Chapter 9

Using Cover Crops and Cropping Systems for Nitrogen Management

Seth M. Dabney
USDA Agricultural Research Service
PO Box 1157
Oxford, MS 38655-2900, USA

Jorge A. Delgado
USDA Agricultural Research Service
2150 Center Avenue, Building D, Suite 100
Fort Collins, CO 80526, USA

Jack J. Meisinger
USDA Agricultural Research Service
10300 Baltimore Avenue
Beltsville, MD 20705-2350, USA

Harry H. Schomberg
USDA Agricultural Research Service
1420 Experiment Station Road
Watkinsville, GA 30677-2373, USA

Mark A. Liebig
USDA Agricultural Research Service
PO Box 459
Mandan, ND 58554-3054, USA

Tom Kaspar
USDA Agricultural Research Service
2110 University Boulevard
Ames, IA 50011-4420, USA

Jeffrey Mitchell
University of California
9240 S. Riverbend Avenue
Parlier, CA 93648, USA

Wayne Reeves
USDA Agricultural Research Service
1420 Experiment Station Road
Watkinsville, GA 30677-2373, USA

INTRODUCTION

Cover crops and cropping systems' effects on N and related aspects of crop production and environmental quality have been reviewed by many authors (Russelle and Hargrove, 1989; Meisinger et al., 1991; Dabney et al., 2001; Grant et al., 2002, Thorup-Kristensen, 2003; Reeves, 1994; Snapp et al., 2005; Crews and Peoples, 2005; Reeder and Westerman, 2006; and Clark, 2007). We address the subject from the perspectives of four diverse regions of the US: the Humid South, the Humid North and Corn Belt, the Northern Plains, and the Irrigated West. After definition of terms used herein and a general discussion of the impacts and interactions of management options involving cover crop species selection, planting date, crop rotation, and tillage, we proceed to the regional perspectives. Following Russelle and Hargrove (1989), we stress that opportunities exist for exploiting complementary spatial and temporal niches reflected by such parameters as rooting depth, water use, and N assimilation potential. The most sustainable cropping systems will maximize uptake and cycling of N and water without loss of nutrients from the system or creation of deficits that reduce economic yield. Tonitto et al. (2006) discussed the potential for diversified rotations using N and non-N-fixing cover crops to maintain crop yields, while reducing N losses. While much remains to be learned concerning N management in different cropping systems, much knowledge has already been developed. Computer models have been constructed to reflect this knowledge for use both as educational aids and management tools to improve site-specific management.

DEFINITIONS AND CONCEPTS

A catch crop is a cover crop grown to take up available N in the soil and thereby reduce leaching losses of N already in a cropping system. To be most effective, cool season catch crops should be planted early in the fall to maximize root growth and N uptake before cold weather limits growth. Brassicas or oat (*Avena sativa* L.) catch crops may grow faster in the fall than more winter-hardy species like rye (*Secale cereal* L.) or wheat (*Triticum aestivum* L.). Catch crop effectiveness is highly correlated with rooting depth but not with root density (Delgado, 2001; Thorup-Kristensen, 2001). Where nitrate leaching is a serious problem, catch crops can beneficially fill any "fallow" periods in a rotation.

Green manure is a cover crop grown mainly to improve the nutrition of subsequent main crops; it often includes legumes that can add N to the cropping system. To be most effective, green manure crops should winter-kill, be grazed, or be killed early in the spring. Doing so prevents pre-emptive competition and allows green manure N to become available during the following crop's growing season. Incorporation of green manure crops with tillage usually speeds the mineralization of organic N.

Asynchrony is the situation where soil N availability does not coincide with crop demand. This asynchrony can lead to mineral N excess (susceptible to loss) or an N deficit that limits crop growth (Figure 1). Asynchrony can result from additions of inorganic fertilizer N, animal manure, green manure, or from soil N mineralization. Tillage and cover crop species and maturity can be manipulated—as well as subsequent cash crop species, varieties, and planting dates—to improve synchrony of mineralization of cover crop and soil organic N with crop demand.

Pre-emptive competition refers to uptake of soil nitrate by cover crops that would not have been lost by leaching and would have been available to subsequent crops (Thorup-Kristensen, 2003). Pre-emptive competition can occur particularly during the late spring growth of non-leguminous cover crops and when cover crops are grown in dry areas where leaching risk is low. In these situations, growing catch crops during only some years may be optimal from the standpoint of maximizing N availability to cash crops.

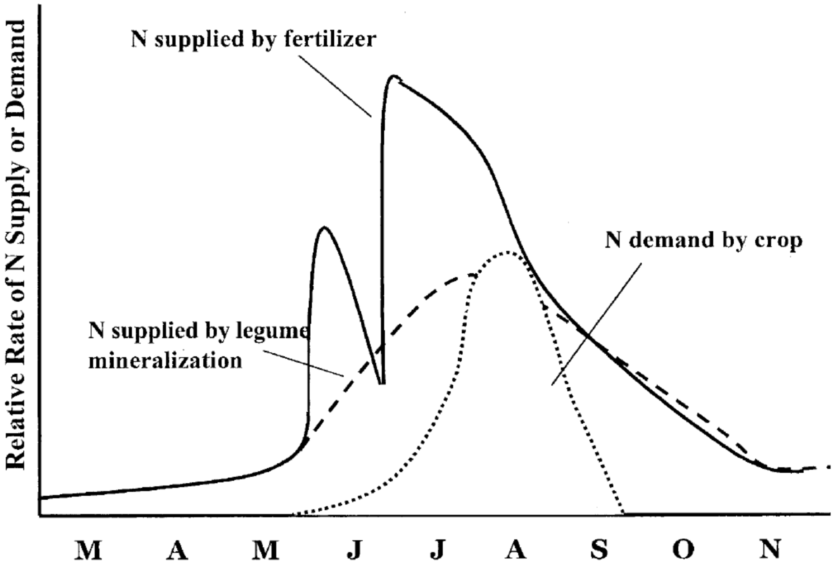

Figure 1. Asynchrony between N supply from fertilizer or green manure crops and N demand by subsequent crops (from Crews and Peoples, 2005).

COVER CROP MANAGEMENT AND SAMPLING

Cover crops can be managed to achieve certain objectives such as conserving N, adding N or C to an agricultural system, optimizing the C:N ratio of residues, supplying residues for erosion control, or improving the availability of N to a subsequent crop. The primary approaches available to managers are species selection, use of multi-species mixtures, optimizing the planting and/or kill date, and tillage system. The three major categories of commonly grown cover crops are grasses, legumes, and brassicas. Grasses typically are the most cold tolerant and produce residues most resistant to decomposition; legumes can contribute N through symbiotic dinitrogen (N_2) fixation; and brassicas can be the most rapid growing under warm conditions, have the ability to take up large quantities of N, and their residues mineralize N rapidly. Brassicas are not used as much as legumes and grass cover crops, but offer promise in a variety of management systems as catch crops and green manure crops and also may significantly impact soil porosity, disease control, and weed populations (Mojtahedi et al., 1991; Smolinska et al. 1997; Francis et al., 1998; Isse et al., 1999; Thorup-Kristensen, 2003; Haramoto and Gallandt, 2004; Williams and Wiel, 2004; Snapp et al., 2005; Collins et al., 2007).

Conserving Nitrogen

Cover crops conserve N by converting mobile nitrate-N into immobile plant protein and by providing timely competition to other N-cycle loss processes, such as leaching or denitrification. Many studies have been conducted to estimate the benefits of various species of cover crops on water quality and on improving N recovery in cropping systems. One of the most noteworthy classic studies was the 10-year trial of Morgan et al. (1942) in Connecticut, using field lysimeters containing a sandy loam soil and growing continuous tobacco (*Nicotania tabacum* L.) fertilized with 200 kg N ha^{-1} from a combination of organic-N and fertilizer-N sources. The tobacco was harvested in August, and within 10 days grass cover crops of oats, rye, or timothy (*Phleum pretense* L.) were planted. Rye was the most effective N-conserving crop, yielding a 66% reduction in the mass of N leached compared to the no-cover control. The rapidly established oats gave a 57% reduction despite winter killing, and the slowly establishing timothy gave a modest 31% reduction. The N conserved by these covers also contributed to an increase in soil organic matter of 0.33% in the surface 15 cm, which converts to an increase of about 330 kg N ha^{-1} or 3300 kg C ha^{-1} (assuming that organic matter contains about 5% N and has a C:N ratio of 10:1).

Cultivation reduces soil organic carbon and organic N, usually reducing the carbon and N bound in particulate organic matter (Cambardella and Elliott, 1992). Cover crops can be used as a management tool to sequester N in the particulate organic matter soil pool. Such an occurrence depends on N inputs, crop residue management, and crop rotation (Al-Sheikh et al., 2005; Cambardella and Elliott, 1992; Havlin et al., 1990; Legg and Meisinger, 1982; Meisinger, 1984).

Improved erosion control is one of the main benefits of winter cover crops (Wendt and Burwell, 1985; Zhu et al., 1989; Mutchler and McDowell, 1990; Lal et al., 1991; Langdale et al., 1991; Delgado et al., 1999; Kaspar et al., 2001). Controlling erosion can prevent a significant loss of particulate N with sediment. The use of cover crops for erosion control is based on the principles of increasing infiltration by improving soil structure and providing continuous ground cover to protect the soil against raindrop impact (Langdale et al., 1991; Dabney, 1998) and or wind erosion forces that can detach and aerially transport off-site soil particles, nutrients and attached organic matter (Delgado et al., 1999). Cover crops are especially valuable when small grains are incorporated into intensive rotations with crops such as lettuce and potato, which leave small amounts of residue, on wind erosion-susceptible, irrigated sandy soils (Al-Sheikh et al., 2005).

A direct field measure of N conservation was provided by a two-year study by Shipley et al. (1992) in Maryland's Coastal Plain. These investigators added ^{15}N labeled fertilizer N to corn at 300 kg N ha^{-1} to provide a pool of labeled residual N, then cover crops of rye, annual ryegrass (*Lolium multiflorum* Lam.), crimson clover (*Trifolium incarnatum* L.), hairy vetch (*Vicia villosa* Roth), or native weed growth were established. The rye cover crop recovered 60% of the residual corn fertilizer N at mid-April, the usual kill date in Maryland. The corresponding ^{15}N recovery by annual ryegrass was 40%, while hairy vetch, crimson clover, or native weeds each recovered less than 10% of the labeled corn fertilizer. The greater effectiveness of the grass cover crops was attributed to a faster and deeper fall root growth along with greater cool-season growth and winter hardiness. These results show that grasses are superior to legumes in conserving N, a fact that was also emphasized by two in-depth reviews of cover crops by Meisinger et al. (1991) and Dabney et al. (2001). These reviews concluded that cover crops can commonly reduce both the mass of N leached and the nitrate-N concentration in the leachate by 20% to 80%. A major factor affecting leaching was the species of cover crop, as the average reduction in nitrate leaching was about 70% for grass or brassica covers and about 23% for legume covers.

Rooting depth is critical for soil nitrate scavenging. Cover crop rooting depth varies with interactions of species, soil properties, climate, and planting date. When cover crops were planted during summer (planting August 1 in Denmark following horticultural crops), Thorup-Kristensen (2001) found that broadleaf cover crops grew deeper roots faster than cereals or annual ryegrass (Figure 2). Thus, planting cover crops as soon as possible in late summer or early autumn is important for maximizing rapid root extension and N uptake (Francis et al., 1998). Delgado (2001) conducted cover crop studies with irrigated vegetable and small grain systems and found a positive correlation among root depth, N use efficiency and nitrate uptake from shallow ground water. In other words, the deeper rooted crops had higher N use efficiencies, better nitrate scavenging abilities, and lower nitrate leaching potential. The deeper rooted cover crops functioned like vertical filter strips to scavenge nitrates from soil and recover nitrates from underground water (Delgado, 2001).

Where residual N from fertilizer or manure and soil N mineralization are limited, cover crop growth may be N-limited. In these situations, application of fertilizer N to non-legume cover crops may increase biomass production without increasing N leaching. For example, Staver and Brinsfield (1998) found that rye cover crop growth following corn was N-limited in Maryland and suggested that increased N inputs would increase cover crop contributions to soil C pools rather than lead to increased nitrate leaching.

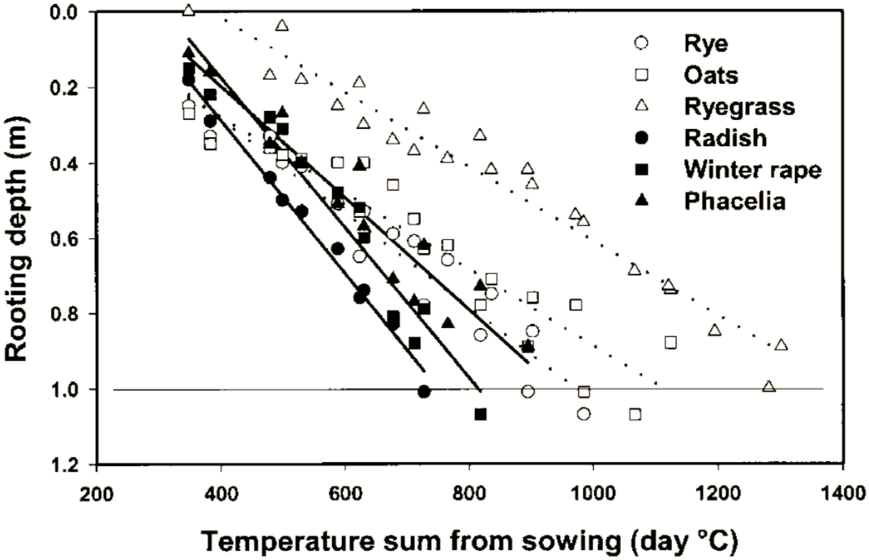

Figure 2. Cover crop rooting depth varies with interactions of species, soil properties, climate, and planting date. When tested during warm weather (planting August 1 in Denmark following horticultural crops), broadleaf cover crops grew deeper roots faster than cereals or annual ryegrass (Thorup-Kristensen, 2001).

Adding N to the Cropping System

The most direct approach for adding N to a cropping system with cover crops is by growing a legume. The ability of legumes cover crops to add N is a major benefit, particularly in areas where fertilizer is scarce or expensive. In fact, before the widespread availability of N fertilizers many cropping systems relied on legume green manures for adding N.

Many studies have documented the ability of legumes (compared to grasses) to supply N to the subsequent grass crop with the difference usually attributed to legume N_2 fixation (Clark et al., 1997a, 1997b, 2007a, 2007b). A hairy vetch cover crop has been shown to regularly supply 50–

155 kg of N ha^{-1} to a succeeding corn crop (Holderbaum et al., 1990a; Clark et al., 1995; Ranells and Wagger, 1996; Seo et al., 2000), while rye cover crop generally requires 10–50 kg N ha^{-1} of additional fertilizer N (Wagger, 1989b; Munawar et al., 1990; Vyn et al., 2000; Clark et al., 2007b). Further discussion of these aspects will be found in the "Regional Perspectives" section.

Legume cover crops can also add significant quantities of N to the soil through N sequestration compared to conventional fertilizers. Seo et al. (2006) followed the fate of ^{15}N labeled hairy vetch residues and ^{15}N labeled fertilizer applied to silage corn on a loam soil in a humid climate (850 mm rainfall) of Korea. Recovery of labeled N in the first-year corn was 32% of the planting-applied fertilizer, but only 15% for the planting-applied hairy vetch residues. However, the post-harvest soil contained 38% of the labeled N from hairy vetch residues, compared to only 15% from planting-applied fertilizer. Total first-year recoveries of ^{15}N in crop plus soil after harvest were 47% from fertilizer and 54% from hairy vetch residues, which is not uncommon for corn grown in high rainfall conditions. These results along with others (Ladd and Amato, 1986; Harris et al., 1994; Janzen et al., 1990) show that fertilizer is about twice as effective as legume residues in supplying N to a crop, while legume residues contribute about twice as much N to the soil. This study demonstrated that a corn N management system employing both fertilizer N and legume cover crop residues can meet both crop N requirements and conserve soil N, an attribute that will become increasingly important as emphasis on developing sustainable management practices increases.

Harper et al. (1995) developed an N budget to estimate sources, sinks, and net system gain in N for crimson clover-forage sorghum (*Sorghum vulgare* Pers.) cropping systems (Figure 3). Crimson clover reseeded from the preceding year and was killed with herbicide the following spring. The forage sorghum crop was planted in the spring and was harvested twice during the summer. Nitrogen in the clover crop increased until anthesis, and then declined slightly prior to desiccation with herbicides. Total N accumulated in the clover at desiccation was 323 kg N ha^{-1} (28 in leaves, 81 in stems, 40 in seeds, 44 in surface-layer roots, and 130 in dead leaves and litter). This was an increase of 82 kg N ha^{-1} from the 241 kg N ha^{-1} in the clover at anthesis. From anthesis to harvest, total aboveground biomass and the N-contents in litter, dead leaves, stems, and seeds increased while live leaf N contents decreased. Allowing legume cover crop growth beyond flowering may increase total C and N inputs, but may decrease cover crop N immediately available to the following crop because of slower mineralization of high C:N residues and N sequestration in hard seed.

Meisinger and Randall (1991) provided guidelines for estimation of N contribution from symbiotic N fixation by annual forage and grain and perennial legumes. Estimates were based on aboveground biomass production, soil organic matter levels, fertilizer and manure applications, and measured or estimated biomass N contents. Annual and first year growth of perennial legumes' non-harvested plant parts (senesced leaves, crowns, roots, harvest losses) contained N approximately equal to 50% of harvested N. Peoples et al. (2001) concluded that 50% of total plant N in both annual and perennial pasture species and 33% in crop legumes are partitioned below ground, implying that the N present in nodulated root systems has frequently been underestimated. Peoples and Baldock (2001) found that, in areas with abundant winter precipitation or under irrigation where buildup of inorganic soil N was minimal, legume N fixation was consistently between 20 and 25 kg shoot N for every Mg of shoot dry matter produced.

Delgado et al. (2010) reported that in fields using cover crops, N use efficiency was greater in N cycling from crop residue than from inorganic N fertilizer. They reported that large field plot studies conducted with the ^{15}N crop residue exchange technique (Delgado et al., 2004) showed that the N recoveries in plants and soil were 87% for crop residue, much higher than the 69% measured for inorganic N fertilizer. Similarly, the N losses from the system of 13% from the cover crop residue were much lower than the 31% observed from inorganic N fertilizer. Delgado et al. (2010) reported that the losses due to NO_3-N leaching from cycling of N from crop residue were much lower than those from the inorganic N fertilizer. Additionally, they found that the emissions of N_2O from crop residues with high C/N ratios were much lower than those simulated from inorganic N fertilizer. Based on these ^{15}N crop residue studies and simulation modeling analysis, Delgado et al. (2010) recommended that the IPCC revise their methodologies to assign lower direct and indirect N_2O emissions to crop residues (at least to crop residues with high C/N ratios). They also recommended that better N management practices that account for N cycling be implemented in order to maximize the benefits of using cover crops.

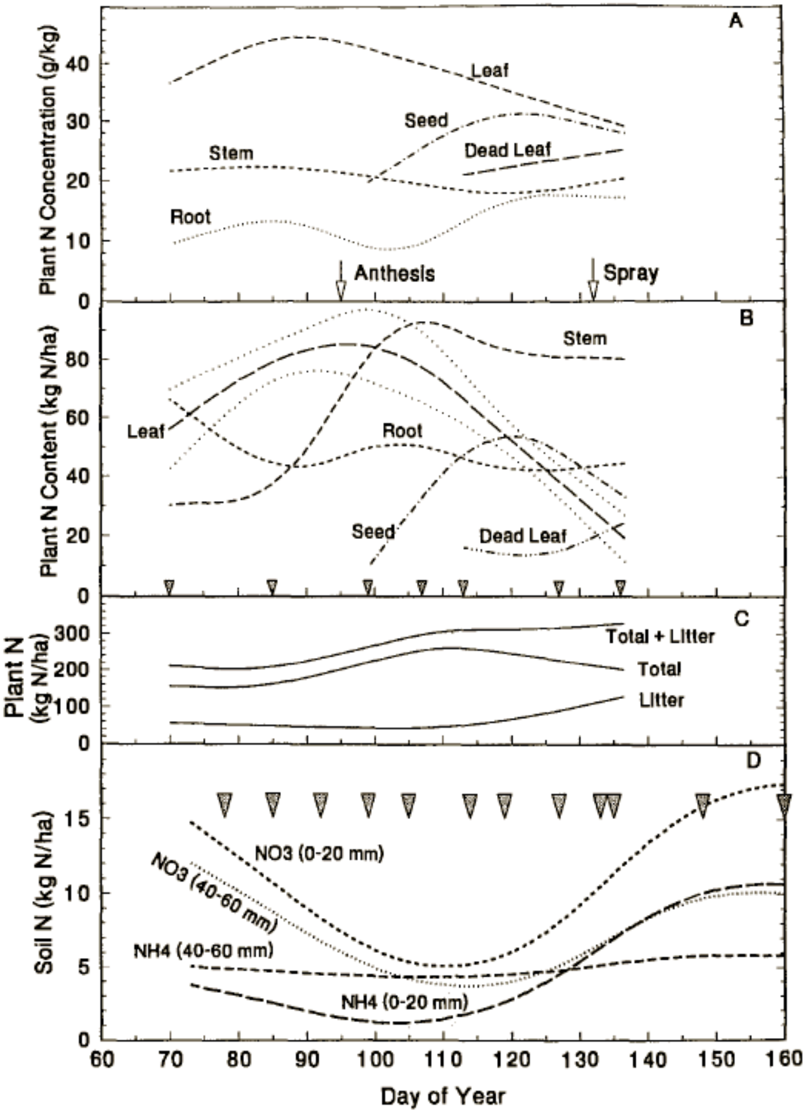

Figure 3. Reseeding legume cover crops can contribute N with little seed cost, but green manure benefit is reduced compared to termination at flowering because 50 to 60 kg N ha^{-1} may be tied up in hard seed (Harper et al., 1995).

Managing Cover Crop Composition

Cover crop composition, including the quantity of residues, the residue N concentration, and the residue C:N ratio, can be managed by species selection, planting date, selective management, and kill date.

Although growth stage, management, climate, lignin, carbohydrates, and cellulose content can affect the cover crop N release rate (Muller et al., 1988; Bowen et al., 1993; Quemada and Cabrera, 1995), the C:N ratio can be a useful guide for determining the potential for N release during decomposition (fertilizer equivalency). Legume cover crops have higher potential for fertilizer equivalency because they usually have C:N ratios lower than 20 (Touchton et al., 1982; Ebelhar et al., 1984; Doran and Smith, 1991). Cereal and other grass cover crops will usually have higher C:N ratios, especially when growth approaches reproductive stages. A C:N ratio greater than 35 carries the potential for net immobilization of N followed by a slow N release rate (Pink et al., 1945, 1948). A C:N ratios lower than this results in net N mineralization and a faster N release rate. A C:N ratio of approximately 25 is used as a threshold delineating between these two processes (Paul and Clark, 1996). Regardless of the C:N ratio, N fertilization can cause similar decomposition dynamics for residues of divergent crop species by increasing N availability to soil microorganisms (Grant et al., 2002).

A plethora of cover crop studies document the effects of management practices on residue production of grass cover crops (Hargrove, 1986; Clark et al., l995, 2007b). Aboveground dry matter productions of 3 to 5 Mg ha^{-1} are common with adapted species of winter cover crops (Seo et al., 2000; Clark et al., 1995, 2007a; Decker et al., 1994; Wagger, 1989a and 1989b; Sarrantonio and Scott, 1988). These production levels are quite sufficient for erosion control and for adding 1 to 2 Mg ha^{-1} of C into the soil. The majority of this added C will be respired as CO_2 by soil microbes, but an environmentally significant portion will be sequestered into more recalcitrant forms of soil organic C and thus contribute to C sequestration, particularly in reduced tillage management systems. Six et al. (2006) found that crop rotations, no-tillage practices, and cover crops increase soil microbial biomass and shift the community structure toward a more fungus-dominated community, thereby enhancing accumulation of microbially derived soil organic matter. Puget and Drinkwater (2001) studied the distribution of incorporated ^{13}C labeled hairy vetch residues and found that more root-derived than shoot-derived C remained in the soil after one corn growing season indicating that root litter was largely responsible for the short-term soil structural improvements from green manures, while rapidly broken down shoot residues serve as the source of N for the following cash crop.

Using grass-legume mixtures is a well-proven method to lower the C:N ratio of the residues (Hargrove, 1986; Clark et al., l995) to promote higher N availability to the subsequent crop. For example, Clark et al. (2007a) showed that using a vetch-rye mixture lowered the C:N ratio from about 60 for pure rye to about 17 for the mixture, while pure vetch had a C:N ratio of about 11. Other research (Vaughan and Evanylo, 1998; Ranells and Wagger, 1996; Clark et al., 1994) has resulted in reports of similar trends in C:N ratios for rye, hairy vetch, and vetch-rye mixtures. Mixtures of legume and non-legume cover crops may increase total biomass production, site adaptability, and combine both catch crop and green manure functionality. In North Carolina, Ranells and Wagger (1997a, 1997b) found that rye-legume bicultures (cereal rye and hairy vetch or crimson clover) scavenged residual soil inorganic N following a summer corn crop, thereby minimizing leaching of N from the plant rooting zone. The bicultures were intermediate between rye alone and vetch alone in reduction of spring soil inorganic N.

Another approach is to manage the composition of the cover crop mixture within the winter-spring growing season. Clark et al. (2007a) used a grass-selective herbicide on hairy vetch-rye mixtures in the early spring in an attempt to allow the rye to function as a residual N scavenger over the fall-winter season, then kill the rye and allowed vetch to grow until May to fix N for the subsequent corn crop. However, their results showed no significant difference in corn N uptake from the mixture treated with the grass-selective herbicide treatment compared to the untreated mixture, probably due to the slow rate of killing the winter-hardened rye. Nevertheless, the vetch-rye mixture functioned like a "dual purpose" cover crop; conserving fall residual N with rye, producing a lower C:N ratio in residues than pure rye, and supplying more N to succeeding corn than pure rye; although the N supplied was still less than pure vetch (Clark, et al., 2007a). Other strategies for managing species composition in cover crop mixtures, such as strategic mowing at specific developmental stages, might also provide opportunities for enhancing the benefits of conserving fall N by the grasses and adding additional N by the legumes. Early kill dates, winter-killing, and grazing all favor lower C:N ratio and more rapid release of cover crop N to subsequent crops (Francis et al., 1998; Vyn et al., 1999).

Tillage System Interactions

Tilling soil generally increases mineralization of soil organic matter. Incorporation of a green manure cover crop speeds mineralization of cover crop N and this may increase (Huntington et al., 1985; Wagger, 1989b; Ball Coelho et al., 2005) or decrease (Dabney et al., 1989) synchrony of N release with subsequent crop demand.

In no-tillage systems, soil organic carbon accumulates over time with most accumulation occurring in the top 5 cm of the soil. In the US and Brazil, the rate of soil organic carbon (SOC) storage in no-tillage compared to conventional tillage has been estimated to range from -0.07 to 0.48 Mg C ha^{-1} y^{-1} (Franzluebbers and Follett, 2005; Causarano et al., 2006; Amado et al., 2006) and is higher when cover crops are used. Because the C:N ratio of soil is frequently in the range of 10 to 12, such an accumulation of SOC must be accompanied by increases in soil organic N, which can be provided by cover crops. More discussion of this topic can be found in the "Regional Perspectives" section.

As the level of soil carbon increases, the rates of additional carbon accumulation may slow over time; therefore, occasional tillage (approximately once every 10 years) to mix surface-soil carbon deeper into the soil profile and to bring lower C soil to the surface may not have an adverse effect on total soil C and may eventually result in a positive gain in soil C (Quincke et al., 2007). Occasional tillage of long-term no-tillage systems, may not appreciably increase the risk of sheet and rill soil erosion because of short term carryover benefits (Dabney et al., 2004), provided that no-tillage management and ground cover are quickly reestablished.

Measuring Cover Crop N Inputs and Cycling

Measuring total C and N inputs to cropping systems is challenging because biomass sampling at any point in time reflects net growth (net primary production less losses due to death or senescence and decay). Frequently the assumption is made that when biomass sampling is done at the time of peak standing biomass, current year losses to senescence, leaf shedding, insect feeding, and decay are negligible (e.g., Briggs and Knapp, 1991). This is unlikely to be true of winter cover crops that may occupy fields for 6 months (October to March) or longer. Fuess and Tesar (1968) showed that alfalfa (*Medicago sativa* L.) leaflet photosynthetic efficiency declined with age, slowly at first but declining by 85% at 28 days of life. These low-efficiency leaflets are parasitic to a plant and are soon shed (creating litter) if not harvested. Alfalfa represents a type of plant with fast-growing, thin, short-lived, nutrient-rich leaves adapted to fertile, resource-rich habitats. In contrast, plants adapted to poorer sites may have inherently slower growth rates and produce fibrous long-lived thick leaves that represent a larger investment in support and storage organs (White et al., 2004).

Many winter cover crop species may resemble alfalfa in tissue lifespans, so that substantial quantities of biomass may have been sloughed and would not be included in the standing crop of above or below-ground biomass at a particular spring harvest date. It is common for cover crop stems to have many leafless nodes in the spring. Long bare stems facilitate mechanical control by rolling (Creamer and Dabney, 2001) but indicate that many leaves have already been sloughed. It should be noted that cover crop litter additions must have occurred to balance decomposition during March and April in Georgia to maintain the constant litter levels observed by Harper et al. (1995) under actively growing crimson clover. This means that the total N accumulated in biomass at some termination date (plotted in Figure 3) is less than the total N cycled.

Roots similarly go through cycles of growth and death so that total N uptake and biomass production cannot be estimated directly from end-of-season sampling (Luo et al., 1995). "Below-ground" legume biomass and N contributions have frequently been underestimated by interpreting point-in-time sampling as gross rather than net production. Point-in-time samples of the macro-root system do not capture root exudation, root turnover, symbiosis with mycorrhiza, and soil biomass derived from decay of sloughed aboveground plant parts. Additional factors contributing to underestimation are sampling from only shallow soil depths and incomplete recovery of fine roots. For example, Reeves et al. (1993) measured biomass and N from aboveground samples and screened roots, taken to the 30-cm depth, of crimson clover at mid-bloom in three growing seasons. The biomass and N contained in root recovered root samples averaged only 24% and 19%, respectively, of that in aboveground samples. Similar distributions of biomass and N taken from cereal rye at milk stage averaged 24% and 14%, respectively, of that contained in aboveground samples. Contrast this to recent estimates of below-ground legume biomass and N contributions at 50% to 100% of measured aboveground contributions (Peoples et al., 2001; Peoples and Baldock, 2001; Rochester and Peoples, 2005).

REGIONAL PERSPECTIVES

Humid South

The Humid South region of the United States contains more than 13 million hectares of cropland in the states of Alabama, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, South Carolina, and Tennessee. The climate of the region is temperate-humid with mild enough winters in most areas (except for the higher elevations of the Appalachian Mountains) to support significant quantities of biomass production from winter cover crops. The soils in the region are highly weathered with low organic matter and have been subjected to a long history of extensive and intensive crop production from the early 1800s. Corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), peanut (*Arachis hypogaea* L.), soybean [*Glycine max* (L.) Merr.], grain sorghum [*Sorghum bicolor* (L.) Moench], and many vegetable crops are grown in the region using a variety of cover crops that are needed to enhance biomass input critical for improving soil productivity and water availability (Langdale and Moldenhauer, 1995).

Both legumes and small grains are used as cover crops in conservation tillage systems in the region (Reeves, 1994). Cereal rye, soft red winter wheat, oat, and barley (*Hordeum vulgare* L.) are the predominant small grain cover crops used with cotton, peanut, soybean and vegetables. Black oat (*Avena strigosa* Schreb.), a recently introduced cover crop in the region, seems to have promise for use in production systems in the coastal plains where rye has previously been used (Bauer and Reeves, 1999; Reeves et al., 2005; Price et al., 2006; Schomberg et al 2006; Price et al., 2007). Crimson clover and hairy vetch are the most common legume cover crops in the region, although producers and researchers have worked with Austrian winter pea (*Pisum sativum* spp.

arvense), common vetch (*Vicia sativa* L.), subterranean clover (*Trifolium subterraneum* L.), arrowleaf clover (*Trifolium vesiculosum* L.), white clover (*Trifolium repens* L.), and several other legumes. Hairy vetch is used more often in the northern parts of the region because of its greater cold tolerance. Crimson clover tends to predominate in the warmer parts of the South. It is relatively acid tolerant, has an earlier date of full bloom, good dry matter and N production, and has a high percentage of hard seed which is beneficial for reseeding. While not yet widely grown, balansa clover [*Trifolium michelianum* Savi var. balansae (Poiss.) Azn.], is also a well-adapted reseeding cover crop. Balansa is winter hardy through zone 7, is adapted to wet soils, flowers by the end of March, produces hard seed 30 days after blooming, and can regenerate stands without tillage for several years from a single hard seed crop (Dabney et al., 2001; Clark, 2007).

The influence of cover crops on N availability has been investigated to gather data reflecting the (1) need for additional N following small grain cover crops, (2) residual N capture by small grains, and (3) amount and availability of N fixed by legumes. In addition to the these areas, research has focused on the indirect effects of cover crops on N availability through impacts on water availability, weed suppression, soil biological processes, and climate, but these interactions are not considered in this review.

Cover crop influences on N availability. Soil-plant N dynamics can be adversely affected in nonleguminous cover crop systems. Mature small grain residues may immobilize soil mineral N during the decomposition process due to their wide C:N ratio. Evidence of residual and fertilizer N immobilization can be found in N rate experiments conducted with rye (Brown et al., 1985; Hargrove, 1986) and wheat (Tyler et al., 1987) where yields following small grain cover crop treatments were reduced compared to fallow treatments. In Alabama, Brown et al. (1985) found that cotton planted into killed rye required an additional 34 kg N ha^{-1} to achieve the same yields as cotton in a no cover crop system. In Georgia, Hargrove (1986) found that yields of grain sorghum without fertilizer N were 0.3 Mg ha^{-1} lower following rye than following no cover crop. In Tennessee, Tyler et al. (1987) showed reduced yields for no-tillage corn following oat with the differences being greater in a good year for corn growth compared to a poor year. In Virginia, Vaughn and Evanylo (1998) found that corn yields were reduced when rye biomass increased significantly between early and late desiccation times and were not affected when rye biomass differences were small between desiccation times. In these cases reductions in yields were not attributed to water stress but were probably due to limited N supply associated with decomposition of small grain residues with a high C:N ratio.

In Alabama, Torbert et al. (1996), using ^{15}N methodology, estimated that N immobilization in a rye-corn conservation tillage system reduced corn yield 0.3 Mg ha^{-1} in 1990 (a year with low biomass production) and

3.5 Mg ha^{-1} in a year with greater biomass production. Schomberg and Endale (2004), using in situ N mineralization measurements, showed that soil inorganic N levels in no-tillage cotton were near zero or negative at planting following a rye cover crop. Soil mineral N levels remained low for 60 days or longer depending on the amount of rye biomass and the C:N ratio of the biomass. An indication of N immobilization following a rye cover crop was also reported by Bauer et al. (1993) in South Carolina, where petiole NO_3-N levels were lower in cotton following green-manured rye than in cotton following winter fallow.

Nitrogen availability following cover crops is directly influenced by chemical composition or resource quality of the residues. Schomberg et al. (2006) compared soil N mineralization rates following four cover crops and found they varied from year to year depending on the amount of cover crop biomass and species of cover crop. The 3-year-average N mineralization rates were 1.6, 1.8, and 2.0 times greater in soil following black oat, crimson clover, and oil seed radish (*Raphanus sativus* var. *oleiformis* Pers.), respectively than the rate following rye. These results would indicate a distinct advantage for N supply following the three former cover crops.

Because of the potential for N immobilization following high C:N ratio cover crops like small grains, N fertilizer rates may need to be increased, particularly where large amounts of residue are produced. This was demonstrated by Reiter et al. (2002) for cotton grown in the Tennessee Valley region of Alabama in an intensive residue (> 4.4 Mg rye residue ha^{-1} annually) production system. The optimum N application rate in their system was 120 lb of N ha^{-1}, which exceeded the rate proposed by Monks and Patterson (1996) for conservation tillage systems in north Alabama by 30 kg N ha^{-1}. The high N demand of microorganisms decomposing small grain residues might decrease over time as the system attains a new equilibrium. However, Schomberg and Endale (2004) observed significant soil N immobilization in a cotton-rye no-tillage system after four years, indicating that a new equilibrium may occur only after a very long period of time.

Boquet et al. (2004) compared no-tillage and surface tillage; wheat, hairy vetch, or volunteer weed cover crops; and five N rates (0, 39, 78, 118, and 159 kg N ha^{-1}) for irrigated cotton production on upland silt loam soils. They found that maximum no-tillage cotton yield was not affected by cover crops, but optimum fertilizer N rates were higher (118 kg N ha^{-1}) under no-tillage than under tillage (78 kg N ha^{-1}) where no cover crop was planted. Equal N (118 kg N ha^{-1}) was required to maximize yield for both tillage systems with a wheat cover crop, but no fertilizer N was required for cotton with a hairy vetch cover crop. Nitrogen in aboveground cover crop biomass ranged from 6 to 24 kg N ha^{-1} for native weeds, 22 to 70 kg N ha^{-1} for wheat, and 80 to 90 kg N ha^{-1} for hairy vetch.

Residual N capture by small grains. Several research studies in the South have focused on using cover crops to capture residual N remaining in the soil profile following a summer crop. In most studies rye was found to be superior for reducing N in the soil profile because of its rapid fall growth and extensive root mass (McCracken et al., 1994). Both hairy vetch and rye equally reduced soil profile NO_3 contents following corn in Kentucky (<0.07 g N m^{-2}) (McCracken et al., 1994). In Georgia, seasonal differences in rainfall during the summer and winter cropping seasons resulted in large differences in yearly response for NO_3 uptake by rye (McCracken et al., 1995). Total NO_3-N leaching loss (kg ha^{-1}) was less each year under rye than under winter fallow (1991 = 3.3 vs. 12.2; 1992 = 29.9 vs. 35.2; 1993 = 9.7 vs. 19.8). Fall residual soil profile N content was a function of rainfall impacts on corn growth and N uptake during the summer. Reduction in NO_3-leaching by rye was related to both water and N during the winter period.

The use of legume-grass mixtures has been proposed as a way to enhance N management with cover crops by combining the N fixing capacity of the legume with the N scavenging ability of the grass. Using ^{15}N labeled fertilizer, Ranells and Wagger (1997b) found that in a rye monoculture 39% of the ^{15}N labeled fertilizer was taken up by the cover crop, compared with 19% in a rye-crimson clover biculture and 4% in a crimson clover monoculture. Total (plant and soil) recovery of ^{15}N in mid-April ranged from 19% in the fallow treatment to 68% in the rye monoculture. Of the 24% recovered in the biculture, 92% was in the rye component. These results indicate that under winter fallow conditions, up to 80% of the ^{15}N fertilizer applied the previous October may have been leached or otherwise lost from the plant-soil system.

Amount and availability of N fixed by legumes. Several research studies have been conducted in the region to determine the amount of N_2-fixed by various legumes and the subsequent fertilizer N replacement value. In general, N contents of aboveground biomass of legumes have ranged from less than 10 to greater than 200 kg N ha^{-1} (Table 1). These estimates are usually based on single-point sampling at the time of cover crop termination and on above-ground N contents. As discussed earlier, this can lead to an underestimate of total N accumulation. Working in Australia using a ^{15}N natural abundance technique to determine cover crop N fixation, Rochester and Peoples (2005) found that in one of two years, balansa clover was the most productive of a number of legume cover crops tested, producing 5.1 Mg ha^{-1} shoot biomass with a total fixation of 245 kg N ha^{-1}, calculated with the estimate that 40% of total plant N was present in or released from root systems.

Table 1. Nitrogen content and fertilizer replacement values of several legumes.

Citation (location)	Cover crop	Total N content (kg N ha^{-1})	Fertilizer replacement value (kg N ha^{-1})	Following crop
Hargrove, 1986	Crimson clover	170	92	Grain Sorghum
(Georgia)	Hairy vetch	153	97	
	Subterranean clover	114	61	
	Common vetch	134	61	
	Rye	38	–12	
Blevins, 1990	Hairy vetch	103	75	Corn
(Kentucky)	Bigflower vetch	67	65	Corn
	Hairy vetch	103	125	Grain Sorghum
	Bigflower vetch	67	135	Grain Sorghum
Ebelhar et al., 1984	Hairy vetch	209	100	Corn
(Kentucky)	Bigflower vetch	60	<50	
	Crimson clover	56	<50	
	Rye	36		
Brown et al., 1985	Crimson clover (Sept.)	133		Cotton
(Alabama)	Hairy vetch (Sept.)	133		Cotton
	Crimson clover (Nov.)	44		Cotton
	Hairy vetch (Nov.)	75		Cotton
Crozier et al., 1994	Crimson clover	110		Corn
(North Carolina)				
McVay, 1989	Crimson clover	108	99	Corn
(Georgia)	Hairy vetch	128	123	Grain sorghum
Oyer and Touchton, 1990	Crimson clover	101		Corn
(Alabama)				

Management of cover crop residues through tillage operations, termination date, and method of termination have been shown to influence the rate of mineralization of N from legume residues and availability of N to the subsequent crop. Legumes are commonly used to provide N for succeeding crops, but the net change in N pools and mineralization rates is rarely measured. Schomberg and Endale (2004) demonstrated increases in net N mineralization with crimson clover in no-tillage systems. The amount of soil N mineralized during the cotton growing season was nearly doubled in the legume system and ranged from 60 to 80 kg ha^{-1} compared with 30 to 50 kg ha^{-1} following rye.

Results from Alabama indicate that benefits of crimson clover in no-tillage corn production systems are more easily maintained within a rotation using a cash crop with a later planting date than corn (Oyer and Touchton, 1990). Allowing crimson clover cover to reseed and establish during the soybean phase of a rotation provided more N to the following corn crop compared to when the clover was fall-seeded. In the first year of the study at the North Alabama Appalachian Plateau location, clover that reseeded before soybean produced 33% more dry matter and 31% more total N than fall-planted clover. In the third year, clover that had reseeded before soybean produced 73% more dry matter and 72% more total N than fall-planted clover. On their Coastal Plains location, the reseeded clover produced 120% more dry matter and 96% more total N in the first and 132% more dry matter with 140% more total N in the second year (a year with more limited rainfall). Reseeded clover established earlier and produced more fall growth than planted clover, producing greater benefit to the subsequent corn crop.

Incorporation of legume residue usually results in faster and more complete decomposition and release of N. Using ^{15}N labeled hairy vetch residues, Varco et al. (1989) showed that incorporation of vetch residues, compared with surface placement, resulted in greater release of soil inorganic N throughout the plow depth, and thereby results in greater first year recovery of vetch N by conventionally tilled corn than by no-tillage corn. Early season N uptake by corn was greater in the conventional tillage system both years while final corn total N content was increased only in the first year. Vetch increased N availability to corn by 60 kg ha^{-1} y^{-1} across tillage systems. Recovery of vetch ^{15}N averaged over both years was 32% with conventional tillage and 20% with no-tillage. Residual recovery of vetch ^{15}N by corn the second year after application was greater with no tillage (7%) than with conventional tillage (3%).

In North Carolina, Wagger (1989a, 1989b) evaluated effects of early and late desiccation on N content and availability from rye, crimson clover, and hairy vetch. Late desiccation increased dry matter 39%, 41%, and 61% and N contents 14%, 23%, and 41%, respectively. Release of N from the cover crop residues was slower for residues desiccated at the later date due to more advanced maturity of the residues and greater C:N ratios. Cover crop type had a pronounced effect on corn growth, with corn dry matter production following a rye cover crop lower than that following legume cover crops. Corn recovery of legume N was estimated at 40 to 45 kg N ha^{-1} (2-year average), representing approximately 36% and 30% of the total N content of crimson clover and hairy vetch, respectively.

Tropical legumes as cover crops. Tropical legumes offer unique cover crops for southern producers due to their ability to fix N_2 and take up residual soil N in the early fall following a summer cash crop. Several summer legumes have been investigated for their rates of N fixation and subsequent contribution of N in corn and vegetable systems. These include cowpea (*Vigna unguiculata* [L.] Walp.), sesbania (*Sesbania exaltata* L.), soybean (*Glycine max* L.), hairy indigo (*Indigofera hirsutum* L.), velvetbean [*Mucuna deeringiana* (Bort.) Merr.], lablab (*Lablab purpureus* L.), and sunn hemp (*Crotalaria juncea* L.) (Mansoer et al., 1997; Creamer and Baldwin, 2000; Balkcom and Reeves, 2005). In Alabama, sunn hemp accumulated 6 to 7.5 Mg biomass ha^{-1} in 9 to 14 weeks when planted in late summer following corn harvest (Mansoer et al., 1997; Balkcom and Reeves, 2005). The variety "Tropic Sunn" used in these studies did not produce seed and was killed by the first frost. Nitrogen content of above-ground residue ranged from 120 to 150 kg ha^{-1} and biomass production was sufficient for good soil erosion protection over winter. Mansoer et al. (1997) found that N losses during the first 4 weeks following mowing were more than 50% and N remaining in the residue in the spring was only 38% of that when sunn hemp was frost-killed the previous fall. Balkcom and Reeves (2005) determined that the N fertilizer equivalence of sunn hemp residues to a following corn crop averaged 58 kg N ha^{-1}. Growing a small grain winter cover crop following sunn hemp could increase the amount of the N recovered from the sunn hemp and help improve system productivity. Schomberg et al. (2007) showed that sunn hemp could fit well into short-rotation sustainable vegetable production systems in the Southeast. Biomass production was maximized with May and June plantings in the Piedmont and April and May plantings in the Coastal Plains. Maximum biomass and N ranged from 8.9 to 13.0 Mg ha^{-1} and 135 to 285 kg ha^{-1}, respectively.

Soil productivity in the South can benefit from cover crops because of the additional biomass inputs that are needed to increase soil organic matter levels. Most soils of the region have a history of crop production greater than 150 years and research over the past 40 years clearly indicate that intensive biomass inputs in conservation tillage systems are beneficial (Reeves, 1997). Nitrogen management in these systems can be challenging; however, with the gains in knowledge of high residue systems, relationships between cover crop composition and soil N dynamics, and new management technologies, producers have the opportunity to better manage N inputs with minimal environmental impact.

Humid North and Corn Belt

Reducing N leaching. The corn-soybean rotation is the predominant cropping system in the Midwestern Corn Belt. Attempts to reduce nitrate losses to surface waters in this region have focused on fertilizer management. Numerous studies, however, have shown that nitrate losses can still be substantial even in the soybean year of the rotation when no N fertilizers are applied or in the corn year even when N fertilizers are applied at less than the economically optimum rate (Baker et al., 1975; Gast et al., 1978; Jaynes et al., 2001; Dinnes et al., 2002). Therefore, fine-tuning N fertilizer management probably will not reduce nitrate losses to acceptable levels, and other management practices, such as cover crops, are needed.

One of the reasons that fertilizer management alone will not solve the problem is that substantial nitrate losses to drainage water or deep percolation occur between maturity and emergence of corn and soybean crops (Kladivko et al., 1999; Cambardella et al., 1999; Kaspar et al., 2007).

In other words, losses occur during the fall, winter, and early spring when the corn and soybean crops are not taking up water and nutrients. Winter cover crops have the potential to increase uptake of nitrate and water during this period in the Midwestern Corn Belt. This would reduce the volume of water percolating through the soil and the amount of nitrate reaching surface and ground water from agricultural lands. Winter cover crops have been shown to reduce nitrate losses in areas of the country where the climate is mild and humid permitting substantial cover crop growth and where most of the nitrate losses occur during the winter (Brandi-Dohrn et al., 1997; Herbert et al., 1995; McCracken et al., 1994; Meisinger et al., 1991). In much of the Midwestern Corn Belt, however, the potential growing season between harvest and planting of corn and soybean is short and cold and the soil is frozen for some of the time. Although there are many possible winter cover crops, small grains, such as winter wheat, or winter rye seem to have the best potential as winter cover crops for Midwestern corn-soybean rotations (Snapp et al., 2005). Small grains grow well at cool temperatures; the seed is relatively inexpensive; they can be successfully established, either by overseeding late in the growing season or by direct planting after harvest; and they are easily killed with tillage or herbicides before planting the next crop (Kessavalou and Walters, 1997; Johnson et al., 1998; Strock et al., 2004; Ball Coelho et al., 2005; Snapp et al., 2005). However, information on winter cover crop effects on nitrate losses in the Midwestern Corn Belt is limited (Dinnes et al., 2002). Rasse et al. (2000) in Michigan found that a rye cover crop following inbred corn lines fertilized at 202 kg N ha^{-1} reduced leaching losses of nitrate-N by 35 and 65 kg N ha^{-1} in two years. In Minnesota, Strock et al. (2004) observed that a rye winter cover crop after corn reduced drainage volume by 11% and nitrate-N loss in drainage water by 13%. In Indiana, Kladivko et al. (2004) observed that the annual nitrate-N load in drainage water was reduced from 38 kg ha^{-1} to 15 kg ha^{-1} (61% reduction) after reducing N fertilizer rates and planting a winter wheat cover crop after corn. For continuous corn in southwestern Ontario, Ball Coelho et al. (2005) found that a rye cover crop maintained groundwater nitrate-N concentrations below 10 mg L^{-1} and reduced residual soil N by 7 to 55 kg N ha^{-1}. Lastly, in a corn and soybean rotation in Iowa, Kaspar et al. (2007) reported that averaged over 4 years a winter rye cover crop reduced flow-weighted NO_3 concentrations by 59% and loads by 61%. On average, annual nitrate-N load in the drainage water was reduced by 31 kg N ha^{-1}, even though the rye cover crop did not significantly reduce cumulative annual drainage. Thus, when a small grain winter cover crop is successfully established and moderate growth occurs, it can substantially reduce nitrate-N losses to drainage water or deep percolation in a corn-soybean rotation.

In the most northern parts of the region, however, potential N uptake is limited by the small amount of autumn growth. Bundy and Andraski (2005), using an ^{15}N-depleted fertilizer method, determined that a rye cover crop planted following sweet corn or potatoes (*Solanum tuberosum*

L.) on irrigated sandy soils in Wisconsin produced only 0.4 to 0.9 Mg ha^{-1} in aboveground dry matter and had little impact on reducing leaching during the growing season or over the winter due to the limited time period for cover crop growth. In contrast, Kaspar et al. (2007) measured 1.73 Mg Ha^{-1} of rye cover crop shoot growth averaged over 4 years in Iowa. Andraski and Bundy (2005) showed that, although N uptake by cover crops was minimal, there was a non-N "rotation effect" that increased yield of a subsequent corn crop, resulting in a lower optimal N rate and a higher corn yield at the optimal N rate. The observation of yield enhancement by a rye cover crop on sandy soils during years with high leaching potential conflicts with other observations of corn yield decreases following a rye cover crop.

Crop yields. Concerns about possible yield decreases following winter cover crops have been partly responsible for their limited adoption in the Midwestern Corn Belt (Dinnes et al., 2002). Small grain winter cover crops can potentially reduce the yield of the following corn or soybean crop in several ways. Cover crops may reduce corn yields by reducing inorganic N levels in the spring, either through uptake while the cover crops are growing or through immobilization of N during decomposition of their residues (Karlen and Doran, 1991; Tollenaar et al., 1993; Wagger and Mengel, 1993). Cover crop water use may also reduce subsequent crop yield if soil water is not replenished before it is needed by the following grain crop (Munawar et al., 1990). Lastly, cover crops may reduce yield because of allelopathy or a rotation effect (Tollenaar et al., 1993; Kessavalou and Walters, 1997). The risk of corn yield reductions following a small grain cover crop is real, but there is potential for cover crop management to eliminate the yield reductions. For example, Tollenaar et al. (1992, 1993) observed reductions in corn silage yields when the rye cover crop was killed immediately before corn planting. Similarly, in Iowa Johnson et al., (1998) reported a 1.6 Mg ha^{-1} corn yield reduction following a rye cover crop killed at corn planting, but no corn yield reduction following an oat cover crop that had winter-killed.

Miguez and Bollero (2005) conducted a review of corn yield response to cover crops and reported that grass winter cover crops, including small grains, did not consistently decrease corn yields in the Midwestern Corn Belt and that many studies reported no effect on yield. Furthermore, they found that the response or lack of response was not dependent on N fertilizer rate. In contrast, Vyn et al. (2000) found no corn yield reduction following a rye cover crop when 150 kg N ha^{-1} was applied and substantial corn yield reductions when no fertilizer was applied. Mixed responses were observed by Kessavalou and Walters (1997) in Nebraska, who measured lower corn yields following a rye cover crop in only one of three years.

Several studies have shown that killing the small grain cover crop two to three weeks before corn planting eliminated the yield reduction (Munawar et al., 1990; Raimbault et al., 1991). Ball Coelho et al. (2005)

reported that, in Southwestern Ontario, rye overseeded in late summer into standing corn increased yields of corn planted one to two weeks after killing rye in late April or early May. The yield response they observed was greater in no-tillage than in conventional tillage, especially during dry years. Additionally, they observed that N was released from rye residues in synchrony with corn crop demand, particularly when residues were incorporated by tillage. Thus, killing small grain cover crops 10 to 14 days before corn planting seems to reduce the risk of corn grain yield reductions and may allow for more timely release of cover crop N. Another potential management strategy would be to use small grain cultivars that do not have a detrimental effect on the following corn crop (Tollenaar et al., 1993; Dinnes et al., 2002). Obviously, for this strategy to succeed, small grain cultivars must be selected or bred for this purpose.

In contrast to the mixed findings on small grain cover crops preceding corn, soybean yields usually are not affected by small grain cover crops, if a good soybean stand is established. In Illinois, Liebl et al. (1992) found that a rye cover crop did not reduce soybean yields in 4 years when killed 2 weeks prior to planting, whereas a rye cover crop killed at planting did reduce yields in all 4 years because of stand reductions related to planting problems associated with residue. Similarly, in Canada, Wagner-Riddle et al. (1994) found no difference in soybean yields between no cover and cover when the rye cover crop was killed either 1 week or 2 weeks before soybean planting. Ruffo et al. (2004) in Illinois and De Bruin et al. (2005) in Minnesota observed no soybean yield decrease when a rye cover crop was killed at least one week before planting. Additionally, De Bruin et al. (2005) observed one decrease and one increase in yield out of 4 site-years when the rye cover crop was killed near the time of soybean planting. Therefore, in general soybean yield seems to be less affected by small grain cover crops than corn. We would assume that the N fixation capacity of soybean partly explains this difference in response.

Very limited work has been completed in the humid North involving legume and brassica cover crops because of their limited growth in cold weather. In Wisconsin, Stute and Posner (1995a) reported that red clover or hairy vetch growing after oat in rotation with corn could contribute the equivalent of 73 to 115 kg N ha^{-1} to the subsequent corn crop. In these studies, Stute and Posner (1995b) used mesh bags to compare soil inorganic N levels following legume incorporation to those following fertilizer N applied at the recommended rate of 179 kg N ha^{-1}. Incorporated hairy vetch and red clover residues released half their N within 4 weeks, while very little N was released after 10 weeks (the time of corn silking). Corn was planted 1 day after cover crops were killed and incorporated by tillage. Synchrony of legume N release with corn demand and levels of residual N in the fall were similar to those from fertilizer N. Similarly, Ruffo and Bollero (2003) estimated that 75% of N contained in hairy vetch tissues was released by the V6 growth stage of no-tillage corn in Illinois.

In southern Ontario, Canada, Vyn et al. (2000) found that red clover was as effective as rye, oat, or oilseed radish in taking up residual soil nitrate present in the soil following wheat harvest. The red clover had been seeded by broadcasting into the wheat in March, while the other cover crops were planted after wheat harvest. Red clover reduced the amount of supplemental N needed by a subsequent corn crop, while the other cover crops had no effect. Fall-killing of the clover cover crop provided similar N availability as spring-killing without risks associated with delayed planting, colder soil, dry seedbed conditions, or competition from incomplete cover crop kill. In another study, Vyn et al. (1999) found that oil seed radish, which winter-killed, was able to accumulate up to 50 kg N ha^{-1} prior to winter-killing and the accumulated N was released earlier in the spring than N accumulated by red clover or annual ryegrass cover crops, which were incorporated into the soil just prior to corn planting.

Modeling N leaching losses. In general, the positive or negative long-term effects of winter cover crops on N cycling and losses throughout the humid North and Corn Belt are uncertain because of the limited data available and because of the wide range of environments and management systems in which cover crops may be used (e.g., climates, soils, nutrient inputs, cover crop seeding rates, planting dates, and spring kill dates). Agricultural systems models can be used to simulate cover crop performance and impact on nitrate losses over a variety of locations, soils, management practices, and climate scenarios. They can be use to identify research needs and to estimate the potential impacts of soil, air and water quality across a wider geographic area.

Meisinger et al. (1991), using the Erosion Productivity Impact Calculator (EPIC) model (Williams et al., 1984), assessed the effect of winter cover crops by running simulations for 10 representative US sites, including two in the Corn Belt (Ames, IA; Jackson, IL). For these two sites, a barley winter cover crop following corn was predicted to reduce nitrate-N leaching by 66% for a sandy soil and by 70% for a clay loam soil. Similarly, Feyereisen et al. (2003) used modeling to predict that, in most years, a rye cover crop planted in southern Minnesota on October 15 would reduce nitrate-N losses in drainage water by at least 25 kg ha^{-1} if terminated on May 1 and by at least 36 kg ha^{-1} if terminated on June 1. Malone et al. (2007) simulated a winter wheat cover crop in a corn-soybean rotation in northeastern Iowa and predicted that the cover crop would reduce nitrate-N drainage losses by 38%. Additionally, Li et al. (2008) used the model RZWQM-DSSAT to simulate a rye winter cover crop for central Iowa and showed that over a range of simulated N fertilizer rates from 11 to 261 kg N ha^{-1} the rye winter cover crop reduced N loss in drainage by 12 to 34 kg N ha^{-1}, but the percentage difference remained relatively constant at 65%–75%. It is notable that for the soils at this simulated site N losses in drainage water were predicted to occur even with no fertilizer N applied.

Northern Plains

Cropping systems: environmental and management context. The northern Great Plains of North America is characterized by a semiarid continental climate, with evaporation exceeding precipitation in any given year (Bailey, 1995). Generally, winters in the region are long, cold, and dry, while summers are warm to hot but are brief. Mean annual temperature in the region varies from -0.2°C to 10.9°C, and frost-free periods range from 93 to 157 days (Padbury et al., 2002). Large diurnal ranges in temperature are common, as are strong winds. Annual precipitation in the region increases from west to east and ranges from 300 to 500 mm (Padbury et al., 2002). Although average values for temperature and precipitation provide a glimpse of climatic conditions, the defining characteristic of the region is its variability. Droughts, wet-periods, intense precipitation events, and extreme temperatures are commonplace (Peterson et al., 1996).

Soils within the northern Great Plains possess high natural fertility and good moisture-holding capacity. Organic matter accumulation and calcification are the dominant pedogenic processes. Taxonomically, northern Great Plains soils are dominated by Mollisols (Soil Survey Staff, 1999).

Cropping systems in the northern Great Plains have evolved considerably. Since the mid-1850s these inherently fertile soils were initially mined through intense cultivation to produce abundant crops and forage, only to result in excessive soil erosion and widespread crop failures in times of drought. Efforts to stabilize production of cereal crops led to the adoption of wheat-fallow cropping systems. This system, while popular with producers because it required limited equipment and managerial skills, has proven to be agronomically inefficient and environmentally unsustainable (Farahani et al., 1998; Liebig et al., 2004). Recognition of the drawbacks of wheat-fallow systems as well as advances in moisture-conserving residue management technology have resulted in a reduction of fallow as well as an increase in the number of types of crops grown including pulse, oilseed, forage, and other specialty crops (Padbury et al., 2002).

Nitrogen management. Nitrogen management challenges within Northern Plains cropping systems result from constraints imposed by climate. Limited precipitation, short growing seasons, and highly variable climatic conditions pose significant management challenges in balancing crop N demands with uptake to ensure optimal crop yield and quality while limiting N loss to the environment. Nitrogen management strategies that lead to an optimal balance between achievement of agronomic and environmental objectives are strongly impacted by cropping decisions affecting the overall management of cropping systems (e.g., intensification and diversification). More specific cropping practices, including the selection of crops and/or forages within a crop sequence exist within this larger rubric for N management.

In this dryland agriculture (semi-arid systems), where precipitation is lower than potential evapotranspiration (PET), N is not susceptible to large surface runoff or NO_3-N leaching events (Westfall et al., 1996; Smith and Cassel, 1991; Williams and Kissel, 1991). For example, Williams and Kissel (1991) reported that the Northern Great Plains (Bismarck, ND) have higher PET than precipitation, except during the colder months. From November to February, Bismarck has a PET of 36 and 47 mm of precipitation. However, even during the colder temperatures, the NO_3-N leaching and surface runoff potentials and are still minimal due to low total precipitation and low permeability in frozen soils (Westfall et al., 1996; Smith and Cassel, 1991; Williams and Kissel, 1991).

Management system considerations. Reducing the frequency of fallow in a cropping system increases cropping intensity. As cropping intensity increases, N removal from the system also increases, which makes supplementation of N with fertilizer and/or increasing the N-supplying capacity of soil critically important for system sustainability (Grant et al., 2002). Kolberg et al. (1996) found N fertilizer requirements increased 44% after changing from a wheat-fallow to a wheat-corn (*Zea mays* L.)–fallow crop sequence. Similar findings in semiarid cropping systems are common (Westfall et al., 1996), which reflects the increased likelihood of crop response to N fertilizer in more intensive cropping systems.

Though increased cropping intensity increases N removal, more intensive cropping systems enhance root and residue input to the soil, thereby increasing soil organic matter and the potential for enhanced N release over time (Grant et al., 2002). The N-supplying capacity of soil, as reflected by N mineralization rates, has been found to be greater in cropping systems with increased cropping intensity than in cropping systems including fallow (Liebig et al., 2006; Grant et al., 2002; Wienhold and Halvorson, 1999). The N-supplying capacity of soil can be further increased in annually cropped systems through N fertilization, which increases plant residue additions to soil (Campbell et al., 1993). Overall, while increasing cropping intensity increases N removal, it has the potential to improve the ability of soil to supply N for crop needs through the mineralization of plant residues.

Increasing cropping system diversity through the inclusion of crop species with different resource requirements can improve N-use efficiency, decrease requirements of fertilizer N, and enhance crop yields. Though N requirements vary based on yield goals, N demands tend to be greater among grain and oilseed crops relative to annual legumes, which can fix their own N (Karlen et al., 1994; Power, 1987).

Variability of resource requirements, particularly differences in N demand and water use, is high within the broad portfolio of crop species adapted to the Northern Plains (Tanaka et al., 2002). In an evaluation of ten crops in the Northern Plains, Merrill et al. (2004) found soil water extraction to be greatest for sunflower (*Helianthus annuus* L.), safflower (*Carthamus tintorius* L.), and soybean (*Glycine max* (L.) Merr.), and least for dry pea (*Pisum sativum* L.), barley, and crambe (*Crambe abysinnica* Hochst ex R.E. Fr.). Among factors affecting water uptake, length of active growing season was more influential than root growth parameters (Merrill et al., 2002), underscoring the importance of seasonal climate effects on annual water use. Such temporal variation in water uptake can make efficient use of applied N difficult. In instances where water is limiting for extended periods, residual soil N can accumulate to a level that allows for fertilization in subsequent years to be eliminated until postharvest soil N status returns to normal (Halvorson et al., 2001).

Diversification of cropping systems with different crop species not only affects N demand and water use, but also affects the amount of N returned to the soil for potential crop uptake. Crops differ in the amount of N supplied to subsequent crops as a result of varying amounts of crop residue produced and varying concentrations of N in residue (Grant et al., 2002).

Unger and Vigil (1998) conducted an extensive review of literature about the impacts of cover crops in the Great Plains and reported the effects of several winter-cover practices on wheat yields in Montana and Colorado. They concluded that cover crops on dryland cropping systems of the Great Plains reduced yields of subsequent crops, when compared to the traditional wheat-fallow rotation, primarily due to the water used by the cover crops. Unger and Vigil (1998) reported that increasing crop residue on the surface with conservation tillage might be an alternative management approach that could help increase soil water retention by lowering evapotranspiration. Such an increase in soil water content could help increase yields of the subsequent crops. These findings are supported by Peterson et al. (1996) and Farahani et al. (1998).

Producers and nutrient managers should be aware that yield responses in this dryland cropping system are also dependent on growing season weather (Merrill et al., 2006). Yield response, especially of corn and soybean that have relatively long growing seasons, could be lower during years with cool, wet springs that delay crop emergence. However, during drought years, high crop residue and no-tillage can increase water use efficiency, which contributes to higher yields (Peterson et al., 1996; Farahani et al., 1998; Merrill et al., 1996). Similar responses to cool, wet springs have also been observed in irrigated systems of the Northern Plains where soil temperatures were lowered by the increased presence of crop residue resulting from no tillage systems. This lowered soil temperature led to 16% lower corn yields in Colorado, compared to conventional tillage corn with quicker emergence (Halvorson and Reule, 2006; Halvorson et al., 2006).

The more intensive cropping systems used across North Dakota, Nebraska, Kansas, Colorado, and Texas increased crop residue, water storage and carbon sequestration in dryland systems (Peterson et al., 1998). Lyon et al. (1996) reported an average 22% higher carbon content in the top 20 cm of no-tillage soil than in a conventional tillage system in Nebraska. Data presented for North Dakota dryland spring wheat-winter wheat-sunflower showed that no tillage resulted in 13% higher carbon content in the top 30 cm of soil, compared to conventional tillage (Black and Tanaka, 1996).

The Northern Plains region is exposed to such high wind conditions that erosion can have negative impacts on soil quality and reduction in yields. Even without tillage, a high-residue production cover crop such as wheat and flax is most desirable in order to reduce soil erosion risk in this arid region (Merrill et al., 2006).

Crop/forage selection considerations. Obtaining maximum agronomic benefits from annual and perennial legumes requires information regarding their effects on subsequent crops. Annual legumes, or pulse crops, occupy an important role in Northern Plains cropping systems due to their positive effect on plant-available N for uptake by subsequent non-legume crops (Grant et al., 2002). However, because most of the N in annual legumes is contained in the seed, the way they are used (either as cover or grain crop) significantly affects the amount of N returned to the soil.

When seed is harvested from pulse crops, N contributions are negligible or slightly positive. In a study near Swift Current, SK, Miller et al. (2003a) found dry pea, lentil (*Lens culinaris* Medik.), and chickpea (*Cicer arietinum* L.) stubbles increased available N levels by 12 and 28 kg N ha^{-1} for loam and clay soils, respectively. In sub-humid regions of the Northern Plains, dry pea contributions to soil N ranged from 6 to 27 kg N ha^{-1} (Liebig et al., 2002; Stevenson and van Kessel, 1996). Among pulse crops, dry pea and lentil resulted in greater soil N levels than chickpea, probably because of differences in rhizobial N_2 fixation (Miller et al., 2003a).

When annual legumes are used as green manure, significant amounts of N can be made available for subsequent crop uptake (Grant et al., 2002). Recent studies regarding green manure N contributions from annual legumes are limited, however. In a review by Power (1987), annual legumes were observed to fix from 95 to 192 kg N ha^{-1} y^{-1} depending on the environment in which they were grown. Because production of large amounts of biomass can lead to excessive water use, Tanaka et al. (2005) argued for the adoption of short term "green fallows" that are grown for only 6 to 8 weeks prior to termination. While this brief growth period results in little N fixation, green fallow legumes can be managed so that soil water content does not differ from that of bare fallow. Additionally, the improved nutrient cycling and microbial activity can increase the yield and N use efficiency of a subsequent wheat crop.

Annual legumes often have a positive rotation effect on subsequent crops. The source of this rotation effect, however, is highly complex, and is probably the interaction of legume effects on soil N status, soil water, and disruption of pest cycles (Miller et al., 2002; Merrill et al., 2004; Krupinsky et al., 2002). Consequently, it is sometimes difficult to associate soil N contributions from annual legumes with increases in subsequent crop yields. Some studies have found soil N contributions from annual legumes to increase subsequent crop yields, provided N is yield-limiting and moisture is sufficient to utilize increased N (Badaruddin and Meyer, 1994; Beckie and Brandt, 1997). In other studies, this association isn't apparent. In a cropping sequence evaluation of 10 crops in western North Dakota, three annual legumes—dry pea (*Pisum sativum* L.), soybean, and dry bean (*Phaseolus vulgaris* L.)—had net positive crop sequence effects on seed yield over a two-year period, despite the fact that fertilizer N was applied to all crops and there were no differences in postharvest soil N levels (Krupinsky et al., 2006). Miller et al. (2003b) adjusted fertilizer N rates for wheat to account for predicted N contributions from chickpea (*Cicer arietinum* L.), lentil (*Lens culinaris* Medik.), and dry pea, yet observed greater wheat yields after the annual legumes compared to wheat after wheat. Such a non-N rotation effect underscores the possibility of other factors contributing to crop yield, such as conserved soil water, reduced plant diseases, or unaccounted for mineralized N (Miller et al., 2002).

Perennial legumes, such as alfalfa (*Medicago sativa* L.), red clover (*Trifolium pretense* L.), and alsike clover (*Trifolium hybridum* L.), occupy an important role in northern Plain agroecosystems as forage crops for beef cattle. Within the Northern Plains, the percentage of arable cropland rotated with forage crops ranges from 5% to 15%, and alfalfa (by far the most prevalent forage legume in the region) is grown on approximately 60% of cultivated forage hayland (Entz et al., 2002). Benefits of forage legumes are significant and include improved yields of annual crops following stand termination, reduced weed infestation, and improved soil quality.

Nitrogen contributions by alfalfa can reduce N fertilizer needs and decrease energy requirements for crop production (Hoeppner et al., 2006). Kelner et al. (1997) found net N addition of alfalfa was 84, 148, and 137 kg N ha^{-1} in the first, second, and third years of the stand, respectively. Single-year effects of alfalfa on N status can also be significant, as is indicated by the Kelner and Vessey (1995) report in which they found a net soil N contribution of 121 kg N ha^{-1} from 'Nitro' annual alfalfa in Manitoba. Such short-term N contributions from alfalfa indicate the potential to improve management efficiencies by shortening forage stand length to 5 years or less (Entz et al., 2002).

Rotational yield benefits from forage legumes in the Northern Plains have been documented in numerous long-term studies (Entz et al., 2002). In one of the more recent evaluations in central Alberta, Hoyt (1990) found wheat yields during the first eight years after forage stand termination to be 66% to 114% greater than continuous wheat. Such yield benefits from forage legumes, however, are not systemic throughout the Northern Plains. In areas where limited precipitation seriously limits crop productivity, alfalfa can create a "forage-induced drought," resulting in depressed crop yields 1 to 2 years after stand termination (Entz et al., 2002).

In addition to the impact of alfalfa on soil N status and yield of annual crops, it is also effective for scavenging nutrients from deep within the soil profile. Alfalfa roots can grow to depths greater than 5.5 m (Karlen et al., 1994), allowing for the extraction of mobile nutrients that may otherwise be lost to the environment. Entz et al. (2001) observed NO_3-N extraction by alfalfa to occur from 0.9 to 2.7 m over a four-year period. Nitrate extraction from deeper soil depths is not limited to alfalfa, however, as non-leguminous crop species with taproots (i.e., sunflower and safflower) can function similarly. Consequently, sequencing deep and shallow-rooted crops can potentially result in increased nutrient use efficiency if sequential crops explore different depths in the soil profile (Grant et al., 2002).

Irrigated West

There are about 55.3 million acres of harvested crops that are being irrigated in the US (USDA, 2002), and 74% of this irrigated land is west of the Mississippi river. Forty six percent of irrigated US crop land is located in Arizona, California, Colorado, Idaho, Montana, New Mexico, Nevada, Utah, Oregon, Washington, and Wyoming. California is the most irrigated state in the US, with 8.7 million irrigated acres. Other states with large irrigated areas west of the Mississippi river are Kansas, Nebraska, and Texas with 2.7, 7.6, and 5.1 million irrigated acres, respectively. Some of the most productive areas with the highest yields in the country are managed under intensive irrigated systems common in the western US. These large irrigated areas dedicated to cash crops such as vegetables and fruits sometimes have multiple crops per year and require high N rates. This intensive agriculture presents a perfect context for the use of cover crop systems.

The potential evapotranspiration (PET) is traditionally greater than precipitation across the irrigated west. For example, in the Central Valley of California, the average precipitation during the summer crop growing period from March to October is minimal but the PET is high. During this period, irrigation is used to make up for the water deficit. Although the potential for runoff and leaching due to precipitation during this period is low, the use of irrigation increases the potential for off-site nutrient transport. Runoff potential is greater for finer soils with low permeability, while NO_3-N leaching potential is greater for coarser soil systems, especially when shallower rooted crops are grown with high N input rates.

Between December and February this area receives an average precipitation twice that of the average PET rate, increasing the potential for NO_3-N leaching during this time, especially if the fields are fallow and therefore have no crop growing that could use the available water. It is important to implement effective conservation and water management practices to reduce the off site transport of nutrients during the summer and winter periods. Cover crops can successfully be used across the western US to protect soil and groundwater quality because they can scavenge residual soil NO_3-N and mine background NO_3-N in groundwater applied as irrigation (Delgado, 1998, 2001; Delgado et al., 1999, 2007a).

South-central Colorado has over 2,000 center pivot irrigation systems located on soils with low soil organic matter (SOM); either coarse sandy soils or fine soils over a coarse gravelly substratum. Similar regions include the Columbia Basin of Washington, Oregon, and Idaho, dominated by sandy to silt loam soils with low soil organic matter. These regions are very susceptible to leaching when irrigated, heavily fertilized, shallow-rooted crops are grown.

Concentrations of background NO_3-N in groundwater higher than the acceptable 10 mg NO_3-N L^{-1} level for potable water (USEPA, 1989) have been reported across the Pacific Northwest, California, Colorado, Idaho and Utah. Although this background NO_3-N in irrigation water can present a drinking water health hazard (USEPA, 1989), it can also be an important source of N for crops. For some regions of the irrigated west, the background NO_3-N in irrigation water can be a significant source of N and should be accounted for during nutrient management planning (Delgado and Follett, 2002). Delgado and Follett reported that the background NO_3-N present in irrigation water applied to seven commercial fields in Colorado varied between 17 and 72 kg NO_3-N ha^{-1} y^{-1}.

Westermann et al. (1988) found recovery rates of 60% to 80% for ^{15}N fertigations conducted for potatoes in Idaho. These results suggest a high uptake potential for background NO_3-N applied with irrigation water. Because this background NO_3-N is readily available, recommendations are for it to be considered a fertigation event during the period between planting and the point at which additional N uptake does not significantly increase yields. By functioning as vertical filter strips, cover crops and deep rooted crop rotations effectively minimize NO_3-N leaching losses (Delgado, 2001, 1998; Delgado et al., 2006b, 2008).

Cover crop systems. In Colorado, Sorghum sudan (*Sorghum bicolor* L. Moench.) is the most widely used summer cover crop grown with limited irrigation in rotation with potatoes (Delgado et al., 2007a, 2008). Some Brassicas and canola are also used with limited irrigation in Colorado. In the Columbia Basin in the Pacific Northwest, the most common cover crops used are field pea (Austrian winter pea), sweetclover, hairy vetch, sudangrass, small grains (wheat, triticale, and rye) and a variety of brassicas. In California, the most common cover crops are mixtures of triticale (×*Triticosecale* Wittm.), rye, and pea for tomatoes (*Lycopersicon esculentum* Mill.) and vetches for field corn. Cover crops are increasingly used, generally during the winter, to break up tomato monocultures in the Central Valley and in cool-season vegetable rotations in the Salinas Valley. In both of these regions, benefits of cover crops have been seen in terms of adding organic matter to the soil

(Lundquist et al., 1999; Herrero et al., 2001; Poudel et al., 2001) scavenging soil nitrogen, and preventing leaching losses (Wyland et al., 1996).

Several studies have found that cover crops increase crop yields and crop quality, while others have found that cover crops reduce yield and quality. Boydston and Hang (1995) reported that potato crops following rapeseed yielded 17% more tubers than potato crops following fallow in Washington's Columbia Basin. Boydston and Vaughn (2002) found that a rye cover crop allowed yields to be maintained with reduced herbicide inputs. Delgado et al. (2007a, 2007b) conducted studies under commercial farm operations in south central Colorado, finding that the total marketable tuber yield increased by 12% to 30% when potatoes followed a sorghum cover crop instead of fallow. During two consecutive years, the sudan sorghum cover cropped areas yielded superior tuber quality over fallow treatments, with a 40% higher production rate of tubers greater than 8 ounces. These preliminary results show that farmers can generate additional income ($60 to $400 more per acre) from the improved yield and quality, which would be more than enough to counterbalance the cost of planting of the sudan cover crop.

In irrigated systems in Colorado where weeds are chemically controlled, winter cover rye has no negative effects, and may increase potato yields planted after winter cover rye (Richard Sparks, personal communication, 2007).

Wright et al. (2003) conducted cover crops studies in irrigated Valencia orange fields (*Citrus sinensis*) in Waddell, Arizona. They reported that there were no significant differences between the clean culture treatment and a clover cover crop treatment. The clover treatment was mowed to remove any weeds emerging from the clover canopy.

In central California, winter cover crop biomass production can exceed 10 Mg ha^{-1}, but such biomass is produced at the expense of soil water depletion and can interfere with soil warming, cultivation, and weed control operations in horticultural systems (Clark, 2007). For example, Mitchell et al. (1999a) found that robust cover crop growth (9 to 11 Mg ha^{-1} for barley or barley vetch; 5.6 Mg ha^{-1} for vetch) from early October to mid-March in the semi-arid San Joaquin Valley of California reduced stored soil water by 6.5 to 7.8 cm compared to fallowed soils. Five cm of supplemental irrigation was used to facilitate cover crop establishment in the fall. Drier soil in the spring may improve field access and reduce potential for soil compaction, but will increase the need for early season irrigation of subsequent crops. The effect of reduced leaching on the long-term salt balance is another consideration.

McGuire et al. (1998) explored the ability of legume cover crop (woolypod vetch and field peas) to replace fallow in a dryland wheat-fallow cropping system in the Sacramento Valley. The cover crop reduced available soil water either 1.5 or 6.6 cm in two years. There was no response of wheat to additional N following the cover crop and no difference between 12 and 112 kg N ha^{-1} following fallow.

Madden et al. (2004) evaluated legume or grass/legume cover crops with three tillage practices for organic processing tomatoes in California. Annual ryegrass regrowth severely reduced tomato yields in one year after grass/legume treatments. The next year, rye/triticale replaced ryegrass/triticale, and yields did not differ among treatments. When the weeds were controlled mechanically, the winter cover crop and winter fallow systems had similar tomato yields.

Earlier termination of cover crops is a strategy being explored to conserve soil water. Joyce et al. (2002) recommended that if the cover crop was destroyed early in the spring before the additional soil water was lost to evapotranspiration, the water could be available for use by subsequent crops. Based on the results of field and modeling studies Islam et al. (2006) proposed a mid-February cover crop termination date after sufficient surface mulch production could increase water availability by protecting the soil from raindrop impact, enhancing infiltration during winter when rainfall occurs primarily during a few intense storms. Without early termination, their model predicted that stored soil water (in the 0 to 90 cm depth) would decrease from 2 cm to 6 cm between February 26 and March 19 during a typical winter in the Central Valley of California.

In irrigated California studies, near with legume mixture of vetch-pea-oat, marketable yields of tomato following the legume mixture were similar to those following a fallow treatment (Hartz et al., 2005). They found mixed results in the production of marketable tomato after several *Brassica* spp. cover crops when compared to fallow treatments, but concluded that the environmental benefits of using legume mixture and brassica cover crops can be achieved without affecting the average marketable tomato yields.

Colla et al. (2000) conducted studies at University of California-Davis in a tomato-safflower, corn, wheat-bean rotation, with a vetch (*Vicia faba*) winter cover crop planted for three years and winter vetch/oats on a fourth year. These were compared to annual winter fallow systems. They found that the marketable yield of tomatoes grown with the winter cover crop system was not different than that grown within the winter fallow system, but the quality of the marketable tomato was better within the winter fallow system than with the cover crop system. Colla et al. (2000) found that the winter cover crop system increased the water holding capacity and soil permeability, as well as infiltration due to an increase in surface macroporosity. Colla et al. (2000) suggested that the lower tomato quality from the cover crop system could have been related to the greater fluctuations in soil water content during the ripening stage of the tomato. Implementation of similar cover crop systems would require improved water management practices for winter cover crops irrigated systems.

Joyce et al. (2002) also investigated the impact of winter cover crops on infiltration and soil water storage in California's Sacramento Valley. They also found that cover crops reduced runoff and retarded the decrease in surface hydraulic conductivity over time. These results and a modeling analysis indicated that winter cover crops could increase soil water storage in the top meter of soil by as much as 47 mm.

The studies from Colla et al. (2000), Joyce et al. (2002), and Islam et al. (2006) suggest that irrigation management is essential to maintaining marketable tomato quality. Since cover crops also increase the infiltration rates, water management for the furrow systems may be more difficult. Drip irrigation systems that can apply irrigation more frequently, reduce the potential for leaching events and increase the potential for better tomato quality.

In irrigated semiarid regions, cover crop selection must include cover crop salinity tolerance, cover crop water use effects on field salt balances and irrigation requirements. Mitchell et al. (1999a) screened cover crops for suitability for use in an irrigated crop rotation where saline drainage water is used and where salt accumulation has led to saline soil conditions. Brassica species produced as much as 20 Mg ha^{-1} of dry matter, roughly twice as much biomass as the annual grass species and four times as much dry matter as the legume species. The brassica species and triticale (*Triticosecale*) were unaffected by the salinity of saline drainage water irrigation cropping systems (3 to 8 dS m^{-1} electrical conductivity of saturation paste extract in the top 15 cm of soil) while growth of other cover crops was reduced by an average 20% to 50%.

Gypsum is often used to ameliorate salt-affected soils and Mitchell et al. (2000) compared the abilities of cover crops and of gypsum to improve soil physical properties and crop productivity in a tomato-cotton rotation with that of winter fallow in soils irrigated with saline drainage waters. While gypsum maintained cotton stand establishment, incorporated cover crops reduced stand establishment because of stubble-reinforced crusts that impeded seedling emergence.

Mining NO_3-N from shallow groundwater and reducing N leaching. In Colorado, an early planted winter rye cover crop has a high potential to reduce the nitrate (NO_3-N) available for leaching in the top 1.5 m of the soil profile (Delgado et al., 1999; Delgado, 1998). Reductions in NO_3-N available for leaching by early-planted winter cover crops planted after lettuce and spinach has been reported to be as high as 56–179 kg NO_3-N ha^{-1} (Delgado, 1998, 2001). Late-planted winter cover crops planted after potatoes result in lesser but still significant recoveries, ranging from 18–31 kg of N ha^{-1}. The early-planted winter cover crops can return large quantities of N and organic matter (as high as 7.6 Mg ha^{-1} of dry plant residue) to subsequent crops.

Winter rye and winter wheat cover crops are used to reduce wind erosion and scavenge nitrates, recycling them into subsequent crops like lettuce, spinach and potato crops, which leave small amounts of plant residue (Delgado, 1998; Delgado et al., 1999). These cover crops can also be used by some farmers for grazing (Delgado et al., 1999) before they are incorporated as green manure for the next crop in the spring. There is concern about grazing these winter cover crops, since they are grown on soils that contain and high levels of NO_3-N that can be toxic to animals (Tucker et al., 1961). The Colorado State University Agricultural Extension Service reported that forage crops with dry weight NO_3-N concentrations of 1,150–2,300 ppm are mildly toxic to livestock, and forage crops with concentrations exceeding 2,300 ppm can be dangerous to livestock (Stanton, 1994), especially if these winter cover crops are used as the only source of feed. Delgado et al. (1999) measured aboveground NO_3-N in commercial winter cover rye grown on soils with high residual soil NO_3-N and found dry weight concentrations as high as 3,500 ppm, which is equivalent to 27 kg NO_3-N ha^{-1}. The farmer observed bloating in some of his steers but also used supplemental hay brought into the field. Delgado and Follett (1998) developed a quick field sap test to assess the NO_3-N levels of the cover crops. Although the test was able to identify the cover crops with high NO_3-N levels, they recommended that the test be calibrated for accurate results and that advice from experts be sought before grazing livestock on winter cover crops that accumulate high quantities of NO_3-N.

Delgado (1998, 2001) studied the spatial N uptake by cover crops. The estimated total N uptake for the winter cover rye grown in the sandy loam areas of the field was 179 kg ha^{-1}. The total uptake for the loamy sand was 91 kg ha^{-1}, which was consistent with the observed NO_3-N in the soil profiles, which were 176 kg ha^{-1} for the sandy loam and 83 lb ac^{-1} for the loamy sand areas. Models such as NLEAP-GIS can be used to assess cover crop N cycling potential and N dynamics across the field (Delgado, 1998; Delgado et al., 1998a, 1998b, 2000, 2001a, 2001b). Berry et al. (2005) and Delgado and Berry (2008) reported that deeper rooted systems and cover crops may represent important components of precision conservation approaches that account for site variability.

Delgado (1998) reported that not only can winter cover crops recover the NO_3-N previously leached from shallower rooted crops, but they can also significantly reduce the NO_3-N leaching in the following crop while mining NO_3-N from groundwater (Delgado, 1998, 2001). Figure 4 shows an NLEAP GIS 4.2–generated regional analysis of the potential for reduced NO_3-N leaching across south central Colorado by using cover crops. This analysis shows that the average NO_3-N leaching across the region was above 70 kg NO_3-N ha^{-1} when no cover crops were used. With the use of winter cover crops, the average NO_3-N leaching was reduced to approximately 45 kg NO_3-N ha^{-1}. When summer cover crops with limited irrigation are also used across half of the study area, the average NO_3-N leaching losses were below 30 kg NO_3-N ha^{-1}.

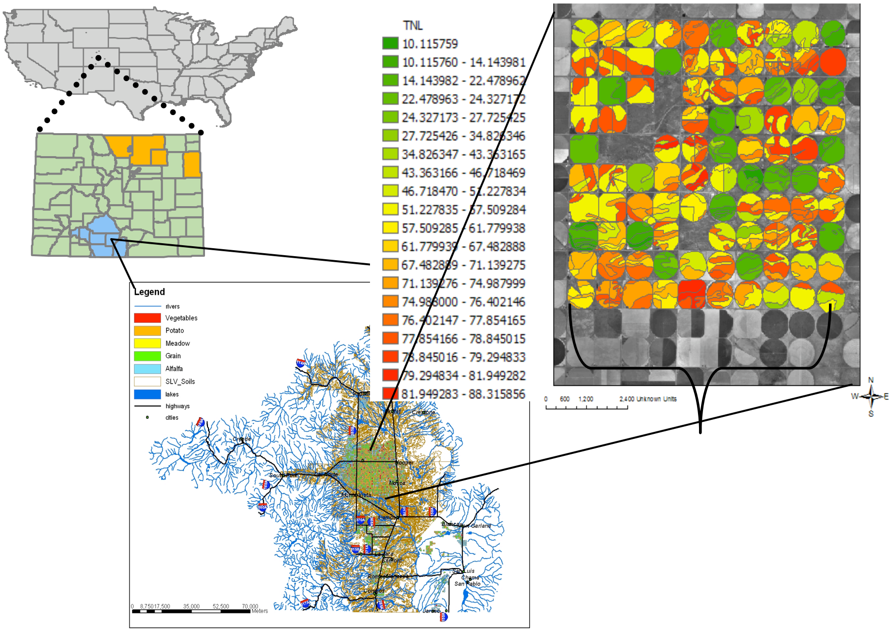

Figure 4. NLEAP predictions of the spatial distribution of nitrogen available for leaching without use of cover crops, with winter cover crops and with use of winter cover crops and summer cover crops. Farms without cover crops averaged above 70 kg NO_3-N leached; farmers with winter cover crops averaged 45 kg NO_3-N ha^{-1} leached; farms with winter cover crops and summer cover crops averaged below 30 kg NO_3-N ha^{-1}.

For some of the aquifers in this region, years of drought will require withdrawal of water at a rate greater than that which natural recharge can sustain. Farmers are looking for management practices that can increase water use efficiency, production, and economic returns from irrigation water. Cover crops promise to achieve all of these goals.

Rotations with cover crops are providing Colorado farmers with a viable management alternative that ensures sustainability of water resources. One particular cover crop/cash crop combination that is proving a viable economic alternative is the sudan sorghum-potato rotation. Delgado et al. (2007a, 2007b) suggested that a viable approach is to grow a summer cover crop with limited irrigation, but to provide enough water to keep the option to either use the aboveground biomass for hay or incorporate it as a green manure and retain all the benefits of a winter cover crop. Delgado et al. (2007a) reported that irrigation water use for crops in south central Colorado can be 457–508 mm for potato, 660–711 mm for alfalfa, 381–432 mm for barley, and 432–483 mm for winter wheat. One viable summer cover crop alternative was sudan sorghum with its minimal irrigation requirements of only 6 to 7 inches.

The sudan sorghum summer cover crop reduces the need for pumped irrigation water by more than 50%, protects water quality through its lower chemical dependence, and does not require any fertilizers, which contribute to NO_3-N leaching. Delgado et al. (2007a) reported that summer cover crops with limited irrigation not only reduce nitrate-N leaching, but also significantly reduce the leaching from the following potato growing systems and scavenge nitrate-N from background irrigated water. Limited irrigation approaches are also used in other regions such as the Northern China Plain to maximize water use efficiency and the sustainability of agricultural systems (Hu et al., 2005).

Delgado et al. (2007b) reported that the average cover crop dry matter production with limited irrigation was 4.5, 4.7, 4.7, and 6.3 Mg ha^{-1} for sudan sorghum, mustard, radish, and canola, respectively. Sudan sorghum extracted twice the amount of copper and manganese as radish, canola, or mustard. Sorghum zinc content was higher than that of the mustard and canola. Mustard, radish, and canola had higher calcium contents than the sudan sorghum. Data from Delgado et al. (2007a and 2007b) show that sudan sorghum increased the macro- and micronutrient uptake of potato tubers. The copper, manganese, and zinc use efficiencies of the sudan sorghum cover crop were 4%, 19% and 4%, respectively. The potassium, calcium, and magnesium use efficiencies were 3%, 22%, and 40%, respectively.

Significant correlation exists between the C/N ratio of the cover crop and the amount of N cycled to the potato. Cover crop barley and cash crop wheat with C/N ratios close to 100, respectively cycled 13% and 6.5% of residue N to potato (Delgado et al. 2004). Cover crops like mustard that are planted in the fall and have C/N ratios lower than 30, cycled much more residue N to following crops (Collins et al., 2006). Using ^{15}N isotopic techniques and a design similar to Delgado et al. (2004), Collins et al. (2006) found that the aboveground mustard cover crop recovered 92–142 kg of N ha^{-1}, with an aboveground biomass that ranged from 4.7–7.4 Mg ha^{-1}. The green fertilization equivalent was about 29% of the total N content of the aboveground cover crop biomass, which is equivalent to 30–40 kg of N ha^{-1} taken up by the potato crop.

CONCLUSIONS

Cover crops can have multiple benefits on N management whether occupying the land for six weeks or six months: they can reduce N leaching losses, reduce erosion N losses, fix N, immobilize N, and increase crop N uptake. Knowledge and proper management are the keys to maximizing benefits.

Cover crops increase the input and cycling of C, N, and other nutrients in agricultural systems. Long-term accumulation of soil organic C and N improves the physical and biological properties of soil, which can increase the productivity and the water and nutrient use efficiencies of crops. The most sustainable agricultural systems will be achieved by maximizing long-term cover crop nutrient and C inputs and retention without creating short-term water and nutrient deficits.

Optimal cover crop management varies by region and cropping system. Benefits are frequently maximized by adopting conservation tillage systems that retain cover crop residues on the soil surface to improve water infiltration. To capture N and reduce environmental losses, cover crops used as catch crops should have rapid root growth potential and should be planted as early as possible. In many situations, to increase N availability to subsequent crops in the form of green manure, cover crops should be killed in the winter or early spring to avoid preemptive competition and speed release of accumulated N. Because legumes' N fixation is facultative, mixtures of legumes and non-legumes offer the flexibility to either improve N scavenging when soil N is abundant, or increase growth and N accumulation when soil N is limited.

Cover crops can increase yields and quality of crops. Summer cover crops with limited irrigation can be used as water management tools to increase water use efficiencies. However, managers must properly control weeds and diseases, maximize nutrient cycling and availability, and control water usage to ensure that no yield reduction or decrease in crop quality occurs.

Computer models such as NLEAP GIS 4.2 can be useful tools for assessing the benefits of cover crops in terms of their potential to reduce NO_3-N leaching across a region or to mine NO_3-N from underground water. Cover crops can be used viably across the US, and we recommend that those considering using cover crops investigate local practices to determine cover crops' potential to maximize yields, crop quality and environmental conservation.

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