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

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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 ×ananassa* 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 succeding 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.) Poiret]. 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 $Mg \cdot ha^{-1}$, while N contribution varies from 38 to 220 $kg \cdot ha^{-1}$ (Table 1). In comparison, nonlegumes produce biomass in the range of 1.5 to 7.1 $Mg \cdot ha^{-1}$ and supply N between 14 and 90 $kg \cdot ha^{-1}$. 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 $kg \cdot ha^{-1}$. 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,

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decompose rapidly in the soil (McKaig et al., 1940; Wagger 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). Wagger 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; Wagger, 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.

			Cover crop		Succeeding crop	
Reference and location	Cover crop	Succeeding crop/rotation	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	---
	Polythylene 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
McVay et al. (1989), Georgia	Hairy vetch	Field corn	3.4	128	8.5	90
	Crimson clover		3.5	108	---	---
	Wheat		1.8	32	3.5	30
	Fallow		---	---	---	---
Shennan (1992), California	Purple vetch	Field corn/	5.3	178	12.3 (103)[z]	---
	Lana woollypod vetch	Field corn/	6.3	220	---	---
	Oats + vetch	Tomato/	6.3	130	10.6 (90)[z]	---
	Faba beans + vetch	Tomato[z]	5.1	174	---	---
	Winter annual grasses		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]	---
Touchton et al. (1984), Alabama	Fallow	Cotton	2.7	31	0.6	---
	Crimson clover		4.5	95	0.9	---
	Common vetch		4.9	118	0.8	---

[z] Values 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 succeding 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_o) 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_o 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_o was significantly correlated with rye yield and N uptake when soil samples were taken immediately after cover crop incorporation. In contrast, N_o 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_o, 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_o when evaluating N mineralization from cover crop residues. N_o 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_o 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_o (Bonde et al., 1988).

Since it takes a long time to determine N_o, 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 Kalembasa, 1976; Smith and Stanford, 1971; Stanford et al., 1973). Soil organic N is linearly related to N_o (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_o 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). Fallowing 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 at al., 1988;

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

Reference	Cover crop	Summer crop	N equivalence ($kg \cdot ha^{-1}$)
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
Eylands and Gallaher (1984)	Crimson clover	Sorghum	75
Flannery (1981)	Hairy vetch	Silage corn	200
Hargrove (1986)	Hairy vetch	Sorghum	97
	Common vetch		61
	Crimson clover		92
	Subterranean clover		61
Herbek et al. (1987)	Hairy vetch	Field corn	66
	Big flower vetch		64
McVay et al. (1989)	Winter pea	Field corn	27–79
Meyer (1987)	Hairy vetch	Barley	75–149
Touchton 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

[z] Source: 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 $Mg{\cdot}ha^{-1}$, respectively, which were within or higher than the range of 5–6 $Mg{\cdot}ha^{-1}$ 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).

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

			Organic component	
Reference	Cover crop	Soil depth (cm)	C ($g{\cdot}kg^{-1}$)	N ($g{\cdot}kg^{-1}$)
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		10.0	0.81
	Hairy vetch		9.7	0.80
	Common vetch		10.2	0.63
	Initial	7.5–15	6.1	0.49
	Fallow		4.8	0.37
	Rye		5.4	0.42
	Crimson clover		4.9	0.41
	Subterranean clover		5.5	0.48
	Hairy vetch		5.5	0.51
	Common vetch		5.1	0.45
Kuo et al. (1995)	Control	0–15	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

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 $g{\cdot}mL^{-1}$) 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 $Mg{\cdot}ha^{-1}{\cdot}year^{-1}$ 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, NO_3^- leaching occurs most frequently during fall-winter-spring when evapotranspiration is low and precipitation 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 Wagger 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 $kg{\cdot}ha^{-1}$. 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 aridic soils (Campbell et al., 1984). Fallowing 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 fallowing 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 $kg{\cdot}ha^{-1}$, 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.

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Table 4. Reduction in NO_3^- leaching from soil due to cover crops.[z]

Reference	Cover crop	Reduction due to cover crop (%)
Bertilsson (1988)	Rape	62
Chapman et al. (1949)	Sweet clover	1
	Purple vetch	10
	Mustard	80
Karraker et al. (1950)	Rye	72
McCracken et al. (1994)	Rye	94
	Hairy vetch	48
Meisinger et al. (1990)	Rye	29
	Hairy vetch	–6
Morgan et al. (1942)	Oats	48
	Rye	62
	Timothy	33
Volk and Bell (1945)	Turnip	84

[z]Source: McCracken et al. (1994) and Meisinger et al. (1991).

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