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Nitrogen mineralization and availability of mixed leguminous and non-leguminous cover crop residues in soil

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Abstract Whereas non-leguminous cover crops such as cereal rye (*Secale cereale*) or annual ryegrass (*Lolium multiflorium*) are capable of reducing nitrogen (N) leaching during wet seasons, leguminous cover crops such as hairy vetch (*Vicia villosa*) improve soil N fertility for succeeding crops. With mixtures of grasses and legumes as cover crop, the goal of reducing N leaching while increasing soil N availability for crop production could be attainable. This study examined net N mineralization of soil treated with hairy vetch residues mixed with either cereal rye or annual ryegrass and the effect of these mixtures on growth and N uptake by cereal rye. Both cereal rye and annual ryegrass contained low total N, but high water-soluble carbon and carbohydrate, compared with hairy vetch. Decreasing the proportion of hairy vetch in the mixed residues decreased net N mineralization, rye plant growth and N uptake, but increased the crossover time (the time when the amount of net N mineralized in the residue-amended soil equalled that of the non-amended control) required for net N mineralization to occur. When the hairy vetch content was decreased to 40% or lower, net N immobilization in the first week of incubation increased markedly. Residue N was significantly correlated with rye biomass ($r = 0.81$, $P < 0.01$) and N uptake ($r = 0.83$, $P < 0.001$), although the correlation was much higher between residue N and the potential initial N mineralization rate for rye biomass ($r = 0.93$, $P < 0.001$) and N uptake ($r = 0.99$, $P < 0.001$). Judging from the effects of the mixed residues on rye N Concentration and N uptake, the proportion of rye or annual ryegrass when mixed with residues of hairy vetch should not exceed 60% if the residues are to increase N availability. Further study is needed to examine the influence of various mixtures of hairy vetch and rye or annual ryegrass on N leaching in soil.

Key words Nitrogen mineralization · Crop residues · Nitrogen leaching · Cover crops · *Secale cereale*

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Introduction

Increased nitrate (NO_3^-) leaching and contamination of groundwater from increased use of nitrogen (N) fertilizer on farmlands calls for farming practices that utilize the residual soil NO_3^- after the fall harvest to minimize N leaching. Winter cover crops can potentially accomplish this role depending on the species used and the planting date (Power and Doran 1988; Meisinger et al. 1991). When seeded in the fall, non-leguminous cover crops (e.g., rye and annual ryegrass) remove NO_3^- from the soil more effectively than do leguminous cover crops (e.g., hairy vetch). Rye and annual ryegrass establish more quickly and produce more extensive root systems than hairy vetch (McCracken et al. 1994; Kuo et al. 1997). Although N sequestered in the fall becomes part of the organic N pool, neither rye nor annual ryegrass increase soil N availability and yields of succeeding crops when incorporated into the soil (Kuo et al. 1996; Torbert et al. 1996).

Unlike non-leguminous cover crops, leguminous cover crops fix atmospheric N and increase soil N availability during decomposition (Touchton et al. 1984; Hargrove 1986; Smith et al. 1987; Frye et al. 1988), and yields and N uptake of summer crops which follow leguminous crops tend to be higher (Decker et al. 1994; Kuo et al. 1996). Because yields of non-fertilized crops which follow leguminous cover crops are equivalent to those produced when fertilizer is supplied at a rate of 10–200 kg N ha^{-1} (Smith et al. 1987), the amount of N fertilizer needed for the succeeding crop to maintain its productivity can be reduced (Torbert et al. 1996).

To decrease N fertilizer requirements for summer crops and reduce NO_3^- leaching during the wet season, mixed leguminous and non-leguminous cover crops may be more appropriate than monocultures of either type of plant. This is based on the consideration that the non-leguminous crop tends to establish more quickly and this is able to remove a higher proportion of the residual N than the leguminous crop during the fall. In contrast, N fixation by the leguminous crop during the spring leads to an increase in available N, which can be utilized by the succeeding summer crop. However, before this practice is adopted, more information is needed regarding the appropriate proportion of each component species, N availability of mixed cover crop residues, and yields and N uptake of succeeding crops. Net N mineralization is a useful index of soil N availability (Stanford and Smith 1972). The objectives of this research were to determine: (1) the rate and amount of net N mineralization in soil after the addition of mixed leguminous and non-leguminous cover crop residues in varying proportions; and (2) the effect of the cover crop mixtures on growth and N uptake of cereal rye, which was used as a test crop.

Materials and methods

Cover crop analysis

Above-ground tissue of hairy vetch (*Vicia villosa*), cereal rye (*Secale cereale* var. Tetra Petkus) or annual ryegrass (*Lolium multiflorum* var. Billion) was collected from fields in April 1994. At the time that the tissue was collected, all the crops were in a vegetative stage. The samples were oven-dried at 60 °C for 72 h and ground to pass through a 1-mm sieve. Hairy vetch was mixed with either cereal rye or annual ryegrass in ratios of 100:0, 80:20, 60:40, 40:60, 20:80, and 0:100. The chemical composition of the mixed residues was analyzed using the following methods: total N by digesting a 0.4-g sample with 5 ml concentrated H_2SO_4 and 7 ml H_2O_2 at 400 °C for 1 h, followed by steam distillation of the digest for the determination of NH_4^+-N (Bremner and Mulvaney 1982); carbon (C) by the Walkley-Black method (Nelson and Sommers (1982); and lignin by the method of Goering and Van Soest (1970). In the total N digestion, H_2O_2 was added in four volumes of 1.75 ml. Water-soluble N (WSN), water-soluble C (WSC) and water-soluble carbohydrate (WSCA) in the mixed residues were determined by shaking 0.5 g of residue with 10 ml distilled water for 30 s (Quemada and Carbrera 1995), followed by analysis of WSC and WSN using the same procedures as described above. WSCA was analyzed by the anthrone method (Brink et al. 1960).

Nitrogen mineralization

Sultan silt loam (fine-silty, mixed mesic, Aquic Xerofluvents) was air-dried, ground and passed through a 2-mm sieve. The mixed cover crop residues were added to the soil at the rate of 10 g kg^{-1} soil on a dry weight basis. A 300-g sample of the residue-amended soil was placed in a plastic bag (0.1 mm in thickness) and mixed thoroughly, and the moisture content was brought to 220 g kg^{-1}, i.e. about 70% of field capacity, with distilled water, before incubating the soil in the dark at 25 °C in a constant temperature room. A polyethylene “breather tube” (1 cm internal diameter) was placed in the opening of each bag, and the top of the bag was wrapped around the tube to allow air to diffuse in and out of the bag. A control without residue addition was also included. Each residue treatment was replicated twice.

After 1, 2, 3, 4, 6, 8, 10, 12, 17, and 30 weeks of incubation, the soil was weighed. Distilled water was added to bring the soil moisture to its initial level, and the soil was mixed well. Three grams of soil from each bag was removed and extracted with 30 ml 2 M KCl. The NH_4^+-N and NO_3^--N concentrations in the extract were analyzed by the steam distillation method (Keeney and Nelson 1982). Total N in the soil before and after the 30-week incubation was determined by the Kjeldahl method (Bremner and Mulvaney 1982). Organic C in the soil before and after incubation was determined by the Walkley-Black method (Nelson and Sommers 1982).

Net N immobilization (N_{im} and net N mineralization (N_{min}) during incubation of the soil were estimated using zero-order and first-order models, respectively, as follows:

$$N_{im} = N_i - qt \quad (1)$$

$$N_{min} = N_o(1 - e^{-kt}) \quad (2)$$

where N_{im} is the amount of inorganic N (NH_4^+-N and NO_3^--N) remaining in the incubating soil after time *t*; N_i is the initial amount of inorganic N before incubation; *q* is the zero-order rate constant; N_{min} is the cumulative amount of net N mineralization; N_o is potentially mineralizable N and *k* is the first-order rate constant. $N_o k$ is the initial potential N mineralization rate.

Rye growth and N uptake

In the greenhouse experiment the mixed cover crop residues of hairy vetch with rye or annual ryegrass were mixed thoroughly with the Sultan silt loam soil at the rate of 10 g kg^{-1} soil. One kilogram of each residue-amended soil was placed in a 4-l pot and pre-incubated in the greenhouse from 3 to 27 October 1994 to determine the relationship between net N mineralization prior to seeding of rye and rye yield, tissue N concentration and N uptake. The average temperature in the greenhouse was 23 °C, and ranged from 21 °C to 28 °C depending on the weather conditions and the time of day. Water was added to the soil to bring the initial soil moisture level to about 22%. During incubation, the soil moisture level was maintained by adding a sufficient amount of H_2O to compensate for the weight loss in the pot due to evaporation. Each residue treatment was replicated three times and arranged in a completely randomized design.

After pre-incubation, soil in the center of the pot was sampled from the surface to the bottom of the pot, mixed, air-dried, and crushed to pass through a 2-mm sieve. The concentration of NH_4^+-N and NO_3^--N in the soil were determined as previously described. On 29 October 1994, 10 ml of a solution containing phosphorus (97 mM as KH_2PO_4) and potassium (192 mM as KCl) and 5 ml of a solution containing calcium (500 mM as $CaCl_2$), magnesium (50 mM as $MgSO_4$), manganese (4.3×10^{-1} mM as $MnCl_2$), zinc (3.1 mM as $ZnSO_4$), copper (1.4 mM as $CuSO_4$), boron (7.9 mM as H_3BO_3), and molybdenum (4.0×10^{-2} mM as H_3MoO_3) were added to the soil surface. No N fertilizer was added to any of the residue treatments.

On 4 November 1994, 15 cereal rye seeds were planted in each pot. They were thinned to 10 plants pot^{-1} 17 days after seeding. Water was added daily to maintain the soil moisture level at 22%. After 54 days of growth, the above-ground rye biomass was determined by cutting plants 1 cm above the soil surface. Plant materials were oven-dried at 60 °C for 72 h to determine the moisture content and then ground to pass through a 1-mm sieve. Total N was determined as previously described.

Data analysis

Analysis of variance was done using the statistical system (SAS Institute 1985) to determine the effects of cover crop chemical characteristics on net N immobilization, net N mineralization, rye yield and N uptake. It was also used to determine the effect of N mineralization on rye yield and N uptake. The modified Gauss-Newton model (SAS Institute 1985) for non-linear regression was used to estimate the parameters (N_o and *k*) of the first order equation, whereas linear regression was used to determine the zero-order rate constant, *q*.

Results and discussion

Cover crop chemical characteristics

When grown as a single crop, the N concentration of the above-ground biomass of hairy vetch was twice as high as that of cereal rye or annual ryegrass (Table 1). As the proportion of rye or annual ryegrass in the residue mixtures was increased, the total N concentration of hairy vetch decreased and its C:N ratio increased (Table 1).

Other major differences in the chemical compositions of the cover crop residues were the increasing concentrations of WSN and decreasing concentrations of WSC and WSCA, as the proportion of hairy vetch in the mixture was increased (Table 2). There was a significant, positive correlation between residue total N and WSN ($r = 0.96$, $P < 0.0001$) but a significant, negative correlation between residue total N and WSC ($r = -0.86$, $P < 0.001$) and between residue total N and WSCA ($r = -0.89$, $P < 0.001$).

Nitrogen mineralization

The proportion of rye or annual ryegrass in the mixed residues with hairy vetch greatly influenced inorganic N levels in incubating soils (Fig. 1). A marked reduction in soil inorganic N occurred in the first week of incubation when the soil was amended with mixtures of rye and hairy vetch that contained 40% or less hairy vetch. The net N immobilization could be related to rapid microbial growth and N assimilation under well-aerated soil conditions (Aulakh et al. 1991; Quemada and Cabrera 1995). Denitrification caused by increased microbial activity, which could be limited in well-aerated soils (Aulakh et al. 1991), and increased volatilization of ammonia during the first few days of active residue degradation (Quemada and Cabrera 1995) could also reduce inorganic N levels in the incubating soils.

The net N immobilization rate in the first week of incubation, q, varied significantly with residues (Table 3), and was highly significantly correlated with residue N concentration ($r = -0.98$, $P < 0.0001$) (Fig. 2). The critical residue N concentration below which net N immobilization occurred was about 32 g N kg^{-1} for the fresh residues. The corresponding C:N ratio was about 10. Other residue chemical characteristics that also correlated significantly with the net N immobilization rate included residue C:N ratio ($r = 0.93$, $P < 0.0001$), WSN ($r = -0.93$, $P < 0.0001$), and WSCA ($r = 0.90$, $P < 0.0001$). Wagger et al. (1985) showed that increasing the C:N ratio of crop residues from 28 to 37 increased the net N immobilization of the applied residue from 12% to 33%. High C:N ratios and

Table 1 Chemical characteristics of hairy vetch and rye or annual ryegrass residues mixed in varying proportions. *N* Nitrogen, *C* carbon. Values in parentheses are standard deviations

Residue	Ratio	Concentration (g kg^{-1})			C:N
		Total N	Total C	Lignin	
Vetch:rye	100:0	34.5 (±1.1)	343 (±17)	117.9 (±6.1)	10
Vetch:rye	80:20	33.5 (±1.0)	343 (±15)	77.7 (±4.0)	10
Vetch:rye	60:40	30.8 (±0.8)	360 (±18)	56.6 (±3.9)	12
Vetch:rye	40:60	26.3 (±1.5)	384 (±20)	63.3 (±4.7)	15
Vetch:rye	20:80	21.7 (±0.7)	360 (±25)	37.6 (±3.2)	17
Vetch:rye	0:100	15.8 (±0.9)	368 (±24)	32.5 (±2.8)	23
Vetch:ryegrass	80:20	33.5 (±1.3)	353 (±23)	66.9 (±4.8)	11
Vetch:ryegrass	60:40	30.2 (±1.2)	364 (±31)	61.9 (±5.0)	12
Vetch:ryegrass	40:60	26.3 (±1.1)	360 (±35)	60.9 (±4.5)	14
Vetch:ryegrass	20:80	22.3 (±0.8)	337 (±25)	51.6 (±3.0)	15
Vetch:ryegrass	0:100	15.1 (±1.1)	368 (±21)	35.6 (±2.7)	24

Table 2 Water-soluble N und C in the hairy vetch and rye or annual ryegrass residues mixed in varying proportions. *WSN* Water-soluble N, *WSC* water-soluble C, *WSCA* water-soluble carbohydrate. For other abbreviations see Table 1. Values in parentheses are standard deviations

Residue	Ratio	Concentration (g kg^{-1})			WSC:WSN	WSCA:WSC (%)
		WSN	WSC	WSCA		
Vetch:rye	100:0	10.0 (±0.9)	55.7 (±2.8)	7.4 (±0.4)	6	0.13
Vetch:rye	80:20	9.0 (±0.8)	58.9 (±2.9)	13.4 (±0.6)	7	0.23
Vetch:rye	60:40	8.4 (±0.7)	65.4 (±3.0)	22.4 (±0.8)	8	0.34
Vetch:rye	40:60	8.0 (±0.6)	73.6 (±4.5)	34.6 (±1.2)	9	0.47
Vetch:rye	20:80	7.0 (±0.5)	78.5 (±5.0)	50.4 (±1.4)	11	0.64
Vetch:rye	0:100	5.7 (±0.6)	94.8 (±6.0)	69.8 (±1.5)	17	0.74
Vetch:ryegrass	80:20	9.5 (±0.8)	67.1 (±6.1)	26.8 (±1.7)	7	0.40
Vetch:ryegrass	60:40	8.0 (±0.4)	76.8 (±7.1)	42.8 (±2.0)	10	0.56
Vetch:ryegrass	40:60	7.5 (±0.3)	98.0 (±7.2)	59.6 (±2.3)	13	0.61
Vetch:ryegrass	20:80	6.4 (±0.3)	114.3 (±8.1)	85.0 (±3.0)	17	0.74
Vetch:ryegrass	0:100	3.9 (±0.1)	127.3 (±9.3)	103.2 (±3.5)	33	0.81

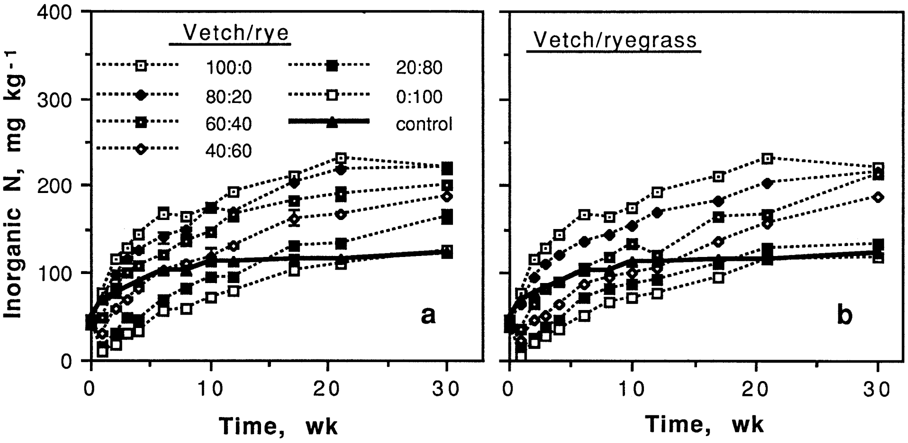

Fig. 1 The effects of time and the addition of (**a**) hairy vetch and rye or (**b**) hairy vetch and annual ryegrass mixed in varying proportions on soil inorganic nitrogen (N) levels. *Vertical bars* represent standard errors

Table 3 N immobilization rate during the first week of incubation and the first-order parameters associated with N mineralization in the soil amended with hairy vetch and rye or annual ryegrass in varying proportions. N_o Potential mineralizable N, k first-order rate constant, $N_o k$ initial potential mineralization rate, $t_{1/2}$ time for mineralization of half of N_o, q net N immobilization rate estimated by linear regression. For other abbreviations see Table 1. Means followed by the same letter within a column for the mixture of hairy vetch and rye or annual ryegrass are not significantly different at P=0.05 when compared by Ducan's multiple range test

Residue	Ratio	q mg kg^{-1} week^{-1}	N_o mg kg^{-1}	k week^{-1}	$N_o k$ mg kg^{-1} week^{-1}	$t_{1/2}$ week	N_o/organic N %	r^2
Vetch/rye								
Control	–	0 d	88.1 e	0.117 ab	10.3 d	5.9 c	5.2 d	0.73
Vetch:rye	100:0	0 d	183.0 a	0.143 a	26.2 a	4.9 c	9.6 a	0.95
Vetch:rye	80:20	0 d	169.1 b	0.129 ab	21.7 ab	5.4 c	9.1 ab	0.98
Vetch:rye	60:40	0 d	163.0 bc	0.116 ab	19.0 bc	6.0 c	9.0 ab	0.99
Vetch:rye	40:60	10.5 c	156.7 c	0.090 bcd	14.2 cd	7.7 bc	9.0 ab	0.95
Vetch:rye	20:80	29.0 b	170.4 b	0.065 d	11.1 d	10.6 a	9.5 a	0.95
Vetch:rye	0:100	36.7 a	139.4 d	0.075 cd	10.4 d	9.3 ab	8.1 c	0.90
Vetch/ryegrass								
Control	–	0 d	88.1 f	0.117 ab	10.3 d	5.9 bc	5.2 d	0.73
Vetch:rygrass	100:0	0 d	183.0 a	0.143 a	26.2 a	4.9 c	9.6 a	0.95
Vetch:ryegrass	80:20	0 d	160.2 bc	0.120 ab	19.3 abc	5.8 bc	8.6 bc	0.98
Vetch:ryegrass	60:40	3.3 c	163.3 bc	0.106 ab	17.3 bcd	6.6 abc	8.9 ab	0.96
Vetch:ryegrass	40:60	18.5 b	152.2 cd	0.094 ab	14.3 cd	7.4 ab	8.5 bc	0.93
Vetch:ryegrass	20:80	26.2 b	140.8 de	0.100 ab	14.1 cd	6.9 abc	7.8 c	0.95
Vetch:ryegrass	0:100	39.8 a	135.3 e	0.083 b	11.3 cd	8.3 a	7.8 c	0.90

low N concentrations of residues such as rye, oat, and wheat stems accentuated net N immobilization (Quemada and Cabrera 1995). Carbohydrate is a readily available energy source for soil microbes (Gupta 1982). As this primary C substrate was increased with increasing proportions of rye or ryegrass, coupled with a reduction in total or water-soluble N, the conditions became favorable for net N immobilization.

The concentration of inorganic N in the soil amended with the residue mixtures with high rye or annual ryegrass contents gradually increased with time after the first week of incubation (Fig. 1). The crossover point (t_c), i.e. the time when the amount of net N mineralized in the residue-amended soil equalled that of the control soil without residue amendment, increased as the percentage of rye or annual ryegrass in the mixed residue increased (Fig. 1). As with q, there was a highly significant correlation between t_c and residue N concentration (Fig. 3a). The t_c for the soil amended with 100% rye or annual ryegrass was assumed to be 30 weeks because after this period of incubation, the amount of net N mineralized in the soil was not different from that of the control soil (P>0.05). The variation in t_c with residue N level implies that the residue N level needed for net N mineralization varied depending on the length of time the residues had been incorporated into the soil. The critical residue N concentration for net N mineralization in soil incubated at 23 °C for 20 weeks was 17.3 g N kg^{-1}, in the study of Frankenberger and Abdelmagid (1985). Both rye and ryegrass had a lower N concentration than 17.3 g N kg^{-1} (Table 1), and required much longer than 20 weeks of incubation for net N mineralization to occur.

As with residue N concentration, the residue C:N ratio at which net N mineralization occurred also depended on the length of time the residues had been incorporated into the soil (Fig. 3b). Quemada and Cabrera (1995) concluded

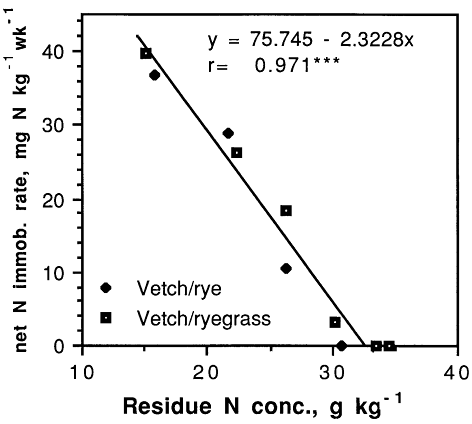

Fig. 2 The relationship between the net N immobilization rate during the first week of incubation and residue N concentration. $^{***}P<0.001$

that a C:N ratio of 20, which Stevenson (1985) considered to be critical for net N mineralization, does not necessarily have to be reached before net mineralization occurs in surface-applied residues incubated at 35 °C for a period of 60–96 days. In this study, even at a residue C:N ratio of about 15 (Table 2), net N mineralization did not occur until after 10 weeks of incubation at 25 °C (Fig. 3b).

The N mineralization potential (N_o) of the residue-amended soil decreased with increasing proportions of rye or ryegrass in the mixed residue (Table 3). It was within the range of 20–300 mg N kg^{-1} soil reported in the literature (Stanford and Smith 1972; Smith et al. 1980; El-Harris et al. 1983). Residue N correlated significantly with N_o (Table 4). There were also significant correlations between N_o and other plant fractions, including WSN, WSC and WSCA. The mean fraction of soil organic N before incubation that was potentially mineralizable was 86.0±5.9 (SD) g kg^{-1}, well within the range of 0–410 g kg^{-1} organic N given in the literature (Stanford and Smith 1972; El-Harris et al. 1983; Serna and Pomares 1992). N_o was higher for the residue-amended soil than for the control soil without residue amendment (Table 3). The half-lives ($t_{1/2}$ or 0.693/k), i.e. the time required to mineralize half of the N_o, was short (Table 3), averaging 7.1 weeks over all treatments, and was comparable with the $t_{1/2}$ of 6.2 weeks of other plant residues incubated at 23 °C (Frankenberger and Abdelmagid 1985).

As with N_o, k and $N_o k$ varied with residue mixtures (Table 3). $N_o k$ and k were significantly correlated with residue N, WSC, and WSCA (Table 4). The water-soluble constituents appeared to correlate better with k or $N_o k$ than did the residue N or C:N ratio for the mixed residues of vetch and ryegrass. The mean k was 0.103 week^{-1}, which is comparable with the mean k of 0.149 week^{-1} determined in the laboratory incubation at 23 °C set-up by Frankenberger and Abdelmagid (1985). Microbial biomass is positively affected by the size of the soluble C pool (Reinertsen et al. 1984). As the size of the soluble C pool was increased with the addition of residues containing more rye or annual ryegrass (Table 2), the net N mineralization rate and rate constant decreased, and N immobilization increased.

Rye growth response to addition of mixed residues

Decreasing the proportion of hairy vetch in the mixture of hairy vetch and rye or annual ryegrass decreased rye growth and N uptake (Table 5). The rye biomass, N concentration and N uptake were better correlated with residue N (Table 5) than with residue C:N ratio, WSC, or WSCA. Residue N, however, was less significantly correlated with rye biomass production, N concentration and N uptake than was the initial potential N mineralization rate ($N_o k$) obtained from the laboratory incubation (Table 5, Fig. 4). There was better correlation of rye growth and N uptake with inorganic N concentration in the pre-incubated soil amended with the residues (N_j) than with residue N. N_j reflected the overall influence of cover crop residues and soil environmental conditions on net N mineralization during incubation. If N_j is the primary source for rye N uptake, it should be more effective than residue N alone in accounting for the variability in N availability to the plants. Significant correlations between crop yields or N uptake and soil inorganic N concentration before planting

Fig. 3 The relationship between the crossover point (t_c), i.e. the time when net N mineralization in the residue-amended soil equalled that of the control soil without residue amendment, and **a** the residue N concentration or **b** residue C:N ratio. $^{***}P<0.001$

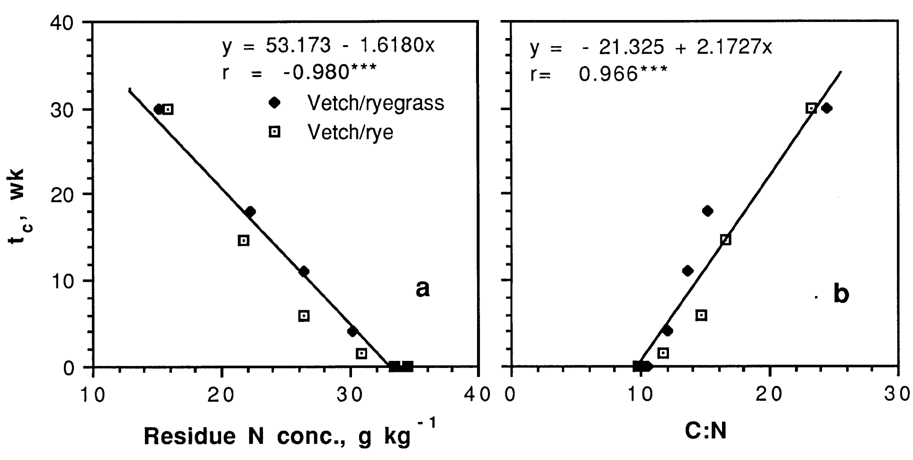

Table 4 Correlation coefficients (r) for the relationship between cumulative amount of net N mineralization in a 30 week incubation (N_C), potential mineralizable N (N_o), mineralization rate constant (k), or initial potential N mineralization rate ($N_o k$) and chemical characteristics of the residues. For other abbreviations see Table 1

Residue chemical characteristics	Vetch/rye				Vetch/ryegrass			
	N_C	N_o	k	$N_o k$	N_C	N_o	k	$N_o k$
Total residue								
N concentration	0.94***	0.78*	0.95***	0.93**	0.86*	0.86*	0.78*	0.79*
$(C:N)^{-1}$	0.89**	0.79*	0.93**	0.93**	0.71	0.76*	0.62	0.66
Lignin concentration	0.59	0.66	0.76*	0.83*	0.47	0.68	0.53	0.63
Water-soluble fraction								
N concentration	0.74	0.76*	0.83*	0.86*	0.94**	0.91**	0.90**	0.90**
C concentration	–0.98**	–0.84*	–0.92**	–0.91***	–0.97***	–0.96**	–0.91**	–0.92**
Carbohydrate concentration	–0.99***	–0.75*	–0.91**	–0.89**	–0.94**	–0.96***	–0.89**	–0.91**
$(C:N)^{-1}$	0.83*	0.81*	0.92**	0.95***	0.96***	0.96***	0.95***	0.97***

*, **, and *** represent 0.05, 0.01, and 0.001 levels of significance, respectively

Table 5 Correlation coefficients (r) for the relationships between rye biomass, N concentration or N uptake and parameters associated with residue chemical characteristics and net N mineralization in soil. *A* Correlation including all but control treatment without residue amendment; *B* correlation including all treatments; N_j soil inorganic N prior to seeding rye; N_c cumulative amount of inorganic N after 30 week incubation; N_o potential mineralizable N determined from laboratory incubation; $N_o k$ initial potential N mineralization rate from laboratory incubation. For other abbreviations see Tables 1 and 2

Soil or residue parameter	*r*					
	Biomass		N concentration		N uptake	
	A	*B*	*A*	*B*	*A*	*B*
Residue						
N	0.81**		0.84***		0.83***	
C:N	–0.72**		–0.73**		–0.70*	
WSN	0.80**		0.78**		0.82**	
WSC	–0.68*		–0.61*		–0.67*	
Water-soluble carbohydrate	–0.79**		–0.65*		–0.77**	
WSC:WSN	–0.65*		–0.58		–0.64*	
Soil						
N_j	0.81**	0.83***	0.96***	0.97***	0.93***	0.93***
N_c	0.76**	0.80**	0.78**	0.81***	0.79**	0.82***
N_o	0.75**	0.75**	0.57	0.61*	0.72**	0.70**
$N_o k$	0.93***	0.94***	0.90***	0.91***	0.99***	0.99***

*, **, and *** represent 0.05, 0.01, and 0.001 levels of significance, respectively

have been shown (Keeney and Bremner 1966; Serna and Pomares 1992; Kuo et al. 1996).

Because $N_o k$ was highly correlated with N_j ($r=0.95$, $P<0.001$), it gave a good indication of the initial phase of N mineralization after the residues had been added to soil in the greenhouse.

Kuo et al. (1996) noted that when cover crop residues had been incorporated into soil for a period of about 4 weeks before net N mineralization was measured, $N_o k$ did not reflect the difference in initial N mineralization potentials among various types of residues, nor could it be used to indicate the initial amount of inorganic N prior to incubation. Fresh cover crop residues are readily degradable with short $t_{1/2}$ of 5–8 weeks (Jenkinson and Rayner 1977; Kuo et al. 1997). The $N_o k$ measured after extensive residue decomposition had occurred was influenced more by indigenous soil organic N than by residue N or the type of residues added. After extensive residue decomposition, the initial inorganic N, not $N_o k$, gave a better indication of N uptake by plants (Kuo et al. 1996). In the present study, net N mineralization in the soils incubated at 25 °C was measured immediately after residues had been added so that $N_o k$ values gave a good indication of the initial N mineralization potentials of the residues, and correlated well with rye biomass production and N uptake.

Although N_o is a significant factor affecting crop yield and N uptake (Keeney and Bremner 1966; Stanford et al. 1973; 1977), it was not as closely associated with rye biomass and N uptake as $N_o k$ (Table 5). Campbell et al. (1993) found similar results. N mineralization potential reflects long-term N availability, which is not as good an indicator of soil N availability as $N_o k$ when assessing N availability within a short period of time after incorporation of easily-decomposable residues.

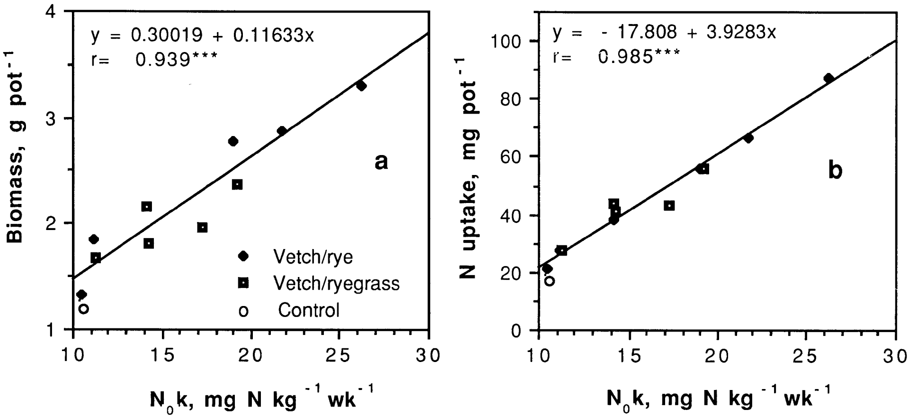

Fig. 4 The relationship between the initial potential N mineralization rate ($N_0 k$) and **a** rye biomass production and **b** N uptake. $^{***}P<0.001$

The proportion of hairy vetch in the mixture of hairy vetch and rye should not be reduced to 40% or less if increases in rye biomass production, N concentration, and N uptake are to be significant (Table 6). Similarly, in order to achieve significant increases in rye N concentration and N uptake, the percentage of hairy vetch in a hairy vetch/ryegrass mixture should not be lower than 40%. When the proportion of hairy vetch was 40% or less, immobilization was intensified, as indicated earlier.

Although increasing the proportion of hairy vetch in the mixture of hairy vetch and rye or annual ryegrass to above 40% further increased the availability of N for the succeeding rye crop, this practice could compromise the effectiveness of the cropping system in reducing N leaching. Further study is needed to determine the effectiveness of various mixtures of hairy vetch and rye or annual ryegrass in reducing N leaching.

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