The literature is extensive regarding the effect of tillage and residue management on soil physical properties. In addition, many reports have dealt with the effect of cover crop-, sod- or meadow-based rotations on soil C and resultant changes in soil physical properties. However, the interactive effects of cropping sequence and tillage/residue management have not been extensively studied. Crookston and Kurle (1989) conducted an experiment to determine the role of crop residues *per se* in providing the "rotation effect". They used a 3-yr sequence of corn and soybean cropping in combination with different residue removal/transfer schemes following grain harvest of both crops to determine if the "rotation effect" was due to the decomposition of above-ground residues. They found that the positive influence of corn preceding soybean and vice versa was not due to the above-ground residues produced by either crop. Bruce et al. (1990) looked at the interaction of crop rotation and tillage on soil physical properties on a Piedmont soil in Georgia. They measured greater sorptivity, aggregate stability, higher air-filled pore space, and lower bulk density after two or more years of sorghum than after soybean. Tillage negated or masked the crop rotation effect on soil physical properties. Grain yield responses of soybean and sorghum were commensurate with changes in soil physical conditions brought about by tillage and crop rotation. On a Ships clay soil (Udic Chromustert) in Texas, reduced soil bulk density in the surface 76-mm following a sorghum-wheat-soybean rotation as compared to continuous soybean or a wheat-soybean rotation was attributed to greater residue production with that cropping sequence. Tillage system, however, had no effect on bulk density (McFarland et al., 1990). At the 100- to 200-mm depth, soil strength was greater in the sorghum-wheat-soybean rotation under conventional tillage compared to no-tillage due to the increased equipment traffic in this intensive cropping system with conventional tillage.

More research needs to be conducted regarding crop rotation-tillage/residue management interactions. A more comprehensive understanding of soil and crop specific responses to crop rotation and tillage/residue management practices is critical to improving economies of production. Griffith et al. (1988), for example, reported that on a low organic matter, poorly drained silt loam soil in Indiana (Typic Ochraqualf), no-tillage compared to moldboard plowing resulted in equivalent yield potential for continuous corn, but increased yield potential when corn was rotated with soybean. The increased yield potential with rotation was linked to improved soil physical conditions. Conversely, on a dark poorly drained silty clay loam high in organic matter (Typic Haplaquoll), continuous corn yields with no-tillage were reduced an average of 9.2% compared to moldboard plowing due to reductions in soil temperature. However, corn yields following soybean with no-tillage were only reduced 2.6% compared to moldboard plowing. On this soil, ridge-tillage and crop rotation produced equivalent yields to corn following soybean that was moldboard plowed. Although more research is needed, the examples discussed here suggest that crop rotation greatly influences the effect of tillage on soil physical conditions and crop response. Tillage can mask crop rotation responses and rotation can alleviate potential adverse effects of reduced tillage on certain soils.

E. Efficient Use of Soil Water and Nutrients

The use of legumes and differences in crop rooting patterns are largely the basis for two principles of crop rotation listed by Pearson (1967), i.e., fertilizer management based on differential crop nutrient use response and efficiency, and the use of a logical sequence and duration of crops. Obviously, the use of a legume in a rotation can affect N fertilizer requirements. The fixation of atmospheric N by legumes is the cornerstone of meadow-based rotations used since before the birth of Christ. The fertilizer-N requirement for a crop following a legume is not necessarily reduced, however, because the yield potential of a crop grown in rotation is often increased, resulting in a response to higher N rates. Crop rotation can increase yield potential and consequent N fertilizer efficiency (Peterson and Varvel, 1989a; Karlen et al., 1991). Nitrogen fertilization minimized differences between continuous vs. rotated (with soybean) grain sorghum yields in Nebraska (Peterson and Varvel, 1989b), and soybean and sorghum grown in a 2-yr rotation maintained high yields without additions of N fertilizer. For an in-depth review of N use efficiency and crop rotation the reader is referred to Pierce and Rice (1988).

Soil nutrients other than N are affected by crop rotation and residue management. Reduced soil disturbance and inversion generally results in a stratification of nutrients (Eckert, 1985; Touchton and Sims, 1987; Dalal et al., 1991; Robbins and Voss, 1991). Root morphology and distribution, as well as rhizophere activity, affect uptake of nutrients. Roder et al. (1989) reported that rooting of both soybean and grain sorghum was reduced following a previous crop of soybean vs. sorghum. Johnson et al. (1992) linked the spore population of mycorrhizal fungi associated with corn or with soybean to reductions in yield and tissue concentrations of P, Cu, and Zn in both crops when either crop followed itself. With no-tillage, crop rotation affected the distribution P, K, Mg, and Ca within the 20-cm depth of an Alfisol in Nigeria (Lal, 1976). Fibrous rooted grass species are generally more effective than tap-rooted species in extracting P (Mays et al., 1980). Conversely, some tap-rooted crops, like white (*Lupinus albus* L.) and blue lupin, can secrete large amounts of organic acids that result in increased availability of P (Gardner and Parbery, 1982; Tadano and Sakai, 1991). This increased P availability can be carried over to succeeding crops grown in rotation (Meredith, 1992). Deep rooting and K extraction by blue lupin improved the K status in the surface 10-cm of a deep sandy soil in Australia, with a subsequent yield response by a following wheat crop (Rowland et al., 1986). The K fertilizer required by a cropping system is dependent on the crops grown in a rotation and the sequence of crops in the rotation determines the time that K should be applied in order to maximize the efficiency of the application (Pretty and Stangel, 1985).

As discussed earlier, tillage/residue management and crop rotation interact with varied influences on soil physical properties, most importantly those that relate to soil water. In semiarid regions the effect of rotation and crop residue management strategies on soil water storage and extraction are critical. In the Southern Great Plains tillage management region, decreasing tillage intensity and increasing surface residues of wheat increased soil water storage which increased sorghum yields (Unger, 1984). Including sunflower (*Helianthus annuus* L.) in the rotation allowed extraction of water deeper within the profile, increasing the total amount of water available for crop production in a fallow-wheat-sorghum-sunflower-wheat rotation. In general, increased soil C, whether from increased surface residues as a result of tillage reductions or from rotations with grasses and legumes, results in greater soil aggregation and infiltration. The end result of these processes is greater soil water storage. Also, the most practical way to increase water use efficiency (WUE) is to increase yield (Pendleton, 1966). Since crop rotations generally increase yield potential, they thus then result in increased WUE.

V. Cover Crops

Pieters (1927) credits Richard Parkinson (1799) as the first person to stress the idea of cover crops. Pieters quotes Parkinson as saying, "... it is seen how earnest my wish is that the surface of the ground should at all times, winter and summer, be well covered, whenever it possibly can be accomplished." Cover crops are defined as crops grown specifically for covering the ground to protect the soil from erosion and loss of plant nutrients through leaching and runoff (Parker, 1915; Pieters and McKee, 1938). Long-term rotations of grass or legume sods have been treated as cover crops in discussions by some workers; however, for the purposes of this chapter, only crops grown in the off-season with an annual planting of a cash crop will be defined as cover crops.

Cover crops are in essence short-term rotations. Traditionally, cover crops were turned under and incorporated before planting of the cash crop; however, the increased emphasis on residue management as a means for reducing soil erosion has led to greater use of cover crops in conservation-tillage systems. Also, in tillage management regions with more than 180 continuous frost-free days, double-cropping a summer crop behind a small grain winter crop is possible (Allmaras et al., 1991). The small grain winter crop thus serves dual purposes, i.e., as a cash crop and as a cover crop.

In residue management systems, a cover crop must meet certain requirements: i) it should be easy to establish; ii) it should have a rapid growth rate so as to provide ground coverage quickly; iii) it should produce a sufficient quantity of dry matter for maintenance of residues; iv) it should be disease resistant and not act as a host for diseases of the cash crop; v) it should be easy to kill; vi) it must be economically viable. The degree that a specific cover crop meets these specifications is dependent on the soil, climate, and succeeding cash crop, as well as characteristics of the cover crop itself.

During the early part of the twentieth century in the United States, in addition to winter cover crops, summer annuals like cowpea, soybean, and velvetbean [*Mucuna deeringiana* (Bort) Merr.] were grown as green manures to be turned under at the end of the season for soil improvement (Pieters, 1927). Currently, only winter-season cover crops are currently used in temperate and subtropical zone cropping systems. Both legumes and grasses (small grains) are used as winter cover crops. Many of the advantages and disadvantages of cover crops are common to both small grains and legumes. Where differences in effects from the two types of covers occur, they are largely related to fixation of N by legumes and resultant differences in N content of residues between the two groups of cover crops.

A. Small Grain Cover Crops

For small grain covers, the residue N content depends on soil N availability, which is dependent on the amount of residual soil N as well as the mineralization rate (Wagger and Mengel, 1988). Residual N is mainly dependent on previous crop N utilization. In addition, the overall growth rate and stage of phenological development that the cover is terminated greatly influences the N uptake of small grain cover crops. Nitrogen content of small grain cover crop residues varies greatly, but generally ranges from 25 to 50 kg N ha^{-1} (Table 3). Often overlooked in reports of N uptake by cover crops is the amount of N present in root residues. For small grains, reports of N present in roots range from 8 to 42% of total N uptake by the cover (Mitchell and Teel, 1977; Scott et al., 1987; Reeves et al., 1993). The C:N ratio of small grain residue is mostly dependent on total dry matter produced and time of termination. Early termination of the cover results in a narrower C:N ratio in the residue, but the total residue produced is reduced. If killed too early, the narrower C:N ratio results in rapid decomposition of the residue, reducing ground coverage. In practice, however, small grain cover crops are usually killed at a stage of development that results in a wide C:N ratio, usually exceeding 30:1 (Table 3). This wide C:N ratio results in an initial, if not persistent, immobilization of N during the cropping season (Aulakh et al., 1991; Doran and Smith, 1991; Somda et al., 1991; Torbert and Reeves, 1991).

Initially, the potential for denitrification and immobilization of N is frequently greater with no-tillage than for conventional-tillage (Doran 1980a; Doran 1980b; Rice and Smith, 1984). This coupled with the wide C:N ratio of small grain cover crop residues dictates the importance of proper N management in these type systems. The use of starter fertilizer to supply 25 to 30 kg N ha^{-1} to crops planted with conservation-tillage behind small grain cover crops has been shown to be a good management practice (Reeves et al., 1986; Touchton et al., 1986;

Table 3. Nitrogen content of small grain cover crops

Cover crop	N content (average)	C:N	Reference
	kg ha^{-1}		
Wheat	--	82	Aulakh et al., 1991
	--	97	Somda et al., 1991
	74	--	Decker et al., 1987
	32	22[b]	McVay et al., 1989
	21[a]	18[b]	Scott et al., 1987
Barley	69	--	Decker et al., 1987
Rye	100	25[b]	Hoyt, 1987
	42[a]	29[b]	Reeves et al., 1993
	42[a]	26[b]	Scott et al., 1987
	85	35	Wagger, 1989
	60[a]	40	Mitchell and Teel, 1977
	24	--	Brown et al., 1985
	36	38[b]	Ebelhar et al., 1984
	14	57[b]	Blevins et al., 1990
	38	42[b]	Hargrove, 1986
	13	54	Huntington et al., 1985

--, Data not available; [a]includes roots; [b]calculated at C=40% dry matter.

Hairston et al., 1987; Reeves et al., 1990; Howard and Mullen, 1991). Although yield increases from starter N applications are dependent on rainfall, accompanying tillage to disrupt compacted soil layers, and crop, they occur frequently enough to justify the practice. In addition, early-season growth of the cash crop is almost always enhanced with starter N applications, providing more rapid canopy coverage of row middles, lessening weed competition.

B. Legume Cover Crops

The N content of legume cover crop residues varies with species, residual soil N, adaptability to specific soil and climatic conditions, and time of termination of growth. Nitrogen contents of a number of winter legume cover crops are listed in Table 4. The values reported in Table 4 are averaged across sites, years and management practices for each reference. In these cases, the N content ranged from 36 to 226 kg ha^{-1}, with the average N content of above-ground residues being 120 kg ha^{-1}. The C:N ratio varied from 25:1 to 9:1, but in all but two reports, the ratio is well below 20:1, the guideline threshold where rapid mineralization of the N in the residue would occur.

In most studies, the N content of root residues has not been determined. In Virginia experiments, roots of an Austrian winter pea (*Pisum sativum* L.) cover

Table 4. Nitrogen content of legume cover crops (values averaged for studies over years, locations, and management practices)

Cover crop	N content	C:N[a]	Reference
	(kg ha^{-1})		
Arrowleaf clover	131	15	Fleming et al., 1981
(*Trifolium vesiculosum* L.)			
Austrian winter pea	161	11	Hoyt, 1987
	68	9	Neely et al., 1987
Berseem clover	67	16	McVay et al., 1989
(*Trifolium Alexandrinum* L.)			
Bigflower vetch	67	13	Blevins et al., 1990
(*Vicia grandiflora* Scop)	60	13	Blevins et al., 1990
	134	10	Hargrove, 1986
Common vetch	85	23	Touchton et al., 1984
(*Vicia sativa* L.)	153[b]	16	Reeves et al., 1993
Crimson clover	170	17	Hargrove, 1986
	108	13	McVay et al., 1989
	88	11	Brown et al., 1985
	126	15	Wagger, 1989
	56	17	Ebelhar et al., 1984
	114	11	Neely et al., 1987
	129	15	Hoyt, 1987
	94	25	Touchton et al. 1984
	163	16	Fleming et al., 1981
	103	13	Blevins et al., 1990
Hairy vetch	104	15	Brown et al., 1985
	209	10	Ebelhar et al., 1984
	158	9	Hoyt, 1987
	125	13[c]	Huntington et al., 1985
	128	11	McVay et al., 1989
	127	9	Neely et al., 1987
	36	8	Power et al., 1991
	161	10	Wagger, 1989
	114	14	Hargrove, 1986
Subterranean clover	226	19	Reeves and Mask, 1992
White lupin			

[a]Calculated as C=40% dry matter; [b]includes roots; [c]actual value reported.

crop contained 47 kg N ha^{-1}, crimson clover (*Trifolium incarnatum* L.) roots 77 kg N ha^{-1}, vetch (species not reported) roots 118 kg N ha^{-1}, and ryegrass (*Lolium multiflorum* Lam.) roots 138 kg N ha^{-1} (McVickar et al., 1946). The soil core technique used to measure roots in this study probably over-estimated the N content of the roots. It is unlikely that ryegrass roots, for example, contained

79% of the total amount of N in the plant as reported. Reeves et al. (1993) reported that 16% of the N in a crimson clover cover crop was found in roots. Mitchell and Teel (1977) reported that 9 to 13% of the N in small grain-legume cover crop mixes was found in roots. The fraction of N in nonharvested roots and crowns of alfalfa, red clover and birdsfoot trefoil (*Lotus corniculatus* L.) forages preceding a corn crop was reported to be 31, 22, and 26%, respectively, of the total plant N (Sheaffer et al., 1991). Kirchmann (1988) reported considerable species variation in the total amount of N partitioned to roots of red clover, white clover (*T. repens* L.), Persian clover (*T. resupinatum* L.), black medic (*Medicago lupulina* L.), Egyptian clover (*T. alexandrium* L.) and subterranean clover (*T. subterranean* L.). The fraction of the total amount of N found in the roots varied from 3% in Persian clover to 45% in white clover. The contribution of N in roots of legume cover crops is not insignificant, and more research needs to be conducted as to the role N from roots plays in residue management strategies.

Management factors strongly influence the N content of legume cover crops and the contribution of N available to the following cash crop. Practices that promote early establishment, i.e., early planting, interseeding, or natural reseeding, result in greater dry matter and consequent N production (Brown et al., 1985; Oyer and Touchton, 1990). The time of termination of the cover crop also affects the N content of the residues. Wagger (1989) reported that delaying the kill date of rye (*Secale cereale* L.) 2 weeks beyond anthesis, crimson clover 2 weeks beyond 50% bloom, and hairy vetch (*Vicia villosa* Roth) 2 weeks beyond 25% bloom increased cover crop dry matter of rye by 39%, clover 41%, and vetch 61%. Corresponding increases in N content were 14% for rye, 23% for clover, and 41% for vetch.

Of primary importance is the use of an adapted species to the tillage management region. The use of winter annual legumes cover crops is limited by extremes in minimum temperature in the northern United States and by their competition with the cash crop for soil water in the western United States. Limited research has shown there is potential for use of winter annual legume cover crops in rotations in semiarid and northern temperate environments (Auld et al., 1982; Badaruddin and Meyer, 1989; Gilley et al., 1989; Power, 1991; Power et al., 1991). In these areas, however, legumes are utilized in the higher rainfall areas and are mainly used as substitution for fallow in rotations. Tillage management regions with the greatest potential for using winter annual legume cover crops are the Coastal Plain, Piedmont, Associated Delta, Eastern Uplands, and Southern Corn Belt (Figure 1).

Crimson clover and hairy vetch are time-proven legume cover crops. They represent the standards by which other species are compared in most research. Crimson clover is earlier to produce maximum dry matter and seed than hairy vetch but it is not as cold hardy. Dry matter production is the major determining factor in N production by winter legume cover crops (Holderbaum et al., 1990). The transition zone where performance of hairy vetch surpasses that of crimson clover corresponds to the plant hardiness zone where the average annual

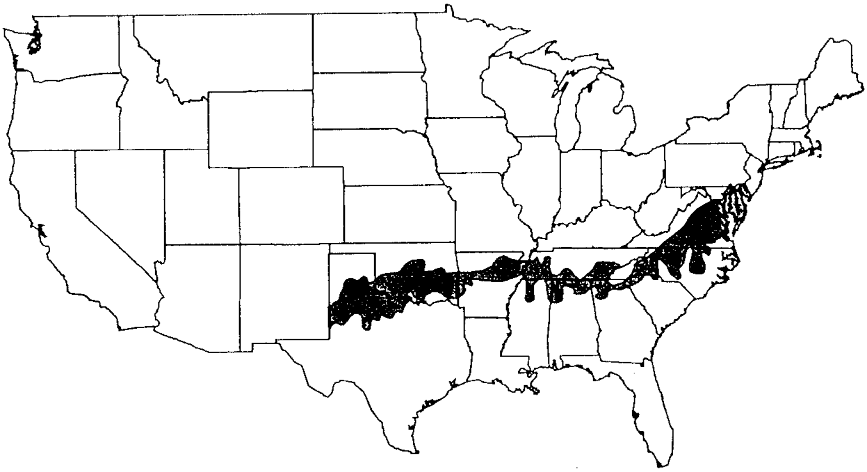

Figure 2. Transition zone for the adaptability of hairy vetch and crimson clover cover crops. The average annual minimum temperature in the zone is –15 to 17.7°C. Hairy vetch is more reliable than crimson clover north of this zone. (Adapted from USDA Plant Hardiness Map, 1990.)

minimum temperature is -15 to -17.7°C (5 to 0°F) (Figure 2). North of this zone, hairy vetch performs better while south of this zone the earlier growth of crimson clover gives it an edge over hairy vetch. Soil factors also play a role in adaptability of legume cover crops. Crimson clover performed better in Tennessee on poorly drained soils and on well limed soils than hairy vetch, but hairy vetch and subterranean clover were more tolerant of soil acidity (Duck and Tyler, 1987).

C. Nitrogen Fertilizer Equivalence

The N contribution from small grain cover crops generally is negative (Brown et al., 1985; Wagger, 1989; Reeves and Touchton, 1991a; Torbert and Reeves, 1991) due to the wide C:N ratio of the residue. Nitrogen fertilizer equivalence for legume cover crops has been extensively reviewed (Hoyt and Hargrove, 1986; Smith et al., 1987; Frye et al., 1988). Nitrogen fertilizer equivalences reported in these reviews ranged from 15 to 200 kg ha^{-1}, with the typical values being about 60 to 100 kg ha^{-1}.

The N contribution is dependent on environmental and management factors that affect the amount of dry matter produced by the cover crop as well as the environmental and management factors that influence the yield potential of the cash crop. Conditions that increase the yield potential of the cash crop will increase the response to N. The N contribution from the legume to the cash crop is generally calculated as the N fertilizer needed following a small grain cover crop (or no cover crop) to obtain a yield equivalent to that following the legume cover crop without N fertilizer. Although practical, this method of calculating N contribution from the cover crop does not discriminate between the N contribution effect of the cover crop and other effects of the cover crop (Smith et al., 1987; Frye et al., 1988). As will be discussed later, cover crop effects that influence yield of following crops include changes in rooting, soil structure, soil water, soil temperature, weed control, etc. Smith et al. (1987) suggests that N accumulation differences rather than yield would be a better indicator of N contribution of the cover crop. Hargrove (1986) suggested that grain N content of the following crop is a more appropriate measure of the N contribution of the cover crop. Russelle et al. (1987) proposed a method of discriminating between N contribution and other, i.e., rotation, effects by using yield-N uptake response curves of a crop grown continuously and N uptake of the crop with and without rotation with a legume. Although the method requires some assumptions, it is practical and does not require the use of N isotopes to determine N contribution of a legume to a following crop.

Only a few studies with ^{15}N have been used to determine the contribution of legume crop residues to following crops. In pot and field studies, recovery of labeled legume residues has ranged from 5 to 28% (Norman and Werkman, 1943; Ladd et al., 1983; Azam et al., 1985; Westcott and Mikkelsen, 1987). There is a real scarcity of isotopic research dealing with the effect of tillage on availability of legume cover crop N. The primary work in this area was done in Kentucky with ^{15}N labeled hairy vetch (Varco et al., 1989). Recovery of vetch ^{15}N by a succeeding corn crop averaged 32% with conventional tillage and 20% with no-tillage. Residual ^{15}N recovery the second year after labeled legume residue was applied to plots was 7% with no-tillage and 3% with conventional tillage.

Incorporation of legume cover crop residues results in more rapid mineralization than when residues are left on the soil surface (Wilson and Hargrove, 1986; Groffman et al., 1987); consequently, legume-residue N may not be available to the succeeding grain crop during the early part of the growing season. In Kentucky, the majority of N mineralized from decomposing residues of hairy vetch left on the soil surface did not become available to corn grown with no-tillage until after silking (Huntington et al., 1985). In another study, N uptake prior to silking was greater with conventional tillage; however, the potential for greater uptake of N from hairy vetch residues during grain fill of corn was found to be greater, dependent on rainfall, with no-tillage than with conventional tillage (Varco et al., 1989). Due to the initial lag in availability of N from legume cover crop residues, fertilizer N applications should be applied at planting in conservation-tillage winter annual legume systems (Reeves et al., 1993). Splitting N applications to corn grown in these systems, as is generally recommended for conventional-tilled corn grown without legume cover crops, is not necessary (Reeves et al., 1993).

D. Benefits of Cover Crops

1. Improved Soil Physical Conditions

Strictly speaking, cover crops are grown to protect the soil from erosion and loss of plant nutrients while green manures are crops that are grown with the purpose of improving soil productivity. Green manures have traditionally been incorporated. In reality, however, the use of cover crops in residue management strategies offers benefits often attributed to green manures. Cover crops affect soil physical properties primarily due to the production of biomass which serves as the source of soil organic matter and substrate for soil biological activity (Bruce et al., 1991) . As discussed previously, certain crops can also physically modify the soil profile (Uhland, 1949; Elkins et al., 1977; Kemper and Derpsch, 1981; Wilson et al., 1982; Henderson, 1989; Meek et al., 1990), as well as affect soil structure through their influence on soil aggregation (McVay et al., 1989; Dexter, 1991).

It is well established that cover crops can maintain or increase soil C and N (Pieters and McKee, 1938; Lewis and Hunter, 1940; Wilson et al., 1982; Hargrove, 1986; Utomo et al., 1987; McVay et al., 1989; Keisling et al., 1990). The benefits of cover crops in maintaining or increasing soil organic matter are negated with tillage (Utomo et al., 1987). Increased soil C is largely responsible for the changes in physical properties associated with cover crops. The most important agronomic factor affected is associated with soil water relationships. Cover crops frequently result in greater infiltration of water, due to direct effects of the residue coverage or to changes in aggregation and formation of macropores by roots.

In Alabama, after 5 years of stripped-tilled corn, a reseeding crimson clover cover crop increased the percentage of water stable aggregates over winter fallow from 44% to 55% on an Appalachian Plateau soil (Typic Hapludult), and from 40% to 49% on a Coastal Plain soil (Typic Kandiudult) (D. W. Reeves, unpublished data). Similar results were reported for a Piedmont soil in Georgia (Bruce et al., 1992). After 5 years, average water stability of aggregates in the 0- to 15-cm depth with no-tillage grain sorghum planted into crimson clover residue was 53% greater than with conventional-tillage grain sorghum following winter fallow and 44% greater than with conventional-tillage soybean after winter fallow. A previous report from this site showed that grain sorghum grown with no-tillage in combination with a crimson clover cover crop resulted in 89% water-stable aggregates while conventional tillage without a cover crop resulted in 58% water-stable aggregates (Bruce et al., 1991). On a Limestone Valley soil (Typic Hapludult) in Georgia, cover crops had no effect on percentage water-stable aggregates, but on a Coastal Plain soil (Rhodic Paleudult) cover crops increased the percentage of aggregates (McVay et al., 1989). Legume cover crops (hairy vetch and crimson clover) tended to increase aggregate stability more than a wheat cover crop. Increased soil organic matter and aggregation with cover crops as opposed to fallow is the result of increased biomass production. This increased biomass production is generated by the cover crop itself, as well as the indirect effect of the cover crop in increasing biomass yield of the following cash crop.

Increases in soil porosity due to the action of roots, especially under reduced tillage conditions, are frequently cited as the cause of greater infiltration. In addition, cover crop residues left on the soil surface reduce surface sealing of soils, increasing infiltration. In Brazil, a range of cover crops including winter annual legumes and rape *(Brassicas* spp.) increased infiltration rates on Oxisols up to 416% and up to 629% on Alfisols compared to wheat stubble (Kemper and Derpsch, 1981). The infiltration increase was attributed to biological loosening by the cover crop root system. In the Georgia Piedmont, infiltration rate, averaged across a slightly, moderately, and severely eroded site, measured after 4 or 5 yr of no-till grain sorghum planted into a crimson clover cover crop was 100% greater than planting either grain sorghum or soybean with conventional tillage following winter fallow (Bruce et al., 1992). Wilson et al. (1982) reported that a number of cover crops increased infiltration and macroporosity on an eroded Alfisol in Nigeria. Legume covers were especially effective. On a Coastal Plain soil in Georgia, infiltration in no-tillage grain sorghum (measured using a sprinkling infiltrometer) averaged 58.4 mm h^{-1} following a hairy vetch cover crop, 42.3 mm h^{-1} following wheat cover, and 37.8 mm h^{-1} following winter fallow (McVay et al., 1989). The measurements were made after 3 years of cropping. Hairy vetch also increased infiltration compared to winter fallow in a no-tillage corn system on a Limestone Valley soil. Similar results showing the benefit of winter legume cover crops with no-tillage cotton are seen in Figure 3 (Touchton et al., 1984). In contrast, on an Aquic Paleudult in North Carolina, Wagger and Denton (1989) found no differences in soil porosity and saturated hydraulic conductivity (K_{sat}) due to cover crops of wheat and hairy vetch compared to winter fallow in a strip-tillage corn experiment. In untrafficked interrows, however, there was a nonsignificant trend for higher K_{sat} with cover crops, especially wheat. Coefficients of variation were high in this experiment, making it difficult to separate treatment differences among cover crops. In Alabama, a crimson clover cover crop increased K_{sat} of undisturbed soil cores (6-cm depth) from a 5-year experiment with strip-tilled corn 342% on a Typic Hapludult and 214% on a Typic Kandiudult compared to winter fallow (D.W. Reeves, unpublished data). In Arkansas, Keisling et al. (1990) measured K_{sat} of a Typic Hapludalf-Aeric Ochraqualf soil association that had been cropped to cotton for 17 years with and without winter cover crops. A rye-hairy vetch cover crop increased K_{sat} 166% in the 0 to 5 cm-depth, 194% in the 5 to 10 cm-depth, and 359% in the 10 to 15 cm-depth compared to no cover crop. The increase in K_{sat} with depth in this experiment was likely due to incorporation of cover crop residue, as the cotton was conventionally-tilled.

Cover crops also affect soil bulk density and soil strength. Since roots occupy the soil space previously occupied by soil pores, they must displace soil particles, increasing the bulk density of soil adjacent to the root (Glinski and Lipiec, 1990). However, as roots die and decompose they leave macropores in

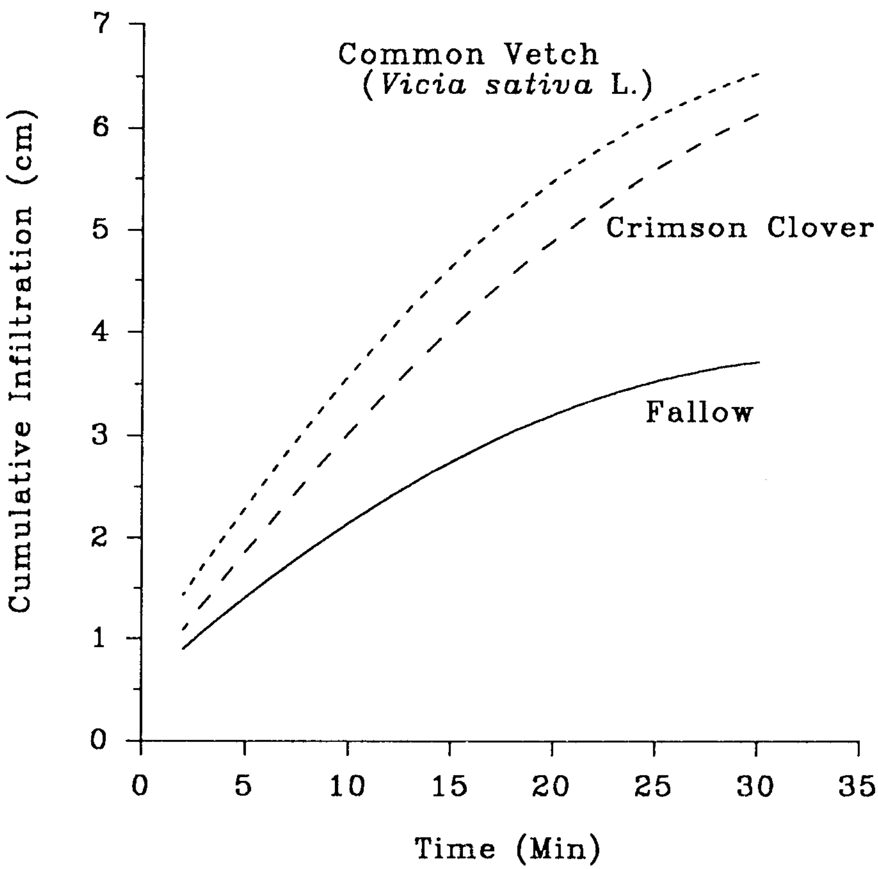

Figure 3. Effect of winter cover crop on cumulative infiltration (ring infiltrometer) following 2 years of no-tillage cotton grown on a Typic Paleudult. (From Touchton et al., 1984.)

the soil. Root fabric increases the bearing capacity of soils in no-tillage and can thus reduce the compactive effects of equipment traffic. Also, increased soil aggregation from below- and above-ground residues can improve soil structure and reduce soil bulk density and soil strength. The result of these processes alters soil strength and bulk density dependent on soil type, crop grown, and residue management system. Wagger and Denton (1989) reported a nonsignificant trend for wheat and hairy vetch cover crops to increase bulk density in the in-row position which had been subsoiled prior to planting corn. They attributed the increased bulk density, as compared to winter fallow, to the cover crops depleting soil water and interfering with soil fracturing with the subsoiler shank. A falling-plunger type penetrometer was used to measure the penetration resistance in corn, cotton, and peanut plots with and without a hairy vetch cover crop on a Coastal Plain soil in North Carolina (Lutz et al., 1946; Welch et al., 1950). In all crops, the penetration resistance (depth of penetration) was greater following the vetch cover crop and the depth of penetration was correlated to soil porosity. In contrast, researchers in Alabama found soil strength in the 6- to 18-cm depth measured at the end of the growing season was 0.3 to 0.5 MPa greater in corn plots planted behind rye and crimson clover cover crops compared to a planting behind a white lupin cover crop or winter fallow (Reeves and Touchton, 1991b). The penetrometer readings were taken when the soil was saturated after the corn had matured, so differences in soil strength between cover crops were residual in nature and were not due to differences in cover crop water use. In Nigeria, bulk density of an Alfisol increased from 1.00 g cm^{-3} under 15 years of secondary forest growth to 1.50 g cm^{-3} after 5 years of cultivation (Wilson et al., 1982). Following 5 years of cultivation, the area was cropped for 2 years using a number of grass and legume cover crops. Grass cover crops reduced bulk density to 1.33 g cm^{-3} and legume covers reduced bulk density to 1.29 g cm^{-3}. In the cotton experiment of Keisling et al. (1990) in Arkansas, bulk density in the 5- to 10-cm depth following a rye-hairy vetch cover crop averaged 1.39 g cm^{-3} compared to 1.29 g cm^{-3} without a cover crop. Bulk densities at the soil surface, and at the 10- to 15-cm depth were similar. In Alabama, neither tillage system (combinations of fall or spring disking or no-tillage) nor cover crops (rye, hairy vetch, crimson clover, or winter fallow) affected infiltration or bulk density on a Typic Paleudult cropped to cotton (Brown et al., 1985).

2. Soil Erosion Control

A cover crop by definition is sown for the purpose of erosion control (Parker, 1915). The value of soil coverage by vegetation is illustrated by the pioneering work from the Missouri Agricultural Experiment Station which showed that a continuous bluegrass (*Poa pratensis* L.) sod reduced annual erosion from 91.8 Mg ha^{-1} on bare soil to 0.7 Mg ha^{-1} with sod (Miller, 1936). This rate of loss under vegetative cover would require over 3,500 years to erode the 18 cm of surface soil on this site (Shelby loam with 3.7% slope) compared to 56 years with continuous conventional-tilled corn cultivation (Enlow and Musgrave, 1938). Cover crops reduce erosion by improving soil structure and increasing infiltration, protecting the soil surface and dissipating raindrop energy, reducing the velocity of water that moves over the soil surface (Smith et al., 1987), and by anchorage of soil by roots. The benefits of cover crops in reducing wind and water erosion and in improving productivity of eroded soils have been recently reviewed (Bruce et al., 1987; Smith et al., 1987; Langdale et al., 1991). Moreover, residue management strategies and erosion control are dealt with in another chapter of this book (see Langdale et al.).

The complementary effect of cover crops used in conjunction with conservation-tillage has been well established in recent research. The importance of the cover crop *per se* in reducing erosion relative to tillage system effects, increases as the amount of previous crop residue decreases. For example, calculated annual soil losses, based on the universal soil loss equation (USLE), of a Maury soil with a 5% slope in Kentucky were 18 Mg ha^{-1} under conventionally tilled corn with corn residue and cover crop turned under in the spring, 2.2 Mg ha^{-1} for no-tillage without a cover crop but 6.7 Mg ha^{-1} of corn residue returned to the soil surface, and 2.0 Mg ha^{-1} for no-tillage with a winter cover crop (Frye et al., 1985). Contrast these values to those reported in a Missouri study where no-tillage corn grown for silage resulted in an annual soil loss of 22.0 Mg ha^{-1} (Wendt and Burwell, 1985). Inclusion of a rye or wheat cover crop reduced soil loss to 0.9 Mg ha^{-1}.

Compared to corn, cotton does not produce large quantities of residue. Approximately 1/3 to 1/2 of modern cotton cultivar dry matter is accumulated in stems and burs (Mullins and Burmester, 1990), the plant parts that can be returned to the soil surface and that don't decompose readily. Consequently, cotton generally produces about 2 to 3.5 Mg ha^{-1} of over-wintering residues. In Mississippi, studies on two Typic Fragiudalfs with 5% slopes reported an annual soil loss of 74.2 Mg ha^{-1} for conventional-tilled cotton (Mutchler and McDowell, 1990). Inclusion of a wheat or hairy vetch cover crop reduced losses to 20.4 Mg ha^{-1}. No-tillage cotton averaged 19.2 Mg ha^{-1} soil loss without a cover crop and 2.3 Mg ha^{-1} with a cover crop. A winter cover crop used in combination with no-tillage or reduced tillage (no-till plant but with 3 cultivations on cotton) was the only management strategy that reduced erosion below tolerance levels (11 Mg ha^{-1} yr^{-1}). The development of improved management strategies for cover crops used in cotton production should be a high priority research focus, since the potential to reduce erosion is so great with this crop.

3. Environmental Quality

The use of cover crops to increase infiltration and reduce erosion also reduces nutrient losses in surface run-off. Nitrogen and phosphorus are the two nutrients most associated with degradation of water quality arising from agriculture (Logan, 1990). Loss of P to the environment is associated with surface runoff while loss of N is primarily through leaching losses of NO_3-N to groundwater.

Sharpley and Smith (1991) recently reviewed the effect of cover crops on surface water quality. They noted that use of a cover crop in various cropping systems consistently decreased N and P transported in runoff (Table 5). Although the amount of N and P transported in runoff is generally reduced with a cover crop, the mean annual concentration of NO_3-N and soluble P may be increased. The proportion of P in runoff that is bioavailable (soluble P plus bioavailable particulate P) may increase when cover crops are included in a residue management system. Management factors such as soil fertility level, residue management system, cover crop type, and growth stage of termination of cover crops in relation to climatological factors influence not only the amount of N and P transported in runoff but the relative proportion of these nutrients that are bioavailable. Sharpley and Smith point out that determination of bioavailable P, not just total P loading, is essential to more accurately estimate the impact of agricultural practices, including the use of cover crops, on eutrophication of surface waters (Sharpley and Smith, 1991).

During the early 1940's scientists investigated the role of cover crops to reduce losses of N via leaching. The motivation for this work was economical, i.e., more efficient use of N fertilizer. Today, concern over environmental contamination of groundwater supplies has triggered a resurgence of interest in the use of cover crops to reduce NO_3-N leaching. Recently, Meisinger et al. (1991) compiled an excellent comprehensive review of the literature concerning the ability of cover crops to reduce NO_3-N leaching. Certain facts were well established in the authors' careful review. Cover crops reduce N leaching primarily by uptake of N for production of biomass; however, reducing leachate by consumption of soil water for growth is also an important mechanism for reducing N leaching. Another factor important to a cover crop's ability to reduce N leaching is the synchronization of cover crop growth and consequent soil water and N demand with the peak leaching season, i.e., in late fall through early spring when precipitation exceeds evapotranspiration.

Averaged over the eleven studies reviewed by Meisinger et al. (1991), the effectiveness of cover crops to reduce N leaching was grasses = brassicas > legumes (Table 6). Cereal rye was very effective in reducing N leaching. This cover crop is cold tolerant, has rapid growth, and produces a large quantity of biomass. Although grasses are effective catch crops in regards to N, their wide C:N ratio results in immobilization of nitrogen, increasing the fertilizer N requirement of following crops. As Meisinger and coauthors pointed out, brassicas are equally effective in reducing the mass of N lost through the root zone; however, brassica cover crops have a much narrower C:N ratio than grass cover crops. For example, the C:N ratio for rape (*Brassica napus* L.) and radish (*Raphanus sativus* L.) reported in two studies was 20:1 or less (Muller et al., 1989; Hargrove et al., 1992). This low C:N ratio would result in substantial mineralization of N to a crop following a brassica cover crop. Brassica cover crops, however, are harder to establish, are more susceptible to plant diseases, and are not as widely adapted to a variety of climatic conditions and soils as grass cover crops. Legume cover crops, as pointed out earlier, can supply N to a following crop, but typically recover only 20 to 30% of the mass of N recovered by grass or brassica cover crops (Meisinger et al., 1991; Shipley et al., 1992).

Simulations using the EPIC (Erosion-Productivity Impact Calculator) model (Williams et al., 1984) show that the greatest potential use of cover crops to reduce NO_3 leaching impacts on water quality in the United States is in the Southeast and irrigated Midwest because of the potential for vigorous growth of cover crops in the fall and winter in these areas (Meisinger et al., 1991). These

Table 5. Effect of cover crops and residue management system (RMS) on N and P transport

Crop/RMS[a]	Cover crop	Nitrate-N[b]	Total N	Soluble P[b]	Total P	Location	Reference
		--------------------kg ha^{-1} yr^{-1}	-------------------				
Corn/CT	None	0.36 (8.78)	0.95	0.01 (0.40)	0.15	MD	Angle et al., 1984
Corn/NT	Barley	0.04 (5.88)	0.12	0.01 (1.65)	0.01		
Corn/CT	None	2.46 (0.41)	--	0.49 (0.28)	--	NY	Klausner et al., 1974
Corn/NT	Ryegrass	1.41 (3.62)	--	0.13 (0.33)	--		
Wheat/CT	None	1.14 (0.66)	--	0.32 (0.28)	--		
Wheat/NT	Ryegrass/alfalfa	0.93 (1.26)	--	0.17 (0.23)	--		
Corn/CT	None	--	--	0.28 (0.13)	4.08	GA	Langdale et al., 1985
Corn/CT	Cereal rye	--	--	0.30 (0.20)	1.39		
Corn/CT	None	0.40 (0.81)	0.48	0.27 (0.55)	3.02	Quebec	Pesant et al., 1987
Corn/NT	Alfalfa/timothy (*Phleum pratense* L.)	0.58 (3.24)	0.59	0.24 (0.22)	0.19		
Cotton/CT	None	3.44 (3.87)	4.11	0.40 (0.43)	0.63	AL	Yoo et al., 1988
Cotton/NT	None	1.40 (1.73)	3.10	0.31 (0.39)	0.44		
Cotton/NT	Wheat	0.56 (1.12)	0.88	0.16 (0.39)	0.20		

Soybean/NT	None	3.36 (4.04)	--	0.46 (0.28)	--	MO	Zhu et al., 1989
Soybean/NT	Common chickweed (*Stelleria media* L.)	0.77 (1.86)	--	0.17 (0.45)	--		
Soybean/NT	Canada bluegrass (*Poa compressa* L.)	0.88 (1.92)	--	0.43 (0.80)	--		
Soybean/NT	Downy brome (*Bromus tectorum* L.)	0.84 (2.06)	--	0.27 (0.52)	--		
Peanut/CT	None	0.15 (0.50)	4.38	0.04 (0.14)	1.35	OK[c]	Sharpley and Smith, 1991
Peanut/CT	Ryegrass	0.08 (0.73)	1.49	0.02 (0.19)	0.47		
Peanut/CT	None	0.35 (0.29)	20.84	0.15 (0.12)	5.89	OK[c]	Sharpley and Smith, 1991
Peanut/CT	Wheat	0.19 (0.75)	3.27	0.04 (0.15)	0.92		

--, Data not available; [a]CT = Conventional tillage, NT=No-tillage; [b]Values in parentheses are mean annual concentrations in mg kg^{-1}; [c]Amounts of N and P transported in OK experiments for 6-month winter period.
(From Sharpley and Smith, 1991.)

Table 6. Percentage reduction of mass of N leached for types of cover crops

Cover crop	*Range*	*Average*	*Reference*
Grasses	31 to 77 %	61%	Morgan et al., 1942 Martinez and Guirard, 1990 Karraker et al., 1950 Meisinger et al., 1990 Staver and Brinsfield, 1990 Nielsen and Jensen, 1985
Brassicas	35 to 87%	62%	Chapman et al., 1949 Volk and Bell, 1945 Muller et al., 1989 Bertilsson, 1988
Legumes	6 to 45%	25%	Chapman et al., 1949 Nielsen and Jensen, 1985 Jones, 1942 Meisinger et al., 1990

(From Meisinger et al., 1991.)

simulations also agreed with the published literature that grasses were superior to legumes as catch crops for nitrogen.

E. Potential Disadvantages of Cover Crops

1. Establishment Costs

There are a number of potential disadvantages to using a cover crop. Fortunately, proper management techniques can decrease the negative effects of cover crops, increasing their acceptance by growers. Foremost among disadvantages is the fact that it costs money to plant the cover crop and to terminate the cover before planting the cash crop. The particular economic situation is dependent on the cash crop grown; cover crop chosen; time and method of establishment, method of termination; and the cash value applied to the environment, soil productivity and soil protection benefits derived from the cover crop. In Alabama, for example, the labor and equipment cost to plant a cover crop is estimated to be about \$12.25 ha^{-1} (Crews, 1992). Using lower limits of recommended seeding rates, at the time of this writing, seed costs for a rye cover crop seeded at 67 kg ha^{-1} would be \$19.76 ha^{-1}, for ryegrass seeded at 56 kg ha^{-1} \$39.52 ha^{-1}, for "Tibbee" crimson clover seeded at 22 kg ha^{-1} \$44.46 ha^{-1}, and for hairy vetch seeded at 34 kg ha^{-1} \$41.99 ha^{-1}. In this example then, the cost of establishment of a cover crop would range from \$32.01 ha^{-1} for rye up to \$56.70 ha^{-1} for "Tibbee" crimson clover. The increased cost of the legume over rye can be offset by the value of the N fertilizer equivalence from the legume, 60 kg N ha^{-1} being a good estimate. It is not unreasonable to estimate that the N fertilizer requirement for a crop following a rye cover crop terminated at a late stage of growth would be increased by 25 kg N ha^{-1} due to immobilization of N by rye residue with a wide C:N ratio. Thus, the difference in cost between a rye cover crop and a legume cover crop would be offset by the value of 85 kg N ha^{-1}. At a price of \$0.57 kg^{-1} for fertilizer N, this differential is worth \$48.45. Ignoring considerations other than seed costs and fertilizer equivalence, legume cover crops are more profitable than grass cover crops. However, the economic risk of establishment is less with rye than with legumes due to differences in susceptibility to diseases and winter kill between rye and legumes.

Yield variance of grain crops following legume cover crops is often greater than when no cover crop is used (Allison and Ott, 1987; Franklin et al., 1989; Ott and Hargrove, 1989). Consequently, although potential profits may be higher with a legume cover crop compared to no cover crop or a grass cover crop, potential risks are also greater. This risk can be reduced by choosing an adapted legume cover crop (Franklin et al., 1989; Ott and Hargrove, 1989) and by ensuring that the cover crop is planted as early as possible to improve winter survival (Bowen et al., 1991). Economic risks and seeding costs can also be reduced by using legumes in natural reseeding cropping systems. Conservation-tillage systems that do not bury cover crop residue and seed facilitate natural reseeding. Reseeding systems can be implemented by using well-planned rotations such as that reported by Oyer and Touchton (1990). They planted crimson clover in the fall, followed that with strip-tilled soybean which was planted late enough to let the clover reseed. Corn was grown the next year in the reseeded clover (and soybean) residue, thus requiring planting of the cover crop every other year rather than annually.

In the South, grain sorghum can be planted late enough to allow crimson clover to reseed in a conservation-tillage system (Touchton et al., 1982). Corn is a more profitable crop than grain sorghum but it cannot be planted as late as grain sorghum. However, newer corn hybrids with tropically adapted germplasm can be planted later than temperate hybrids and they show great potential for being grown in conservation-tillage systems with reseeding winter annual legumes. In Alabama studies with tropical corn hybrids, equivalent or greater grain and silage yields were obtained with 50 kg N ha^{-1} in a reseeding crimson clover as with 200 kg N ha^{-1} in a fallow system (Reeves, 1992).

The introduction of legume cover crops that bloom and set seed earlier also widens the window of opportunity for achieving a reseeding system using conservation-tillage techniques. In adapted areas, crimson clover is favored over hairy vetch because it matures earlier. A new variety of crimson clover, "AU Robin", has recently been registered that sets seed 7 to 10 days earlier than "Tibbee", the earliest-maturing crimson clover cultivar previously available (van Santen et al., 1992).

Leaving 25% to 50% of the row area alive when desiccating the cover crop is another method shown to effectively allow reseeding without reducing corn grain yields (Ranells and Wagger, 1991). However, potential problems with soil water use by the strips of live cover crop during spring droughts increases the risks of yield reductions with this system (Touchton and Whitwell, 1984).

2. Soil Water Depletion

Although the residue from cover crops can increase infiltration and reduce evaporation losses, transpiration losses of soil water by the cover crop can negatively affect cash crop yields. Short term soil water depletion at the time of planting the cash crop may or may not be overcome and offset by soil water conservation later in the growing season from the cover crop residue in conservation-tillage systems, dependent on rainfall distribution in relation to crop development. In Kentucky, the early growth of corn was decreased during years of low spring rainfall due to transpiration from a hairy vetch cover crop (Corak et al., 1991). By 4 weeks after corn planting, however, soil water was conserved by the mulch from the vetch cover crop. Similar results were reported by Utomo et al. (1987) for no-till corn with both a rye and hairy vetch cover crop and by Frye and Blevins (1989) for a hairy vetch cover. Campbell et al. (1984a) reported that desiccating a rye cover crop at the time of planting a soybean crop resulted in dramatic soil water depletion by the cover crop, which delayed emergence and growth of the soybean. The reduced growth, however, resulted in greater grain yield due to more efficient water rationing by smaller soybean plants during a drought later in the season compared to conventional-tilled soybean plants following incorporation of the rye 25 days before soybean planting. Long term studies in Arkansas showed that yield decreases of cotton following plowed down cover crops of rye, hairy vetch, or rye+vetch and rye+crimson clover mixtures occurred in years characterized by a dry spring and early summer (Keisling et al., 1990).

On soils with root-restricting layers, in-row subsoiling may overcome the detrimental effect of soil water depletion by cover crops (Ewing et al., 1991) but the most universal management factor for reducing risks from early-season soil water depletion by cover crops is to desiccate the cover some time prior to planting the cash crop. Research has shown that the risk of yield reductions due to early-season depletion of soil water can be reduced by killing the cover crop 2 to 3 weeks before planting the cash crop (Wagger and Mengel, 1988; Munawar et al., 1990). On poorly drained soils, soil water depletion by the cover crop could promote an earlier planting date for the cash crop, but the practical advantage of this is probably not realistic. From a residue management standpoint, the risk for early-season soil water depletion is the same regardless of the tillage system; however, the potential for yield increases as a result of increased soil water storage and conservation later in the growing season can only be achieved in a system where cover crop residues are left on the surface.

There are a number of advantages and disadvantages to killing a cover crop early. The decision to desiccate the cover crop early must be weighed against the loss of potential benefits from a later kill date. In addition to reducing soil water depletion, killing the cover early could reduce phytotoxic effects of residues to some crops, could result in less residue to serve as the source of disease inoculum, could improve planter operation, and could improve N mineralization of nonlegume cover crops. On the other hand, killing the crop early could reduce the residue available for soil and water conservation, reduce allelopathic weed control, reduce N contribution to the following crop from legume covers and disallow potential reseeding of the cover crop. Some of these aspects have already been discussed and others will be discussed later in this chapter; however, the decision as to when to kill the cover crop must be site and situation specific.

3. Stand Reductions

Stand reductions in conservation-tillage systems following winter cover crops are frequently reported for cotton (Grisso et al., 1984; Brown et al., 1985; Hutchinson and Sharpe, 1989; Rickerl et al., 1989; Hutchinson and Shelton, 1990), and less so for corn (Campbell et al., 1984b; White and Worsham, 1989; Eckert, 1988) and soybean (Campbell et al., 1984a; Eckert, 1988). These reductions have been attributed to interference from cover crop residue with planter operations resulting in poor seed-soil contact (Mitchell and Teel, 1977; Grisso et al., 1984; Campbell et al., 1984b; Eckert, 1988), soil water depletion (Campbell et al., 1984a, 1984b; Eckert, 1988; Hutchinson and Shelton, 1990), wet soils due to residue cover (Eckert, 1988), reductions in soil temperature from residue cover (Grisso et al., 1985), allelopathic effects of cover crop residues (White et al., 1986; Hicks et al., 1989; Bradow and Bauer, 1992), increased levels of soilborne pathogens (Rickerl et al., 1986), increased predation by insects and other pests (Campbell et al., 1984b; Gaylor et al., 1984; Hutchinson and Shelton, 1990), and in the case of legume covers, un-ionized ammonia (Megie et al., 1967).

Although allelopathic effects of cover crop residue can reduce plant stands, these effects can also reduce weed populations and suppress weed growth (Shilling et al., 1984; White and Worsham, 1989; Mohler and Calloway, 1992). Lack of tillage *per se* and allelopathic effects of cover crop residue can both contribute to the suppression of weeds in conservation-tillage systems (Worsham, 1991). In addition, certain plant pathogens may be reduced by cover crops. Soil populations of *Thielaviopsis basicola*, the cause of black root rot in cotton, as well as the number of diseased cotton seedlings were reduced following hairy vetch and crimson clover cover crops compared to following winter fallow in Arkansas (Kendig and Rothrock, 1991). Although hairy vetch suppressed development of black root rot, populations of *Rhizoctonia solani* were increased following vetch compared to winter fallow (Rothrock, 1991). A better understanding of the effect of cover crops on soil ecology, including cover crop residue interaction with plant pathogens and weeds, is needed to better manage cropping systems that utilize cover crops.

Cotton is especially susceptible to stand reductions following cover crops, especially winter annual legumes. Although research suggests that legume residue may harbor higher plant pathogen populations than grass cover crops (Rothrock and Hargrove, 1988) and that cotton, compared to other crops, is especially sensitive to allelopathic effects of cover crop residues (White and Worsham, 1989; Hicks et al., 1989), lint yield reduction in cotton is not highly sensitive to stand reductions due to compensatory boll production by individual plants as plant populations decrease. This fact coupled with judicious management can reduce the risk of using cover crops in cotton to a level that is acceptable considering the advantages from using cover crops. Some research has shown that cotton cultivars vary in their sensitivity to cover crops (Hoskinson, 1984; Hicks et al., 1989; Bauer et al., 1991). Screening cultivars for sensitivity to cover crop residues would provide useful information to growers. Incorporation of cover crop residue increases the inhibitory effect to cotton seedlings (Hicks et al., 1989; White et al., 1986). Therefore, residue management systems that leave cover crop residue on the surface reduce the risk of stand reductions following winter cover crops provided the residue does not interfere with planter operation.

Probably the two most important management factors for reducing stand losses and poor growth of crops following cover crops are to desiccate the cover crop 2 to 3 weeks before planting the cash crop, and to obtain good seed/soil contact and seed placement, i.e., proper depth control. Due to budget restraints, researchers often work in small plots (which allow little room for error) and have to make do with planting equipment that is not specifically designed to work in heavy residue situations, thus the stand problems associated with equipment reported in the literature may be not as unavoidable as it would seem. Good seed placement is more challenging where residues remain on the soil surface; however, growers now have many options in planter design to facilitate planting in heavy residue. Certainly for cotton, and for corn in northern areas, equipment that removes crop residue from the immediate seeding area can help to reduce stand losses. It is well established that surface residues reduce soil temperature (van Wijk et al., 1959; Mitchell and Teel, 1977; Lal et al., 1980; Utomo et al., 1987). The relative influence of this temperature reduction on crop growth is greater in northern areas of the crop's adapted zone (van Wijk et al., 1959). Removal of residue from the zone of seed placement will not only increase soil temperature in this zone but will decrease the amount of residue that comes in contact with the seed. This results in better seed/soil contact and less allelopathic effects from residue to the developing seedling.

VI. Research and Technology Transfer Needs

The benefits of crop rotation and cover crops are well established if not well practiced in modern highly capitalized and mechanized agricultural production systems. To paraphrase an often quoted axiom of the real estate industry, "There are three areas that research on cover crops and crop rotations should address: i) *economics*, ii) *economics*, and iii) *economics*." Unless a practice is economically viable, there is no incentive for growers to adopt it. Specifically, efforts should:

i) Define the role of rotation practices and cover crops in integrated pest management (IPM) schemes. The allelopathic effects of previous crop and cover crop residues on weed ecology and crop performance need to be more closely researched. The short- and long-term agroecological interactions, especially in regard to weeds, plant pathogens, and insects, between cropping systems and residue management schemes need to be better understood. These findings have environmental as well as economic implications.

ii) Develop cropping systems that are more economically conducive to the integration of rotations and cover crops. Research areas should include reseeding cover crop systems; breeding and screening of cover crop germplasm to develop improved cover crops, e.g., improved cold tolerance of legume covers, maximization of early biomass (and in the case of legumes, N) production, and early seeding; and developing management practices and alternative rotations that improve compatibility of cover crops and crop rotation in production systems. The latter should include development of dual use cover crops and rotations, e.g., crops that serve as cash crops as well as cover crops.

iii) Develop economic risk analyses for crop rotations and cover crops. Although some work has been done in this area, more work is needed and the transfer of this information is critical for decision making by growers. We also need to develop improved management schemes that reduce the economic risk associated with the use of cover crops and rotations. Development of expert systems that facilitate the selection of cover crops and management schemes based on cover crop adaptability, hub crop selection, soil type, and climatic data would aid in managing environmental risk as well as economic risk by growers who use cover crops.

iv) Determine the economic value of the indirect, long-term or subtle benefits of rotations and cover crops, i.e., increased soil productivity, decreased erosion, and potential value in improving or maintaining environmental quality. Improve the transfer of information regarding the monetary value of these effects to growers, action agencies, and policy makers.

v) Continue research on nutrient, especially N and P, loss mechanisms and nutrient cycling in systems that integrate rotations and cover crops. Develop improved management practices for systems that use cover crops and rotations that result in more efficient use of soil water and plant nutrients. This research addresses both economic and environmental concerns.

vi) Prevent the decline of long-term tillage studies and long-term rotation studies. These studies are an invaluable source of information regarding basic soil/plant interactions as well as data base sources for economic analyses. Future studies should focus on the interactive role of rotations in residue management strategies.

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