Winter Cover Crops for Sustainable Agricultural Systems: Influence on Soil Properties, Water Quality, and Crop Yields

Upendra M. Sainju¹ and Bharat P. Singh²

Agricultural Research Station, Fort Valley State University, 1005 State College Drive, Fort Valley, GA 31030-3298

The goal of a sustainable agricultural system is to adopt methods that depend primarily on renewable inputs for maintaining current levels of crop productivity. One-third of the productive capacity of American crops results from the use of N fertilizers (Poincelot, 1986). Therefore, inorganic nitrogen constitutes one of the main synthetic inputs used in agriculture. The N supplied by fertilizers is difficult to manage in the field because it is subject to loss from leaching, denitrification, and volatilization. Excessive fertilization and poor soil and crop management practices have increased NO_3^- pollution in the groundwater (Follett, 1989; Hallberg, 1989; Linville and Smith, 1971). Practices that immobilize and recycle residual NO_3^- in the soil after crop harvest are needed to prevent leaching of commercial N fertilizer and to control groundwater contamination.

Cover crops planted in the fall use residual NO_3^- , thereby reducing its loss from the soil (Power and Doran, 1988). Depending on the species, winter cover crops can supply N to the following crop and enhance organic C and N concentrations in the soil (Hargrove, 1986; Kamprath et al., 1958; Kuo et al., 1995, 1996; McVay et al., 1989; Meisinger et al., 1991; Wilson et al., 1982). Before the availability of relatively inexpensive N fertilizers, legume cover crops were commonly used as green manure to supply N needs of the succeeding crops. Cover crops provide vegetative cover in erosion-prone areas in the winter (Frankenberger and Abdelmagid, 1985; Smith et al., 1987) and improve physical, chemical, and biological properties of the soil (Hoyt and Hargrove, 1986; Power and Doran, 1988; Vigil and Kissel, 1991). They are effective in reducing weeds in strawberry (*Fragaria xananassa* Duch.) (Newenhouse and Dana, 1989; Pritts and Kelly, 1993; Smeda and Putnam, 1988) and vegetables (Wallace and Bellinder, 1992). Decreased insect populations in orchards and vineyards (Altieri and Schmidt, 1985; Bugg, 1992; Yan and Duan, 1988) and reduced pathogen severity in lettuce (*Lactuca sativa* L.) (Van Bruggen et al., 1990) also result from the use of cover crops.

The objectives of this paper are to discuss the salient characteristics of legume and nonlegume cover crops and examine the effect of the two types on: 1) soil N mineralization, and N uptake and yield of the succeeding crop, 2) soil organic C and N, and physical properties, and 3) NO_3^- leaching from the soil and potential groundwater pollution. Research needs are also addressed.

COVER CROP GROWTH AND N ACCUMULATION

Cover crop growth and C and N contributed by them depends on species, length of the growing season, climate, and soil conditions (Shennan, 1992). Among leguminous species suitable for use as cover crops are hairy vetch (*Vicia villosa* Roth), purple vetch (*V. benghalensis* L.), big flower vetch (*V. grandiflora* Scop), lana woolypod vetch (*V. dasycarpa* Ten.), crown vetch (*Coronilla varia* L.), crimson clover (*Trifolium incarnatum* L.), subterranean clover (*T. subterraneum* L.), Kura clover (*T. ambiguum* L.), sweet clover (*Melilotus* spp.), lupines (*Lupinus* spp.), and Austrian winter pea [*Pisum sativum* var. *arvense* (L.) Poirét]. Nonleguminous cereal cover crop species include rye (*Secale cereale* L.), oat (*Avena sativa* L.), barley (*Hordeum vulgare* L.), annual ryegrass (*Lolium multiflorum* Lam.), wheat (*Triticum aestivum* L.), and timothy (*Phleum pratense* L.). Several brassica species, such as mustard [*Brassica juncea* (L.) Czerniak], canola (*B. napus* L.), turnip (*B. rapa* L. Rapifera Group), and radish (*Raphanus sativus* L.), also grow well as a winter cover crop. The choice of a cover crop depends on whether the primary purpose is to supply N to the succeeding crop and reduce N fertilizer use, to reduce NO_3^- leaching, or to improve soil properties (Meisinger et al., 1991). Legume cover crops fix N symbiotically from the atmosphere and supply it to the succeeding crop. Nonlegume cover crops, in contrast, are effective in reducing NO_3^- leaching from the soil during winter months by absorbing large amounts of available N through their extensive root systems (Kuo et al., 1995; McCracken et al., 1994). The biomass yield of legumes ranges from 0.7 to 9.3 $\text{Mg}\cdot\text{ha}^{-1}$, while N contribution varies from 38 to 220 $\text{kg}\cdot\text{ha}^{-1}$ (Table 1). In comparison, nonlegumes produce biomass in the range of 1.5 to 7.1 $\text{Mg}\cdot\text{ha}^{-1}$ and supply N between 14 and 90 $\text{kg}\cdot\text{ha}^{-1}$. The variation in the biomass yield and N contribution of the cover crops from one place to another results from species adaptation to the site due to variation in soil and climatic conditions (Meisinger et

al., 1991; Shennan, 1992). Higher concentration of N in the legume cover crops also results in greater N contribution than nonlegume cover crops (Kuo et al., 1995; Meisinger et al., 1991; Shennan, 1992).

SUMMER CROP YIELD AND SOIL N MINERALIZATION

Most studies of cover crop influence on summer crop yields have concentrated on cereal crops. Legumes increased yield and N uptake of the summer crops more than did nonlegume cover crops or a fallow treatment (Table 1). Legume cover crops increased yields of tomato (*Lycopersicon esculentum* Mill.) (Stivers and Shennan, 1991), brassica (Schonbeck et al., 1993), strawberry (Newenhouse and Dana, 1989), lettuce (Stirzaker and White, 1995), and orange (*Citrus sinensis* L.) (Pratt et al., 1957). Abdul-Baki and co-workers (Abdul-Baki and Teasdale, 1993; Abdul-Baki et al., 1996; Teasdale and Abdul-Baki, 1995) found that hairy vetch mulch supplied N and increased the tomato yield more than black polyethylene mulch or bare soil. Hairy vetch mulch also increased tomato production late in the season and increased monetary returns, even during adverse climatic conditions, compared to polyethylene mulch or bare soil (Kelly et al., 1995). In Kansas, muskmelon (*Cucumis melo* L.) yields following legume cover crops were similar to those with synthetic N fertilizer (Singogo et al., 1996). However, the increase in soil mineral N from legumes was not accompanied by higher yields of snap beans (*Phaseolus vulgaris* L.) (Nesmith and McCracken, 1994a, 1994b), pea (*Pisum sativum* L.) (Turley et al., 1992), or oil palms (*Elaeis guineensis* Jacq.) (Agamuthu and Broughton, 1986).

Legume winter cover crops provide substantial amounts of N to the succeeding crop (Frye et al., 1988; Hargrove, 1986; Smith et al., 1987; Touchton et al., 1984; Vigil and Kissel, 1991) (Table 2). The yield increases of the summer crops following legumes were equivalent to that produced by fertilizer N at 15 to 200 $\text{kg}\cdot\text{ha}^{-1}$. However, nonlegumes produced crop yields and N uptake equivalent to or less than that produced by controls without a cover crop. The larger crop yield following a legume compared to nonlegume cover crop results from differences in legume and nonlegume chemical composition, primarily N and lignin concentrations, and C : N ratio (Kuo et al., 1996). Legumes, because of their high N concentration and low C : N ratio,

Received for publication 5 Mar. 1996. Accepted for publication 25 June 1996. The cost of publishing this paper was defrayed in part by the payment of page charges. Under postal regulations, this paper therefore must be hereby marked advertisement solely to indicate this fact.

¹Research Associate.

²Professor.

decompose rapidly in the soil (McKaig et al., 1940; Waggoner et al., 1985; Yaacob and Blair, 1980) and release N earlier than do nonlegumes (Kuo et al., 1995, 1996; Sainju and Kuo, 1994). The half life of cover crops, after incorporation into the soil, ranges from 2 to 9 weeks (Buchanan and King, 1993; Gale and Gilmour, 1988; Jenkinson and Rayner, 1977; Kuo and Sainju, 1994; Sainju and Kuo, 1994; Varco, 1986; Wilson and Hargrove, 1986). Stute and Posner (1995) found that, in Wisconsin, hairy vetch and red clover released half of their N within 4 weeks after incorporation into the soil, thereby synchronizing their N release with corn (*Zea mays* L.) N demand. The soil

mineral N content and grain yield of corn following legumes was similar to that obtained from applying fertilizer N at 179 kg-ha⁻¹. In contrast, Huntington et al. (1985) found that, in Kentucky, most of the N mineralized from hairy vetch residues in a no-till system became available to corn late in the growing season and was unlikely to be taken up by the crop.

Large C : N ratios result in N immobilization and reduced N availability to the succeeding crop (Allison and Klein, 1962; Aulakh et al., 1991). Waggoner et al. (1985) found that increasing the C : N ratio of the crop residue from 27 to 38 decreased N mineralization of the applied residue from 33% to 12%. For

mineralization of N to occur in the soil, the C : N ratio of the applied residue should be <25 (Vigil and Kissel, 1991; Waggoner, 1989) or N concentration of the residue should be in the range 16.6 to 18.9 g·kg⁻¹ (Iritani and Arnold, 1960). Nitrogen concentration of a cover crop varies with the stage of growth (Kuo et al., 1996). Therefore, extent of mineralization would also depend on the growth stage at which a cover crop is incorporated into the soil.

Cover crops increase N cycling in the soil because of increased biological activity compared to N fertilization (Radke et al., 1988). However, only 17% to 30% of N mineralized from legume cover crops is available to plants

Table 1. Cover crop yields and their N contributions, and yield and N uptake of succeeding crop.

Reference and location	Cover crop	Succeeding crop/rotation	Cover crop		Succeeding crop	
			Yield (Mg·ha ⁻¹)	N contribution (kg·ha ⁻¹)	Yield (Mg·ha ⁻¹)	N uptake (kg·ha ⁻¹)
Clark et al. (1994), Maryland	Hairy vetch	Field corn	0.73–5.19	38–161	5.5–10.7	---
	Rye		2.90–7.10	58–90	3.1–6.1	---
	Hairy vetch + rye		3.44–8.13	104–185	5.2–8.4	---
	Control		---	---	3.6–6.9	---
Decker et al. (1994), Maryland	Hairy vetch	Field corn	2.9–5.1	109–206	7.2–8.9	140–204
	Austrian winter pea		1.9–4.7	73–180	7.5–8.9	144–201
	Crimson clover		2.1–6.5	59–170	7.2–8.9	138–190
	Wheat		2.1–4.0	35–42	6.2–7.2	128–165
	Control		---	---	6.3–7.7	121–175
Ebelhar et al. (1984), Kentucky	Hairy vetch	Field corn	5.1	209	6.4	---
	Big flower vetch		1.9	60	4.2	---
	Crimson clover		2.4	56	4.4	---
	Rye		3.4	36	---	---
	Fallow		---	---	4.4	---
Hargrove (1986), Georgia	Rye	Sorghum	4.03	38	2.6	---
	Crimson clover		7.17	170	3.9	---
	Subterranean clover		4.00	114	3.8	---
	Hairy vetch		4.25	153	4.0	---
	Common vetch		4.30	134	3.7	---
Huntington et al. (1985), Kentucky	Rye	Field corn	1.5	14	0.9	17
	Hairy vetch		3.3	125	4.1	110
	Control		---	---	0.4	14
Kamprath et al. (1968), North Carolina	Austrian winter pea	Field corn	1.96	51	3.0	---
	Oats + hairy vetch		2.92	87	3.3	---
	Hairy vetch		3.01	120	3.9	---
	Austrian winter pea	Cotton	2.05	79	95.9	---
	Oats + hairy vetch		3.31	106	87.7	---
	Hairy vetch		3.18	131	87.2	---
Kelly et al. (1995), Maryland	Hairy vetch mulch	Tomato	---	---	104	---
	Polyethylene mulch		---	---	80	---
	Bare soil		---	---	55	---
Kuo et al. (1995a), Washington	Rye	Silage corn	5.3	60	7.4	112
	Annual ryegrass		7.1	56	7.2	62
	Hairy vetch		3.2	120	12.3	179
	Austrian winter pea		3.9	100	9.6	118
	Canola		3.3	44	7.8	78
	Control		2.1	30	7.6	73
	Hairy vetch		3.4	128	8.5	90
McVay et al. (1989), Georgia	Crimson clover	Field corn	3.5	108	---	---
	Wheat		1.8	32	3.5	30
	Fallow		---	---	---	---
	Purple vetch		5.3	178	12.3 (103) ^z	---
	Lana woollypod vetch		6.3	220	---	---
Shennan (1992), California	Oats + vetch	Tomato/	6.3	130	10.6 (90) ^z	---
	Faba beans + vetch	Tomato ^z	5.1	174	---	---
	Winter annual grasses	Field corn/	2.9	51	---	---
	Austrian winter pea		3.2	110	11.1 (77) ^z	---
	Oats		5.4	52	6.8 (62) ^z	---
	Bell beans		---	---	10.2 (84) ^z	---
	Fallow		2.7	31	0.6	---
Touchton et al. (1984), Alabama	Crimson clover	Cotton	4.5	95	0.9	---
	Common vetch		4.9	118	0.8	---

^zValues outside parentheses is field corn yield, value inside parentheses is tomato yield. Summer crops were 2 years of field corn and 2 years of tomato in 4 years rotation.

as opposed to 60% to 70% N availability from N fertilizers (Huntington et al., 1985; Ladd and Amato, 1986; Radke et al., 1988; Smith et al., 1987). Nitrogen mineralized from the incorporated cover crop residues can substitute part or all of the commercial N fertilizer needs of the succeeding crop (Morris et al., 1993). McVay et al. (1989) reported that hairy vetch and crimson clover can provide all the N requirements of sorghum [*Sorghum bicolor* (L.) Moench] or two-thirds of the N requirement of corn.

There are several ways of determining the amount of N mineralized in the soil. The N mineralization potential (N_0) of the soil is a commonly used method. It reflects the amount of N available in the soil during the growing season (Maimone et al., 1991) and correlates significantly with N uptake and crop yield (Keeney and Bremner, 1966; Stanford et al., 1973, 1977). N_0 is determined by incubating soil at constant temperature and moisture for 24 weeks (Campbell and Souster, 1982; Stanford, 1982). Timing of soil sampling for incubation is important. Sainju et al. (1995) reported that N_0 was significantly correlated with rye yield and N uptake when soil samples were taken immediately after cover crop incorporation. In contrast, N_0 in the soil samples taken 3 weeks after incorporation did not correlate with silage corn yield or N uptake because a substantial portion of N from the cover crop residues had already mineralized during the first 3 weeks of incorporation (Kuo et al., 1996). However, when initial inorganic N (N_i) was included in the multiple linear regression with N_0 , the coefficient of determination (r^2) increased from 0.69 to 0.75 for silage corn yields and from 0.75 to 0.86 for N uptake. This result indicated that N_i should be considered together with N_0 when evaluating N mineralization from cover crop residues. N_0 is also used to determine the effects of various agricultural practices, such as N fertilization, tillage, crop rotation, and manure addition on soil fertility (Campbell and Souster, 1982; Carter and Rennie, 1982; Doran, 1980; El-Haris et al., 1983). N_0 constitutes from 0% to 41% of total soil N depending on soil, tillage, crop rotation, season, past N fertilization, and level of toxins and lignin content (El-Haris et al., 1983; Marion et al., 1981; Serna and Pomares, 1992; Stanford and Smith, 1972). Most of the N mineralized in the soil comes from microbial cells and microbial metabolites (Bonde and Rosswall, 1987) and microbial biomass N constitutes 55% to 89% of N_0 (Bonde et al., 1988).

Since it takes a long time to determine N_0 , alternative methods for estimation of mineralizable N have been suggested. The amount of N mineralized in 1 to 6 weeks of incubation also relates closely with N uptake and crop yield; thus, this amount can be substituted as an index of N mineralization (Dolmat et al., 1980; Gasser and Kalembsa, 1976; Smith and Stanford, 1971; Stanford et al., 1973). Soil organic N is linearly related to N_0 (Bonde and Rosswall, 1987; Bonde et al., 1988; El-Haris et al., 1983; Kuo et al., 1996; Marion et al., 1981). Therefore, it is possible to extrapolate

N_0 from organic N concentration values.

A linear correlation exists between the concentration of N_i in the soil and crop N uptake and yield (Dahnke and Vasey, 1973; Keeney and Bremner, 1966; Kuo et al., 1996; Serna and Pomares, 1992; Smith, 1966; Stanford et al., 1977; Stanford and Legg, 1968). As a result, N_i is often used in projecting the amount of soil mineral N potentially available to the summer crop. The presidedress soil NO_3^- test (PSNT), a measure of soil NO_3^- status at 4–6 weeks after summer crop planting, is also often used for determining soil N availability to plants. Brown et al. (1993) and Sainju and Kuo (1994) reported that NO_3^- concentration in the soil peaked 42 to 78 days after legume cover crop residue incorporation. The close relationship between PSNT and summer N availability is well established from the work of various investigators (Heckman et al., 1995; Klausner et al., 1993; Magdoff, 1991; Meisinger et al., 1992). Kuo et al. (1996) discovered that, in a cover crop-silage corn rotation, PSNT predicted silage corn yield and N uptake more accurately than did N_i . The value of PSNT depended on the species, N concentration, C : N ratio, and the amount of N accumulated in the cover crop. The PSNT values following hairy vetch and Austrian winter pea were higher than following rye, ryegrass, canola, or a bare ground control. Climate significantly influences the mineralization rate of cover crop residues and the effectiveness of PSNT. Roth et al. (1992) found PSNT ineffective in predicting the effect of alfalfa residues on corn yield in Pennsylvania.

SOIL ORGANIC C AND N, AND PHYSICAL PROPERTIES

Soil organic matter (soil organic C and N) continuously degrades in the soil following cultivation without adequate plant materials being returned to the soil or without C and N

being replaced by soil amendments (Cambardella and Elliott, 1993; Campbell and Souster, 1982; Collins et al., 1992; Odell et al., 1984; Tiessen et al., 1982; Van Doren et al., 1976). Cultivation disintegrates macro-aggregates, exposing new soil surfaces and altering temperature, aeration, and moisture content of the soil for microbial degradation, thus resulting in accelerated soil C and N oxidation (Cambardella and Elliott, 1993; Dalal and Mayer, 1986; Woods and Schuman, 1988). Rate of decline of soil organic C and N due to cultivation depends on the types of crops grown and crop rotation (Hobbs and Brown, 1957), method of disposal of crop residues (Gosdin et al., 1949; Oveson, 1966), soil characteristics (Anderson and Browning, 1949), fertilization (Mazurak and Conrad, 1966), and tillage practices (Hobbs and Brown, 1957). Following the land without plant residues being returned to the soil increases the rate of organic matter depletion (Elliott, 1986; Hargrove, 1986; Havlin et al., 1990; Ridley and Hedlin, 1968).

Crop management practices can influence sequestering of atmospheric CO_2 into the plant and soil (Council for Agricultural Science and Technology, 1992). The atmospheric CO_2 fixed by winter cover crops is assimilated into the soil after incorporation of their residues. If the cover crop is a legume, the atmospheric N_2 fixed by it can also be incorporated into the soil. Cover crop residues are helpful in maintaining or increasing the concentration of organic C and N in the soil (Table 3). The extent of the increase of organic C and N following incorporation of cover crop residues is regulated by a combination of factors, including the amount and quality of residues, rate and manner of application, soil type, frequency of tillage, and climatic conditions (Smith et al., 1987; Stevenson, 1982).

The amount of increase in organic C and N concentrations depends on the quantity of cover crop residues returned to the soil (Biederbeck et al., 1984; Black, 1973; Frye et al., 1988;

Table 2. Legume cover crop N equivalent to fertilizer N for crop production.²

Reference	Cover crop	Summer crop	N equivalence (kg-ha ⁻¹)
Breman and Wright (1984)	Hairy vetch	Sorghum	89
Brown et al. (1985)	Hairy vetch	Cotton	67–101
	Crimson clover		34–67
Buntley (1986)	Hairy vetch + wheat	Field corn	56
Ebelhar et al. (1984)	Hairy vetch	Field corn	87
	Big flower vetch		15
	Crimson clover		22
	Crimson clover	Sorghum	75
	Hairy vetch	Silage corn	200
Eylands and Gallaher (1984)	Hairy vetch	Sorghum	97
	Common vetch		61
	Crimson clover		92
	Subterranean clover		61
	Hairy vetch	Field corn	66
Herbek et al. (1987)	Big flower vetch		64
McVay et al. (1989)	Winter pea	Field corn	27–79
Meyer (1987)	Hairy vetch	Barley	75–149
Touhton et al. (1984)	Hairy vetch	Cotton	68
	Crimson clover		68
Varco et al. (1984)	Hairy vetch	Field corn	78
Worsham (1986)	Hairy vetch	Field corn	200
	Crimson clover		100

²Source: Frye et al. (1988) and Smith et al. (1987).

Havlin et al., 1990; Kamprath et al., 1958; Karraker et al., 1950; Larson et al., 1972; Lewis and Hunter, 1940; Varvel 1994). Since organic N is closely retained with organic C in the soil (Smith et al., 1987), the soil N concentration is governed more by the quantity of residue input than the N concentration or the amount of N supplied by the cover crop (Allison, 1973; Rasmussen et al., 1980). Cover crops may differ in their biomass yield because of inherent genetic differences or adaptability to the prevalent climatic and soil conditions.

The control of climate on C and N contribution to the soil by cover crops is evident from comparing the results of similar studies conducted in the Pacific Northwest and southeastern United States. Kuo et al. (1995) reported that in the Pacific Northwest, organic C and N concentrations in the soil significantly increased after winter cover cropping with nonlegumes, such as rye and annual ryegrass, for 6 years. But there was no change in soil organic C or N concentrations with legumes, such as hairy vetch and Austrian winter pea. Rye and annual ryegrass, established in the fall, accumulated considerable amounts of dry matter before the onset of winter dormancy, and resumed growth with the start of spring. The temperature in the Pacific Northwest,

however, was not suited for sustained growth of hairy vetch and Austrian winter pea in fall. The bulk of legume growth, therefore, was limited to spring. As a result, nonlegumes yielded 59% more biomass than did legumes. The total (top growth + root) biomass yields of rye and ryegrass were 5.3 and 7.1 Mg·ha⁻¹, respectively, which were within or higher than the range of 5–6 Mg·ha⁻¹ of plant residue needed to maintain organic C and N levels in the soil (Larson et al., 1972; Rasmussen et al., 1980). However, in studies conducted in the southeastern United States (Hargrove 1986; McVay et al., 1989; Touchton et al., 1984), hairy vetch produced more biomass yield than either rye or wheat. As a consequence, hairy vetch was more effective in this region for increasing soil organic N and C concentrations than was rye or wheat.

Another factor affecting soil organic N and C concentrations is the rate at which cover crop residues incorporated into the soil decompose (Dalal and Mayer, 1986; Jenkinson and Rayner, 1977). The decomposition rates vary with the species and growth stage at incorporation (Frankenberger and Abdelmagid, 1985). The differences among species in the rate of decomposition is primarily due to variation in their chemical composition (Quemada and Cabrera, 1995; Staaf and Berg,

1981). The decomposition rate of plant residues depends on the size of available C and N pools as they affect the size of microbial biomass (Reinertsen et al., 1984). Climate, particularly temperature and moisture, regulates the rate of decomposition (Stanford and Smith, 1972).

Cover crops influence soil physical properties, such as water relationships, aggregation, infiltration capacity, bulk density, temperature, and hydraulic conductivity. The influence of cover crops on soil water content is the result of (1) reduced evaporation due to a mulch effect, (2) increased infiltration and retention of precipitation, (3) loss of water by transpiration from the cover crop canopy, and (4) altered water use by the summer crop if its growth is affected (Smith et al., 1987). Low rate of water loss under mulch is attributed to (1) barrier to water vapor movement, (2) reduction in solar radiation from shading, and (3) insulation of the soil surface (Smith et al., 1987). Roberson et al. (1991) found that cover cropping increased the heavy fraction of soil carbohydrates (denser than 1.7 g·mL⁻¹) responsible for binding the soil particles together. This fraction resulted in increased macro-aggregate slaking resistance and saturated hydraulic conductivity of an orchard soil. Cover cropping also increased water-stable aggregates (McVay et al., 1989) and water infiltration capacity of the soil (McVay et al., 1989; Proebsting, 1952; Williams, 1966; Williams and Doneen, 1960).

Cover crop mulch reduced soil temperature, promoting root development of oil palms (Agamuthu and Broughton, 1986), strawberry (Newenhouse and Dana, 1989), and tomato (Kelly et al., 1995). It reduced soil erosion through diminished raindrop impact and surface runoff, and increased water infiltration and transpiration. Frye et al. (1985) estimated that soil loss by erosion decreased from 18 to 2 Mg·ha⁻¹·year⁻¹ by planting a cover crop in fall. After surveying the literature, Langdale et al. (1991) concluded that cover crop reduces soil erosion by 62% in Ultisols and between 47% to 96% in Alfisols relative to bare soil in the southeastern United States.

GROUNDWATER NITRATE

When amendments such as manure, crop residues, or N fertilizer are used to supply crop N requirements, only a part of the applied and mineralized N is taken up by plants. The remaining N, if not immobilized in the soil, is subject to leaching and denitrification. Nitrate, the mineralized form of N taken up by plants, is the most mobile form of N. It is soluble in water and carries a negative charge. Therefore, it is not retained by negatively charged soil colloids (Legg and Meisinger, 1982; Russelle and Hargrove, 1989) and is free to move with the percolating water. As a result, it can easily leach from the soil profile and contaminate groundwater (Meisinger et al., 1991).

In humid regions, NO₃⁻ leaching occurs most frequently during fall–winter–spring when evapotranspiration is low and precipitation

Table 3. Cover crop effects on soil organic C and N concentrations.

Reference	Cover crop	Soil depth (cm)	Organic component	
			C (g·kg ⁻¹)	N (g·kg ⁻¹)
Frye et al. (1986)	Fallow	0–7.5	10.6	1.2
	Hairy vetch		13.5	1.5
	Big flower vetch		12.7	1.4
	Rye		11.5	1.2
Hargrove (1986)	Initial	0–7.5	11.3	0.77
	Fallow		7.9	0.58
	Rye		8.7	0.65
	Crimson clover		8.4	0.65
	Subterranean clover	7.5–15	10.0	0.81
	Hairy vetch		9.7	0.80
	Common vetch		10.2	0.63
	Initial		6.1	0.49
	Fallow		4.8	0.37
	Rye		5.4	0.42
	Crimson clover		4.9	0.41
Kuo et al. (1995)	Subterranean clover	0–15	5.5	0.48
	Hairy vetch		5.5	0.51
	Common vetch		5.1	0.45
	Control		15.7	1.22
	Austrian winter pea		16.0	1.26
	Hairy vetch		15.8	1.28
	Canola		15.4	1.23
	Cereal rye		16.6	1.34
	Annual ryegrass		16.6	1.28
McVay et al. (1989)	Fallow	0–5	8.5–10.1	1.0–1.3
	Wheat		8.9–11.8	1.1–1.4
	Crimson clover		10.6–12.8	1.3–1.5
	Hairy vetch		10.2–11.8	1.3–1.5
	Fallow	5–10	7.2–8.7	0.90–1.0
	Wheat		7.3–9.5	1.0–1.2
	Crimson clover		7.7–10.3	1.0–1.2
	Hairy vetch		7.4–9.3	1.0–1.2
Touchton et al. (1984)	Fallow	0–11	7.0	0.32
	Crimson clover		8.7	0.43
	Hairy vetch		10.8	0.42
Wilson et al. (1982)	Initial	0–15	17.0	1.6
	Fallow		12.0	1.2
	Grasses		15.0	1.8
	Legumes		16.0	2.0

exceeds the water-holding capacity of the soil. The amount of leaching depends on soil texture, plant N uptake, N transformations, precipitation, evapotranspiration, fertilizer input, and drainage (Campbell et al., 1994). Soil may contain abundant NO_3^- during the leaching-prone period for several reasons. Part of the N fertilizer applied to the summer crop may go unused. The soil and summer crop residue mineralization may also supply additional NO_3^- to the soil. Contamination of groundwater increases when excessive N fertilizer is applied to the soil accompanied by poor soil and plant management practices (Hallberg, 1989; Linville and Smith, 1971). Because vegetable production systems involve large inputs of N, they are very sensitive to NO_3^- leaching (Power and Schepers, 1989). Liang and Mackenzie (1994) and Waggoner et al. (1985) found that losses of NO_3^- due to leaching from fall to spring increased with increasing N fertilization rates and ranged from 6 to 260 kg-ha⁻¹. They noted that the change in NO_3^- concentration during this period was a function of fall soil NO_3^- level and precipitation during winter months. With above-average precipitation, a significant amount of NO_3^- can leach beyond the root zone even in arid soils (Campbell et al., 1984). Following the land also increases NO_3^- leaching (Campbell et al., 1984, 1994).

Winter cover crops use NO_3^- remaining in the soil after the fall harvest, thereby reducing the amount available for leaching (Meisinger et al., 1991; Power and Doran, 1988). They also use water that might otherwise solubilize N and transport it through runoff and infiltration (Meisinger et al., 1991). A cover crop that establishes quickly and grows vigorously in the fall is ideal for preventing leaching (Meisinger et al., 1991). Nonlegumes reduced NO_3^- leaching from 29% to 94% compared to -6% to 48% by legumes (Table 4). Kuo et al. (1995) reported that rye and annual ryegrass effectively removed NO_3^- from the soil and lowered its concentration in the soil leachate compared to a control without a cover crop. Both crops established themselves early in the fall and produced extensive root systems for scavenging residual NO_3^- after fall harvest. On the contrary, hairy vetch increased leachate NO_3^- concentration. McCracken et al. (1994) discovered that rye reduced NO_3^- concentration in the soil leachate by 94% compared to 48% by hairy vetch. The effectiveness of hairy vetch was limited to the spring season when it grew vigorously. Meisinger et al. (1991) estimated that nonlegumes and legumes reduced NO_3^- leaching by 70% and 23%, respectively. Staver and Brinsfield (1990) also found rye effective in controlling NO_3^- leaching. Campbell et al. (1994) observed that following followed by legume cover crops increased NO_3^- leaching from the soil.

Grasses have been widely used as nonlegume cover crops to control NO_3^- leaching from the soil. Several nongrass species, such as mustard, canola, radish, and turnip prevent leaching of NO_3^- (Meisinger et al., 1991). Jackson et al. (1993) and Stivers and Jackson (1991) found that oilseed cover crops also effectively removed NO_3^- from the soil.

The ability of a species to affect N leaching depended on the rapidity with which it could establish and develop a root system during the relatively low temperatures of the fall season.

RESEARCH NEEDS

Neither legume nor nonlegume cover crops, alone, appear to supply adequate amounts of N to a summer crop and to also reduce NO_3^- leaching and depletion of organic C and N from the soil. While legumes can supply N to the summer crop, nonlegumes are more effective in controlling NO_3^- leaching. Therefore, cover crops comprising of a mixture of legume and nonlegume need examination for achieving both objectives. However, growth of two species in mixture may not be similar to that when planted separately. The effect of member species on N mineralization and availability and NO_3^- leaching may also be different in a mixture than when planted alone. Sainju et al. (1995) obtained a decrease in soil N mineralization and yield, and N uptake by the test crop, when the ratio of hairy vetch to rye or annual ryegrass in the cover crop residue mixture was decreased. The predicted and observed values of soil N mineralization and yield, and N uptake of the test crop, were similar for various crop residue mixture combinations. Clark et al. (1994) found that the best seeding rate for a mixture of hairy vetch and rye for corn production in Maryland was 21 and 47 kg-ha⁻¹, respectively. Information on the performance of cover crops in a mixture and their influence on soil and water properties and succeeding crop yields is still evolving. More research is required to determine the compatibility of diverse legume-nonlegume combinations; their proper mixing ratios also need to be established.

Research on cover crops, to a large extent, has been confined to their effects on succeeding cereal crops. Less information is available on sustainable production of horticultural crops using cover crops. Horticultural crops require a higher degree of management and more intense cultural practices than do cereal crops. Therefore, research on the effect of cover crops on soil and water properties, and yield of vegetables, orchard, and ornamental crops is warranted. Date of planting and time of incorporation of cover crops under differing soil and climatic conditions need to be established

to optimize the N use by the succeeding crop. Knowledge of the rate of decomposition of cover crops is required to synchronize N mineralization with the N demand of the summer crop. Determination of the distribution and depth of penetration of roots of various cover crops is essential for evaluating their suitability for use in preventing NO_3^- leaching. Cost-benefit analysis of cover cropping is needed to determine if it is a viable production system before it is commercially adopted. Research is also required to determine the role of cover crops in integrated disease and insect control of summer crops. Finally, allelopathic responses of various summer crops to cover crop species need to be understood to develop proper cropping combinations.

Literature Cited

- Abdul-Baki, A.A. and J.R. Teasdale. 1993. A no-tillage tomato production system using hairy vetch and subterranean clover mulches. *HortScience* 28:106-108.
- Abdul-Baki, A.A., J.R. Teasdale, R. Korcak, D.J. Chittwood, and R.N. Huettel. 1996. Fresh-market tomato production in a low-input alternative system using cover-crop mulch. *HortScience* 31:65-69.
- Agamuthu, P. and W.J. Broughton. 1986. Factors affecting the development of the rooting system in young oil palms. *Agr. Ecosyst. Environ.* 17:173-180.
- Allison, F.E. 1973. Soil organic matter and its role in crop production. Elsevier, Amsterdam.
- Allison, F.E. and C.J. Klein. 1962. Rates of immobilization and release of nitrogen following additions of carbonaceous materials and nitrogen to soils. *Soil Sci.* 93:383-386.
- Altieri, M.A. and L.L. Schmidt. 1985. Cover crop manipulation in northern California orchards and vineyards: Effects on arthropod communities. *Biol. Agr. Hort.* 3:1-24.
- Anderson, M.A. and G.M. Browning. 1949. Some physical and chemical properties of six virgin and six cultivated Iowa soils. *Soil Sci. Soc. Amer. Proc.* 14:370-374.
- Aulakh, M.S., J.W. Doran, D.T. Walters, A.R. Mosier, and D.D. Francis. 1991. Crop residue type and placement effects on denitrification and mineralization. *Soil Sci. Soc. Amer. J.* 55:1020-1025.
- Bertilsson, G. 1988. Lysimeter studies of nitrogen leaching and nitrogen balance as affected by agricultural practices. *Acta Agr. Scand.* 38:3-11.
- Biederbeck, V.O., C.A. Campbell, and R.P. Zentner. 1984. Effect of crop rotation and fertilization on some biological properties of a loam in south-

Table 4. Reduction in NO_3^- leaching from soil due to cover crops.²

Reference	Cover crop	Reduction due to cover crop (%)
Bertilsson (1988)	Rape	62
Chapman et al. (1949)	Sweet clover	1
	Purple vetch	10
	Mustard	80
	Rye	72
Karraker et al. (1950)	Rye	94
McCracken et al. (1994)	Hairy vetch	48
	Rye	29
	Hairy vetch	-6
Meisinger et al. (1990)	Oats	48
	Rye	62
	Timothy	33
Volk and Bell (1945)	Turnip	84

²Source: McCracken et al. (1994) and Meisinger et al. (1991).

- western Saskatchewan. *Can. J. Soil Sci.* 64:355–367.
- Black, A.L. 1973. Soil property changes associated with crop residue management in a wheat-fallow rotation. *Soil Sci. Soc. Amer. Proc.* 37:943–946.
- Bonde, T.A. and T. Rosswall. 1987. Seasonal variation of potentially mineralizable nitrogen in four cropping systems. *Soil Sci. Soc. Amer. J.* 51:1508–1514.
- Bonde, T.A., J. Schnurer, and T. Rosswall. 1988. Microbial biomass as a fraction of potentially mineralizable nitrogen in soils from long-term field experiments. *Soil Biol. Biochem.* 20:447–452.
- Bremner, J.W. and D.L. Wright. 1984. Using winter legume mulches as a nitrogen source for no-tillage corn and grain sorghum production, p. 6–17. In: J.T. Touchton (ed.). *Proc. Seventh Annual Southeast No-Tillage Systems Conf.*, Auburn, Ala.
- Brown, R.E., G.E. Varvel, and C.A. Shapiro. 1993. Residual effects of interseeded hairy vetch on soil nitrate-nitrogen levels. *Soil Sci. Soc. Amer. J.* 57:121–124.
- Brown, S.M., T. Whitewell, J.T. Touchton, and C.H. Burmester. 1985. Conservation tillage systems for cotton production. *Soil Sci. Soc. Amer. J.* 49:1256–1260.
- Buchanan, M. and L.D. King. 1993. Carbon and phosphorus losses from decomposing crop residues in no-till and conventional till agroecosystems. *Agron. J.* 85: 631–638.
- Bugg, R.L. 1992. Using cover crops to manage arthropods on truck farms. *HortScience* 27:741–745.
- Buntley, G.J. 1986. Tennessee no-tillage updates, p.100–102. In: R.E. Phillips (ed.). *Southern Region No-Till Conf. Southern Region Series Bul.* 319. Lexington, Ky.
- Cambardella, C.A. and E.T. Elliott. 1993. Carbon and nitrogen distribution in aggregates from cultivated and native grassland soils. *Soil Sci. Soc. Amer. J.* 57:1071–1076.
- Campbell, C.A., R. DeJong, and R.P. Zentner. 1984. Effect of cropping, summer fallow, and fertilizer nitrogen on nitrate-nitrogen lost by leaching on a brown Chernozemic loam. *Can. J. Soil Sci.* 64:61–74.
- Campbell, C.A., G.P. Lafond, R.P. Zentner, and Y.W. Jame. 1994. Nitrate leaching in a Udic Haploboroll as influenced by fertilization and legumes. *J. Environ. Qual.* 23:195–201.
- Campbell, C.A. and W. Souster. 1982. Loss of organic matter and potentially mineralizable nitrogen from Saskatchewan soils due to cropping. *Can. J. Soil Sci.* 62:651–656.
- Carter, M.R. and D.A. Rennie. 1982. Changes in soil quality under zero tillage farming systems: Distribution of microbial biomass and mineralizable C and N potentials. *Can. J. Soil Sci.* 62:587–597.
- Chapman, H.D., G.F. Leibig, and D.S. Rayner. 1949. A lysimeter investigation of nitrogen gains and losses under various systems of cover cropping and fertilization, and a discussion of error sources. *Hilgardia* 19:57–102.
- Clark, A.J., A.M. Decker, and J.J. Meisinger. 1994. Seeding rate and kill date effects on hairy vetch-cereal rye cover crop mixtures for corn production. *Agron. J.* 86:1065–1070.
- Collins, H.P., P.E. Rasmussen, and C.L. Douglas, Jr. 1992. Crop rotation and residue management effects on soil carbon and microbial dynamics. *Soil Sci. Soc. Amer. J.* 56:783–788.
- Council for Agricultural Science and Technology (CAST). 1992. Preparing U.S. agriculture for global climate change, Task Force Rpt. No. 19. CAST, Ames, Iowa.
- Dahnke, W.C. and E.H. Vasey. 1973. Testing soils for nitrogen, p. 97–114. In: L.M. Walsh and J.D. Beaton (eds.). *Soil testing and plant analysis*. SSSA, Madison, Wis.
- Dalal, R.C. and R.J. Mayer. 1986. Long-term trends in fertility of soils under continuous cultivation and cereal cropping in southern Queensland. II Total organic carbon and its rate of loss from the soil profile. *Aust. J. Soil Res.* 24:281–292.
- Decker, A.M., A.J. Clark, J.J. Meisinger, F.R. Mulford, and M.S. McIntosh. 1994. Legume cover crop contributions to no-tillage corn production. *Agron. J.* 86:126–135.
- Dolmat, M.T., W.H. Patrick, Jr., and F.J. Petersen. 1980. Relation of available soil nitrogen to rice yield. *Soil Sci.* 129:229–237.
- Doran, J.W. 1980. Soil microbial and biochemical changes associated with reduced tillage. *Soil Sci. Soc. Amer. J.* 44:765–771.
- Ebelhar, S.A., W.W. Frye, and R.L. Blevins. 1984. Nitrogen from legume cover crops for no-tillage corn. *Agron. J.* 76:51–55.
- El-Haris, M.K., V.L. Cochran, L.F. Elliott, and D.F. Bezdicek. 1983. Effect of tillage, cropping, and fertilizer management on soil nitrogen mineralization potential. *Soil Sci. Soc. Amer. J.* 47:1157–1161.
- Elliott, E.T. 1986. Aggregate structure and carbon, nitrogen and phosphorus in native and cultivated soils. *Soil Sci. Soc. Amer. J.* 50:627–633.
- Eylands, V.J. and R.N. Gallaher. 1984. Nitrogen fertilizer requirements for grain sorghum following winter legumes in conventional and no-tillage systems, p. 70–75. In: J.T. Touchton (ed.). *Proc. Seventh Annual Southeast No-Tillage Systems Conf.*, Auburn, Ala.
- Flannery, R.L. 1981. Conventional vs. no-tillage corn silage production. *Better Crops* 66:3–6.
- Follett, R.F. 1989. Nitrogen management and groundwater protection. Elsevier, Amsterdam.
- Frankenberger, W.T., Jr. and H.M. Abdelmagid. 1985. Kinetic parameters of nitrogen mineralization rates of leguminous crops incorporated into soil. *Plant and Soil* 87:257–271.
- Frye, W.W., J.J. Varco, R.L. Blevins, M.S. Smith, and S.J. Corak. 1988. Role of annual legume cover crops in efficient use of water and nitrogen, p. 129–154. In: W.L. Hargrove (ed.). *Cropping strategies for efficient use of water and nitrogen*. ASA Spec. Publ. 51. ASA, CSSSA, and SSSA, Madison, Wis.
- Frye, W.W., J.H. Herbek, and R.L. Blevins. 1986. Nitrogen from legume cover crops for no-tillage corn. 1986 Grain Research. Univ. of Kentucky, Lexington.
- Frye, W.W., W.G. Smith, and R.J. Williams. 1985. Economics of winter cover crops as a source of nitrogen for no-till corn. *J. Soil Water Conserv.* 40:246–249.
- Gale, P.M. and J.T. Gilmour. 1988. Net mineralization of carbon and nitrogen under aerobic and anaerobic conditions. *Soil Sci. Soc. Amer. J.* 52:1006–1010.
- Gasser, J.K.R. and S.J. Kalembsa. 1976. Soil nitrogen: IX. The effects of leys and organic manures on the available-N in clay and sandy soils. *J. Soil Sci.* 27:237–249.
- Gosdin, G.W., M. Stelly, and W.E. Adams. 1949. The organic matter, nitrogen content, and carbon nitrogen ratio of Cecil soil as influenced by different cropping systems on classes II, III and IV land. *Soil Sci. Soc. Amer. Proc.* 14:203–208.
- Hallberg, G.R. 1989. Nitrate in groundwater in the United States, p. 35–74. In: R.F. Follett (ed.). *Nitrogen management and groundwater protection*. Elsevier, Amsterdam.
- Hargrove, W.L. 1986. Winter legumes as a nitrogen source for no-till grain sorghum. *Agron. J.* 78:70–74.
- Havlin, J.L., D.E. Kissel, L.D. Maddux, M.M. Claassen, and J.H. Long. 1990. Crop rotation and tillage effects on soil organic carbon and nitrogen. *Soil Sci. Soc. Amer. J.* 54:448–452.
- Heckman, J.R., W.T. Hlubik, D.J. Probst, and J.W. Paterson. 1995. Pre-sidedress soil nitrate test for sweet corn. *HortScience* 30:1033–1036.
- Herbek, J.H., W.W. Frye, and R.L. Blevins. 1987. Nitrogen from legume cover crops for no-till corn and grain sorghum, p. 51–52. In: J.F. Power (ed.). *The role of legumes in conservation tillage systems*. Soil Conserv. Soc. Amer., Ankeny, Iowa.
- Hobbs, J.A. and P.L. Brown. 1957. Nitrogen and organic carbon changes in cultivated western Kansas soils. *Kansas Agr. Expt. Sta. Tech. Bul.* 89.
- Hoyt, G.D. and W.L. Hargrove. 1986. Legume cover crops for improving crop and soil management in the southern United States. *HortScience* 21:397–402.
- Huntington, T.G., J.H. Grove, and W.W. Frye. 1985. Release and recovery of nitrogen from winter annual cover crops in no-till corn production. *Commun. Soil Sci. Plant Anal.* 16: 193–211.
- Iritani, W.M. and C.Y. Arnold. 1960. Nitrogen release of vegetable crop residues during incubation as related to their chemical composition. *Soil Sci.* 89:74–82.
- Jackson, L.E., L.J. Wyland, and L.J. Stivers. 1993. Winter cover crops to minimize nitrate losses in intensive lettuce production. *J. Agr. Sci.* 121:55–62.
- Jenkinson, D.S. and J.H. Rayner. 1977. The turnover of soil organic matter in some of the Rothamsted classical experiments. *Soil Sci.* 123:298–305.
- Kamprath, E.J., W.V. Chandler, and B.A. Krantz. 1958. Winter cover crops: Their effects on corn yields and soil properties. *North Carolina Agr. Expt. Sta. Tech. Bul.* 129.
- Karraker, P.E., C.E. Bortner, and E.N. Fergus. 1950. Nitrogen balance in lysimeters as affected by growing Kentucky bluegrass and certain legumes separately and together. *Kentucky Agr. Expt. Sta. Bul.* 557.
- Keeney, D.R. and J.M. Bremner. 1966. Comparison and evaluation of laboratory methods of obtaining an index of soil nitrogen availability. *Agron. J.* 58:498–503.
- Kelly, T.C., Y.C. Lu, A.A. Abdul-Baki, and J.R. Teasdale. 1995. Economics of hairy vetch mulch system for producing fresh market tomatoes in the Mid-Atlantic region. *J. Amer. Soc. Hort. Sci.* 120:854–860.
- Klausner, S.D., W.S. Reid, and D.R. Bouldin. 1993. Relationship between late spring soil nitrate concentrations and corn yields in New York. *J. Prod. Agr.* 6:350–354.
- Kuo, S., E.J. Jellum, and U.M. Sainju. 1995. The effect of winter cover cropping on soil and water quality, p.56–64. *Proc. Western Nutrient Mgt. Conf.*, Salt Lake City, Utah.
- Kuo, S. and U.M. Sainju. 1994. Winter cover cropping influence on soil organic carbon and carbohydrate levels in soil, p. 272. In: *Agronomy abstracts*. ASA, Madison, Wis.
- Kuo, S., U.M. Sainju, and E.J. Jellum. 1996. Winter cover cropping influence on nitrogen mineralization and corn yields. *Soil Biol. Fert.* 22:310–317.
- Ladd, J.N. and M. Amato. 1986. The fate of nitrogen from legume and fertilizer sources in soils successively cropped with wheat under field conditions. *Soil Biol. Biochem.* 18:417–425.
- Langdale, G.W., R.L. Blevins, D.L. Karlen, D.K. McCool, M.A. Nearing, E.L. Skidmore, A.W. Thomas, D.D. Tyler, and J.R. Williams. 1991. Cover crop effects on soil erosion by wind and

- water, p. 15–22. In: W.L. Hargrove (ed.). Cover crops for clean water. Soil and Water Conserv. Soc., Ankeny, Iowa.
- Larson, W.E., C.E. Clapp, W.H. Pierre, and Y.B. Morachan. 1972. Effects of increasing amounts of organic residues on continuous corn: II. Organic carbon, nitrogen, phosphorus, and sulfur. *Agron. J.* 64:204–208.
- Legg, J.O. and J.J. Meisinger. 1982. Soil nitrogen budgets, p. 503–566. In: F.J. Stevenson et al. (eds.). Nitrogen in agricultural soils. Agron. monograph 22. ASA, CSSA, and SSSA, Madison, Wis.
- Lewis, R.D. and J.H. Hunter. 1940. The nitrogen, organic carbon, and pH of some southeastern Coastal Plain soils as influenced by green-manure crops. *J. Amer. Soc. Agron.* 32:586–601.
- Liang, B.C. and A.F. Mackenzie. 1994. Changes of soil nitrate-nitrogen and denitrification as affected by nitrogen fertilizer on two Quebec Soils. *J. Environ. Qual.* 23:521–525.
- Linville, K.W. and G.E. Smith. 1971. Nitrate content of soil cores from corn plots after repeated nitrogen fertilization. *Soil Sci.* 112:249–255.
- Magdoff, F. 1991. Understanding the Magdoff presidedress nitrate test for corn. *J. Prod. Agr.* 4:297–305.
- Maimone, R.A., L.A. Morris, and T.R. Fox. 1991. Soil nitrogen mineralization potential in a fertilized loblolly pine plantation. *Soil Sci. Soc. Amer. J.* 55:522–527.
- Marion, G.M., T. Kummerow, and P.C. Miller. 1981. Predicting nitrogen mineralization in chaparral soils. *Soil Sci. Soc. Amer. J.* 45:956–961.
- Mazurak, A.P. and E.G. Conrad. 1966. Changes in content of total nitrogen and organic matter in three Nebraska soils after seven years of cropping treatments. *Agron. J.* 58:85–88.
- McKaig, N., Jr., W.A. Carns, and A.B. Bowen. 1940. Soil organic matter and nitrogen as influenced by green manure crop management on Norfolk coarse sand. *J. Amer. Soc. Agron.* 32:842–852.
- McCracken, D.V., M.S. Smith, J.H. Grove, C.T. MacKown, and R.L. Blevins. 1994. Nitrate leaching as influenced by cover cropping and nitrogen source. *Soil Sci. Soc. Amer. J.* 58:1476–1483.
- McVay, K.A., D.E. Radcliffe, and W.L. Hargrove. 1989. Winter legume effects on soil properties and nitrogen fertilizer requirements. *Soil Sci. Soc. Amer. J.* 53:1856–1862.
- Meisinger, J.J., P.R. Shipley, and A.M. Decker. 1990. Using winter cover crops to recycle nitrogen and reduce leaching, p. 3–6. In: J.P. Mueller and M.G. Waggoner (eds.). Conservation tillage for agriculture in the 1990's. North Carolina State Univ. Spec. Bul. 90–1.
- Meisinger, J.J., W.L. Hargrove, R.L. Mikkelsen, Jr., J.R. Williams, and V.W. Benson. 1991. Effects of cover crops on groundwater quality, p. 57–68. In: W.L. Hargrove (ed.). Cover crops for clean water. Soil and Water Conserv. Soc., Ankeny, Iowa.
- Meisinger, J.J., V.A. Bandel, J.S. Angle, B.E. O'Keefe, and C.M. Reynolds. 1992. Presidedress soil nitrate test evaluation in Maryland. *Soil Sci. Soc. Amer. J.* 56:1527–1532.
- Meyer, D.W. 1987. Influence of green-manured, hayed or grain legumes on grain yield and quality of the following barley crop in the northern Great Plains, p. 94–95. In: J.F. Power (ed.). The role of legumes in conservation tillage systems. Soil Conserv. Soc. Amer., Ankeny, Iowa.
- Morgan, M.F., H.G.M. Jacobson, and S.B. LeCompte, Jr. 1942. Drainage water losses from a sandy soil as affected by cropping and cover crops. Connecticut Agr. Expt. Sta. Bul. 466.
- Morris, T.F., A.M. Blackmer, and N.M. El-Hout. 1993. Optimal rates of nitrogen fertilization for first year corn after alfalfa. *J. Prod. Agr.* 6:344–350.
- Nesmith, D.S. and D.V. McCracken. 1994a. Influence of tillage and sidedress nitrogen on snap bean following a hairy vetch cover crop. *Commun. Soil Sci. Plant Anal.* 25:2959–2970.
- Nesmith, D.S. and D.V. McCracken. 1994b. Snap bean response to soil tillage management and cover crops. *Commun. Soil Sci. Plant Anal.* 25:2501–2512.
- Newenhouse, A.C. and M.N. Dana. 1989. Grass living mulch for strawberries. *J. Amer. Soc. Hort. Sci.* 114:859–862.
- Odell, R.T., S.W. Melsted, and W.M. Walker. 1984. Changes in organic carbon and nitrogen of Morrow plot soils under different treatments, 1904–1973. *Soil Sci.* 137:160–171.
- Oveson, M.M. 1966. Conservation of soil nitrogen in a wheat summer fallow farming practice. *Agron. J.* 58:444–447.
- Poincelot, R.P. 1986. Toward a more sustainable agriculture. AVI, Westport, Conn.
- Power, J.F. and J.W. Doran. 1988. Role of crop residue management in nitrogen cycling and use, p. 101–113. In: W.L. Hargrove (ed.). Cropping strategies for efficient use of water and nitrogen. ASA Spec. Publ. 51. ASA, CSSA, and SSSA, Madison, Wis.
- Power, J.F. and J.S. Schepers. 1989. Nitrate contamination of groundwater in North America. *Agr. Ecosyst. Environ.* 26:165–187.
- Pratt, P.F., B. Goulben, and R.B. Harding. 1957. Changes in organic carbon and nitrogen in an irrigated soil during 28 years of differential fertilization. *Soil Sci. Soc. Amer. Proc.* 21:215–219.
- Pritts, M.P. and M.J. Kelly. 1993. Alternative weed management strategies for strawberries. *Pennsylvania Fruit News* 73:136–138.
- Proebsting, E.L. 1952. Some effects of long continued overcropping in a California orchard. *Proc. Amer. Soc. Hort. Sci.* 60:87–90.
- Quemada, M. and M.L. Cabrera. 1995. Carbon and nitrogen mineralized from leaves and stems of four cover crops. *Soil Sci. Soc. Amer. J.* 59:471–477.
- Radke, J.K., R.W. Andrews, R.R. Janke, and S.E. Peters. 1988. Low input cropping systems and efficiency of water and nitrogen use, p. 193–218. In: W.L. Hargrove (ed.). Cropping strategies for efficient use of water and nitrogen. ASA Spec. Publ. 51. ASA, CSSA, and SSSA, Madison, Wis.
- Rasmussen, P.E., R.R. Allmaras, C.R. Rhode, and N.C. Roger, Jr. 1980. Crop residue influences on soil carbon and nitrogen in a wheat-fallow system. *Soil Sci. Soc. Amer. J.* 44:596–600.
- Reinertsen, S.A., L.F. Elliott, V.L. Cochran, and G.S. Campbell. 1984. Role of available carbon and nitrogen in determining the rate of wheat straw decomposition. *Soil Biol. Biochem.* 16:459–464.
- Ridley, A.O. and R.A. Hedlin. 1968. Soil organic matter and crop yields as influenced by the frequency of summer fallowing. *Can. J. Soil Sci.* 48:315–322.
- Roberson, E.B., S. Saring, and M.K. Firestone. 1991. Cover crop management of polysaccharide-mediated aggregation in an orchard soil. *Soil Sci. Soc. Amer. J.* 55:734–739.
- Roth, G.W., D.B. Beegle, and P.J. Bohn. 1992. Field evaluation of a presidedress soil nitrate test and quicktest for corn in Pennsylvania. *J. Prod. Agr.* 5:476–481.
- Russelle, M.P. and W.L. Hargrove. 1989. Cropping systems: Ecology and management, p. 277–317. In: R.F. Follett (ed.). Nitrogen management and groundwater protection. Elsevier, Amsterdam.
- Sainju, U.M. and S. Kuo. 1994. Winter cover cropping influence on nitrogen status in soil. p. 271. In: Agronomy abstracts. ASA, Madison, Wis.
- Sainju, U.M. and S. Kuo, and W.C. Anderson. 1995. Nitrogen mineralization of mixed leguminous and nonleguminous crop residues and its effect on plant growth, p. 234. In: Agronomy abstracts. ASA, Madison, Wis.
- Schonbeck, M., S. Herbert, R. DeGregorio, F. Mangan, K. Guillard, E. Sideman, J. Herbst, and R. Jaye. 1993. Cover cropping systems for brassicas in the northeastern United States. *J. Sust. Agr.* 3:105–132.
- Serna, M.D. and F. Pomares. 1992. Evaluation of chemical indices of soil organic nitrogen availability in calcareous soils. *Soil Sci. Soc. Amer. J.* 56:1486–1491.
- Shennan, C. 1992. Cover crops, nitrogen cycling, and soil properties in semi-irrigated vegetable production systems. *HortScience* 27:749–754.
- Singogo, W., W.J. Lamont, Jr., and C.W. Marr. 1996. Fall-planted cover crops support good yields of muskmelon. *HortScience* 31:62–64.
- Smeda, R.J. and A.R. Putnam. 1988. Cover crop suppression of weeds and influence on strawberry yields. *HortScience* 23:132–134.
- Smith, J.A. 1966. An evaluation of nitrogen soil test methods for Ontario soils. *Can. J. Soil Sci.* 46:185–194.
- Smith, M.S., W.W. Frye, and J.J. Varco. 1987. Legume winter cover crops. *Adv. Soil Sci.* 7: 95–139.
- Smith, S.J. and G. Stanford. 1971. Evaluation of a chemical index of soil nitrogen availability. *Soil Sci.* 111:228–232.
- Staaf, H. and B. Berg. 1981. Plant litter input to soil, p. 147–162. In: F.E. Clark and T. Rosswall (eds.). Terrestrial nitrogen cycles: Processes, ecosystem strategies and management impacts. Swedish Natural Sci. Res. Council, Stockholm.
- Stanford, G. 1982. Assessment of soil nitrogen availability, p. 651–688. In: F.J. Stevenson (ed.). Nitrogen in agricultural soils. ASA, CSSA, and SSSA, Madison, Wis.
- Stanford G., J.N. Carter, D.T. Westermann, and J. J. Meisinger. 1977. Residual nitrate and mineralizable soil nitrogen in relation to nitrogen uptake by irrigated sugar beets. *Agron. J.* 69:303–308.
- Stanford, G. and J.O. Legg. 1968. Correlations of soil N availability indexes with N uptake by plants. *Soil Sci.* 105:320–326.
- Stanford, G., J.O. Legg, and S.J. Smith. 1973. Soil nitrogen availability evaluations based on nitrogen mineralization potentials of soils and uptake of labelled and unlabelled nitrogen by plants. *Plant and Soil* 39:113–124.
- Stanford, G. and S.J. Smith. 1972. Nitrogen mineralization potentials of soils. *Soil Sci. Soc. Amer. Proc.* 36:465–472.
- Staver, K.W. and R.B. Brinsfield. 1990. Patterns of soil nitrate availability in corn production systems: Implications for reducing groundwater contamination. *J. Soil Water Conserv.* 45:318–323.
- Stevenson, F.J. 1982. Origin and distribution of nitrogen in soil, p. 1–42. In: F.J. Stevenson (ed.). Nitrogen in agricultural soils. ASA, CSSA, and SSSA, Madison, Wis.
- Stirzaker, R.J. and I. White. 1995. Amelioration of soil compaction by a cover-crop for no-tillage lettuce production. *Aust. J. Agr. Res.* 46:553–568.
- Stivers, L.J. and L.E. Jackson. 1991. Winter cover crops to improve nitrogen cycling in the Salinas Valley. *Proc. Calif. Plant and Soils Conf.*, San Luis Obispo, Calif., 31 Jan.–1 Feb. 1991.
- Stivers, L.J. and C. Shennan. 1991. Meeting the nitrogen needs for processing tomatoes through winter cover cropping. *J. Prod. Agr.* 4:330–335.
- Stute, J.K. and J.L. Posner. 1995. Synchrony be-

- tween legume nitrogen release and corn demand in the upper Midwest. *Agron. J.* 87:1063–1069.
- Teasdale, J.R. and A.A. Abdul-Baki. 1995. Soil temperature and tomato growth associated with black polyethylene and hairy vetch mulches. *J. Amer. Soc. Hort. Sci.* 120:848–853.
- Tiessen, H.J., W.B. Stewart, and J.R. Bettany. 1982. Cultivation effects on the amounts and concentrations of carbon, nitrogen, and phosphorus in grassland soils. *Agron. J.* 74:831–835.
- Touchton, J.T., D.H. Rickerl, R.H. Walker, and C.E. Snipes. 1984. Winter legumes as a nitrogen source for no-tillage corn. *Soil Tillage Res.* 4:391–401.
- Turley, D.B., S.E. Ogilvy, C. Hayward, and J.B.S. Freer. 1992. Effects of wheat and rye cover crops on the establishment and yield of peas. *Aspects Appl. Biol.* 30:339–342.
- Van Bruggen, A.H.C., P.R. Brown, C. Shennan, and A.S. Greathead. 1990. The effect of cover crops and fertilization with ammonium nitrate on corky root of lettuce. *Plant Dis.* 74:584–589.
- Van Doren, D.M., Jr., G.B. Triplett, Jr., and J.E. Henry. 1976. Influences of long term tillage, crop rotation, and soil type combinations on corn yield. *Soil Sci. Soc. Amer. J.* 40:100–105.
- Varco, J.J. 1986. Tillage effects on transformation of legume and fertilizer nitrogen and crop recovery of residue nitrogen. PhD Diss., Univ. of Kentucky, Lexington (Diss. Abstr. 47:4356).
- Varco, J.J., W.W. Frye, J.H. Herbek, and R.L. Blevins. 1984. Effects of legume cover crops on yield of no-till corn, p. 40–56. In: J.J. Touchton (ed.). *Proc. Seventh Annual Southeast No-Tillage Systems Conf.*, Auburn, Ala.
- Varvel, G.E., 1994. Rotation and nitrogen fertilization effects in changes in soil carbon and nitrogen. *Agron. J.* 86:319–325.
- Vigil, M.F. and D.E. Kissel. 1991. Equations for estimating the amount of nitrogen mineralized from crop residues. *Soil Sci. Soc. Amer. J.* 55:757–761.
- Volk, G.M. and C.E. Bell. 1945. Some major factors in the leaching of calcium, potassium, sulfur, and nitrogen from sandy soils: A lysimeter study. *Florida Agr. Expt. Sta. Bul.* 416.
- Wagger, M.G. 1989. Time of desiccation effects on plant composition and subsequent nitrogen release from several winter annual cover crops. *Agron. J.* 81:236–241.
- Wagger, M.G., D.E. Kissel, and S.J. Smith. 1985. Mineralization of nitrogen from nitrogen-15 labeled crop residues under field conditions. *Soil Sci. Soc. Amer. J.* 49:1220–1226.
- Wallace, R.W. and R.R. Bellinder. 1992. Alternative tillage and herbicide options for successful weed control in vegetables. *HortScience* 27:745–749.
- Williams, W.A. 1966. Management of nonleguminous green manures and crop residues to improve the infiltration rate of an irrigated soil. *Soil Sci. Soc. Amer. Proc.* 30:631–634.
- Williams, W.A. and L.D. Doneen. 1960. Field infiltration studies with green manures and crop residues on irrigated soils. *Soil Sci. Soc. Amer. Proc.* 24:58–61.
- Wilson, G.F., R. Lal, and B.N. Okigbo. 1982. Effects of cover crops on soil structure and on yield of subsequent arable crops grown under strip tillage on an eroded Alfisol. *Soil and Tillage Res.* 2:233–250.
- Wilson, D.O. and W.L. Hargrove. 1986. Release of nitrogen from crimson clover residue under two tillage systems. *Soil Sci. Soc. Amer. J.* 50:1251–1254.
- Woods, L.E. and G.E. Schuman. 1988. Cultivation and slope position effects on soil organic matter. *Soil Sci. Soc. Amer. J.* 52:1371–1376.
- Worsham, A.D. 1986. No-tillage research update—North Carolina. In: R.E. Phillips (ed.). *Southern Region No-Till Conf. Southern Region Series Bul.* 319, Lexington, Ky.
- Yaacob, O. and G.J. Blair. 1980. Mineralization of ¹⁵N-labelled legume residues in soils with different nitrogen contents and its uptake by Rhodes grass. *Plant and Soil* 57: 237–248.
- Yan, Y.H. and J.J. Duan. 1988. Effects of cover crops in apple orchards on predator community on the trees. *Acta Phytophyl. Sinica* 15:23–27.