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Compared cycling in a soil-plant system of pea and barley residue nitrogen

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Abstract

Field experiments were carried out on a temperate soil to determine the decline rate, the stabilization in soil organic matter and the plant uptake of N from ^{15}N-labelled crop residues. The fate of N from field pea (*Pisum sativum* L.) and spring barley (*Hordeum vulgare* L.) residues was followed in unplanted and planted plots and related to their chemical composition. In the top 10 cm of unplanted plots, inorganic N was immobilized after barley residue incorporation, whereas the inorganic N pool was increased during the initial 30 days after incorporation (DAI) of pea residues. Initial net mineralization of N was highly correlated to the concentrations of soluble C and N and the lignin:N ratio of residues. The contribution of residue-derived N to the inorganic N pool was at its maximum 30 DAI (10–55%) and declined to on average 5% after 3 years of decomposition.

Residual organic labelled N in the top 10 cm soil declined rapidly during the initial 86 DAI for all residue types. Leaching of soluble organic materials may have contributed to this decline. At 216 DAI 72, 59 and 45% of the barley, mature pea and green pea residue N, respectively, were present in organic N-forms in the topsoil. During the 1–3 year period, residual organic labelled N from different residues declined at similar rates, mean decay constant: 0.18 yr^{-1}. After 3 years, 45% of the barley and on average 32% of the pea residue N were present as soil organic N. The proportion of residue N remaining in the soil after 3 years of decomposition was most strongly correlated with the total and soluble N concentrations in the residue. The ratio (% inorganic N derived from residues):(% organic N derived from residues) was used as a measure of the rate residue N stabilization. From initial values of 3–7 the ratios declined to on average 1.9 and 1.6 after 2 and 3 yrs, respectively, indicating that a major part of the residue N was stabilized after 2 years of decomposition. Even though the largest proportion of residue N stabilized after 3 years was found for barley, the largest amount of residue N stabilized was found with incorporation of pea residues, since much more N was incorporated with these residues.

In planted plots and after one year of decomposition, 7% of the pea and 5% of the barley residue N were recovered in perennial ryegrass (*Lolium perenne* L.) shoots. After 2 years the cumulative recovery of residue N in ryegrass shoots and roots was 14% for pea and 15% for barley residue N. The total uptake of non-labelled soil N after 2 years of growth was similar in the two residue treatments, but the amount of soil N taken up in each growth period varied between the treatments, apparently because the soil N immobilized during initial decomposition of residues was remineralized later in the barley than in the pea residue treatment. Balances were established for the amounts of barley and mature pea residue N remaining in the 0–10 cm soil layer and taken up in ryegrass after 2 years of decomposition. About 24% of the barley and 35% of the pea residue N were unaccounted for. Since these apparent losses are comparable to almost twice the amounts of pea and barley residue N taken up by the perennial ryegrass crop, there seems to be a potential for improved crop residue management in order to conserve nutrients in the soil-plant system.

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Introduction

Increased knowledge on crop residue decomposition in agroecosystems is required to improve the synchronisation of nutrient release and crop demand. This is a requirement to optimise the use of nutrients and reduce their losses to the wider environment. In the short-term incorporation of crop residues provides the energy and nutrients for microbial growth and activity, and, is thus the driving force of the mineralization-immobilization processes in the soil and a source of N for plants (Jansson and Persson, 1982). In the long term, incorporation of crop residues is important for the maintainance of soil organic C and N in arable soils (Campbell and Zentner, 1993; Powlson et al., 1987; Rasmussen and Parton, 1994). Crop residue management practices have been shown to increase the soil microbial biomass and the N-mineralization potential of soils (Franzluebbers et al., 1994; Powlson et al., 1987).

The decomposition of crop residues in soil can be described by two first-order reactions, which account for an initial rapid breakdown of easily decomposable components, followed by a much slower decay of stabilized residues and decomposition products (Amato et al., 1987; Sørensen, 1981). Several biotic and abiotic factors, including the chemical composition of crop residues, influence initial residue decomposition and plant nutrient availability (e.g. Jenkinson, 1981; Parr and Papendick, 1978). Among these, the soil temperature and moisture content, the availability of inorganic nutrients, especially N, are important (Jenkinson, 1981; Mary et al., 1995). The C/N ratio of materials provides only a rough indication of the initial rate of residue decomposition and net mineralization of N in soil (Jenkinson, 1981), and a better prediction is obtained from knowledge of soluble matter concentration, water content, lignin (L) and polyphenol (P) concentrations, L/N and L + P/N ratios (Becker et al., 1994; Fox et al., 1990; Müller et al., 1988; Vigil and Kissel, 1991; Waksman and Tenney, 1928). Reinertsen et al. (1984) suggested that the pool of soluble residue C is the dominant factor determining N-immobilization during early decomposition. During the slower phase of decomposition, the soil texture and management practices become important factors in the stabilization of microbial decomposition products, e.g. in the formation of organo-mineral complexes and recalcitrant humic substances (Christensen, 1992; Sørensen, 1981).

The aim of this study was to determine the effect of crop residue chemical composition on the rate of residue N net mineralization (decline in residue-derived N in the top soil) in uncropped soil during 3 years of decomposition. Since the decomposition of plant roots containing ^{15}N-labelled residue N would complicate the determination of the residue N decline rate, decline rates were determined in unplanted soil. On the other hand, plant rhizospheres may either stimulate or suppress the turnover of soil organic matter (Dormaar, 1990). Thus, additional plots were amended with mature pea and barley crop residues to determine the plant uptake and residual organic labelled N in soil cropped to perennial ryegrass during 2 years following incorporation of residues.

Materials and methods

Site, soil and plots

The experiments were carried out at Risø, Denmark during 1987–1990. The average annual precipitation, was 550 mm. The average minimum and maximum daily air temperatures were 8 and 17 °C, respectively, during the growth season (April to August) and -2 and +4 °C during the winter. However, winters were unusually mild throughout the experiment, with temperatures 3–5 °C higher than the average, and only a few days of frozen topsoil during the 1987/88 winter.

The soil (0–20 cm) was a sandy loam (Typic Hapludalf) with 11.4 % clay (<0.002 mm), 13.6% silt (0.002–0.02 mm), 48.6% fine sand (0.02–0.2 mm) and 26.4% coarse sand (0.2–2 mm). The soil contained 1.1 % total C and 0.13 % total N; pH in water was 6.9.

The microplots were confined within PVC cylinders of 20 or 31.5 cm in diameter and 50 cm in length pushed into the soil to a depth of 45 cm in May 1987. White mustard (*Sinapis alba* L.) was grown on all plots until the residues were incorporated. The top 10 cm soil from all plots were bulked and most mustard roots removed. The soil was homogenized and sieved (6 mm) and the residue mixed into the appropriate portions of soil. The amended soil was returned to the plot the same day and compressed to approximately the original bulk density (1.3–1.4 g cm^{-3}).

Crop residues

White-flowered and determinate pea (*Pisum sativum* L. spp. *sativum* cv. Bodil), purple flowered and inde-

Table 1. Some characteristics and the amounts of crop residues incorporated in the 0–10 cm soil layer in unplanted and planted plots

Plant species (Treatment)	Residue component	Residue added (g kg^{-1} soil)	Residue composition (% of dry matter)					
			Atom % ^{15}N excess	Total N (%)	Total C (%)	Ligin (%)	Water extractable[a] N (%)	Water extractable[a] C (%)
Barley	Straw	2.82	3.34	1.10	42.6	6.7	0.2	3.4
(Barley)	Awn	0.70	3.46	0.80	44.5	ND	ND	ND
	Root	0.63	3.28	1.49	42.5	ND	ND	ND
Determinate pea	Straw	2.15	1.41	2.44	44.4	11.5	0.5	7.4
(Pea x 1, Pea x 2)[b]	Empty pod	0.86	0.69	2.31	44.1	8.2	0.8	6.5
	Root	0.64	3.21	2.80	46.3	15.7	0.3	2.9
Determinate pea	Straw	4.49	1.19	3.03	47.1	3.3[c]	0.7[c]	12.8[c]
(Green pea)	Empty pod	1.72	0.55	2.73	44.9	3.6	1.6	18.1
	Root	0.63	2.66	3.71	40.7	10.7	0.8	5.0
Indeterminate pea	Straw	2.06	0.79	2.66	48.6	11.9	0.7	6.2
(Arvense pea)	Empty pod	0.43	0.37	4.53	44.3	ND	ND	ND
	Root	0.58	2.59	3.24	46.9	ND	ND	ND

[a] Proximate analysis.
[b] The amounts of residue added in the pea x 2 treatment were twice those given in the table.
[c] Estimated from separate leaf and stem analysis assuming 75% leaves and 25% stem dry matter.
ND: Not determined.

terminate pea (*P. sativum* L. spp. *arvense* cv. Timo) arid spring barley (*Hordeum vulgare* L. cv. Golf) were grown outside in 20 L pots containing sand. Pots, were watered automatically with a nutrient solution containing basic nutrients (Jensen, 1994a). A total of 0.6 and 3.0 g N per pot as KNO_3, with ca, 17 and 4 atom % ^{15}N, were applied in 3 split applications to peas and barley, respectively. Plants were harvested at maturity (16 weeks). White-flowered pea plants were also harvested after 12 weeks at the green pod/green pea growth stage. Above-ground plant parts were separated into straw (stem + leaves), empty pods and seeds. Roots were washed free of sand. Materials were dried at 60 °C for 20 h. The dried residues were chopped into 2.5 cm pieces and some characteristics are shown in Table 1.

Fate of residue N in unplanted soil (Experiment 1)

The decline in crop residue-derived N in unplanted soil was studied in the 20 cm-diameter plots. The residues were incorporated in 4.1 kg dry soil per plot on 14 September 1988. The amounts of residue incorporated per kg soil are shown in Table 2. The treatments were: no residues incorporated (Control), barley residues (4.2 g kg^{-1} soil; Barley), mature determinate pea residues (3.7 g kg^{-1} soil; Pea x 1), mature determinate pea residues (7.4 g kg^{-1} soil; Pea x 2), determinate pea residues from the green pea growth stage (6.8 g kg^{-1} soil, Green pea) and mature indeterminate pea residues (3.1 g kg^{-1} soil, Arvense pea). Two plots were used for each pea residue treatment, 4 plots were amended with barley residues and there were 2 control plots.

Two soil cores per plot was sampled to the depth of 8 cm using a stainless steel auger (17 mm diameter) 0,10, 30, 86, 216, 357 (nominally 1 yr), 734 (nom. 2 yr) and 1099 (nom. 3 yr) days after incorporation (DAI) of residues. After sampling, holes were filled with acid washed quartz sand. The plots were kept free of weeds by frequent hand-weeding.

Fate of residue N in planted soil Experiment 2

The cumulative uptake of N from labelled crop residues and from soil by perennial ryegrass (*Lolium perenne* L., cv. Patora) was determined during 2 years following residue incorporation. Residues were incorporated in 10.6 kg dry soil per 31.5–cm plot and 3 replicate plots

Table 2. Residue dry matter, C and N incorporated per kg dry soil in the two experiments and the C:N ratios of total and soluble organic matter

Crop residue	Residue DM ($g\ kg^{-1}$)	Tot. N ($mg\ kg^{-1}$)	Tot. C ($g\ kg^{-1}$)	Sol. N[a] ($mg\ kg^{-1}$)	Sol. C[a] ($mg\ kg^{-1}$)	Total C:N	Soluble C:N
Barley	4.16	46	1.78	8	141	39	18
Pea x 1	3.65	80	1.63	20	234	18	12
Pea x 2	7.30	160	3.26	40	468	18	12
Green pea	6.84	206	3.13	64	917	15	14
Arvense pea	3.07	93	1.47	19	172	16	9

[a] The % soluble C and % soluble N in the respective residue mixtures were calculated from Table 1. It was assumed that the % sol. C and N in barley awns and roots were similar to the concentrations in the straw. For Arvense pea pods and roots were used the values in the respective plant parts of the determinate pea.

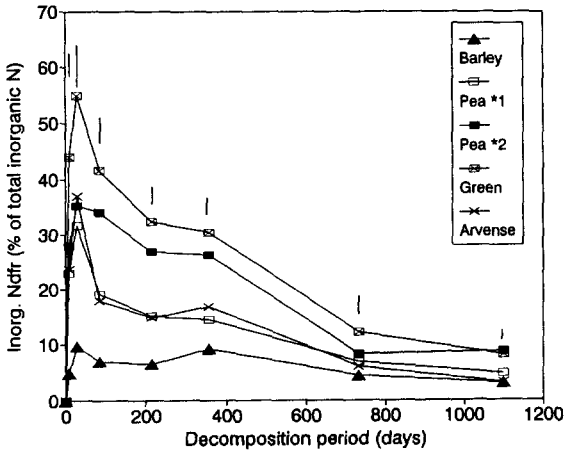

Figure 1. Percent of soil inorganic N derived from residues (Inorg. Ndfr) in the 0–10 cm soil layer of unplanted plots. Bars indicate $LSD_{0.05}$.

were used. Only barley (Barley) and mature determinate pea (Pea x 1) residues were used in this experiment. The same amounts of residues (per kg dry soil) were added as in Experiment 1 (Table 2).

Ryegrass was sown (300 mg seed plots) 2 days after residue incorporation. The ryegrass was cut (2 cm above the soil surface) 7 times during the two years following incorporation (see Fig. 3). At the final harvest soil was sampled to the 8 cm depth. The top 10 cm of soil was removed from the plots and roots recovered by washing. All plant materials were dried at 80 °C for 20 h and ground. Visible roots were removed from the soil sample.

Analytical methods

Soil samples were immediately brought to the laboratory for determination of dry matter content (105 °C for 24 h) and KCl extractable inorganic N. Duplicate portions of 10 g of fresh soil were extracted with 100 mL 2 *M* KCl. Nitrate (+ NO_2^-) and ammonium in extracts were determined using a Technicon Autoanalyzer and the sodium salicylate-sodium nitroprusside hypochlorite method for ammonium and the sulfanilamide-naphthyl-ethylenediamine method for NO_3^- after reducing the NO_3^- to NO_2^- with hydrazine (Jensen, 1994a).

Soil total N was determined on duplicate subsamples of 60 mg air-dried (99.2% dry matter) ground (Fritsch mortar mill II for 15 min) soil and total N and C in plant materials were determined on 10 mg subsamples of finely ground (Tecator Cyclotec mill with a 0.5 mm sieve) residues using an elemental analyzer (Carlo Erba NA1500 N/C). The ^{15}N-enrichment in soil and plant materials was determined simultaneously on an isotope ratio mass spectrometer coupled on-line to the elemental analyzer (Jensen, 1991). The inorganic N in KCl extracts was concentrated using a diffusion procedure prior to determination of the ^{15}N-enrichment (Jensen, 1991).

The lignin content of crop residues was determined using the acid-detergent fiber method of van Soest (1963). Water soluble N and C in residues were determined by extraction in cold water (10 mg of ground material mL^{-1}); N and C in the extract were determined by elemental analysis.

Calculations and statistics

The ^{15}N-enrichments were corrected for the natural ^{15}N-abundance of the soil (0.3703 atom % ^{15}N). Concentrations ($\mu g\ N\ g^{-1}$ dry soil) of residue-derived inorganic and total N in soil were calculated under the assumption that the N in residue mixture compo-

Table 3. Inorganic N concentration (μg N g^{-1} soil) in unplanted soil (0–10 cm) as influenced by residue incorporation

Residue treatment	Sampling (days after residue incorporation)						
	10	30	86	216	357	734	1099
Control	13.0	18.4	0.2	5.4	12.2	3.7	4.0
Barley	3.1	6.6	0.3	5.1	13.4	9.4	13.1
Pea x 1	19.5	22.5	2.0	5.6	10.8	3.5	17.0
Pea x 2	16.1	24.2	3.8	7.3	22.7	5.5	16.7
Green pea	29.1	51.3	4.0	8.5	29.7	4.8	23.4
Arvense pea	21.6	20.5	1.3	6.8	15.6	5.4	10.8
$LSD_{0.05}$	3.5	7.7	0.6	1.5	4.0	3.4	NS

nents mineralized at the same rate. The concentration of residue-derived organic N in the soil was calculated as the difference between concentrations of residue-derived total and inorganic N. The decline constant for the residue-derived organic N was calculated assuming first-order reaction rate kinetics (Voroney et al., 1989).

Analysis of variance was carried out using the GLM procedure in SAS (1990). $LSD_{0.05}$ was used for comparisons if the main effect of treatment was significant.

Results

Fate of residue N in unplanted soil

The initial concentration of inorganic N in the soil was 17.0 ± 1.2 (SD). Incorporation of pea residues, especially the green pea residues, increased the inorganic N pool in the top 10 cm soil layer during the initial period of decomposition, whereas barley residues caused a net immobilization (Table 3). Although the inorganic N-concentration was lower at 86 and 216 DAI, it was found to be significantly higher after incorporation of pea residues than in the barley residue and control treatments (Table 3)

The inorganic N concentration in the soil, sampled 1 and 2 years after incorporation, was significantly influenced residue treatment, but no significant effect was observed after 3 years (Table 3). After one year, the green pea and the pea x 2 treatments had caused a higher net mineralization of N than in the other treatments (Table 3). At the sampling 2 years after residue incorporation, a significantly higher inorganic N concentration was observed after barley residues than after the other treatments.

The proportion of residue-derived N in the inorganic N-pool reached a maximum 30 DAI and then

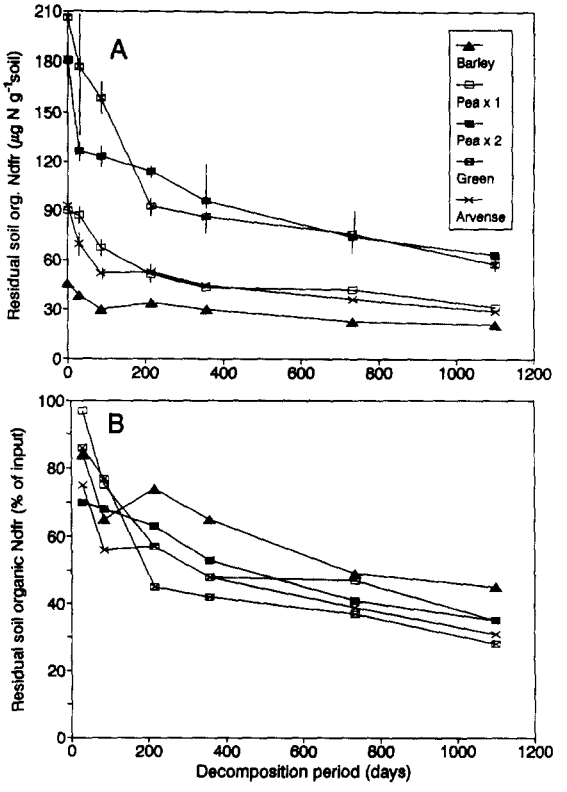

Figure 2. Decline in residue-derived organic N in the 0–10 cm soil layer of unplanted plots. (**A**) Residual soil organic N derived from residues (Ndfr). Values at t = 0 were calculated from the amounts added. (**B**) Residual soil organic N derived from residues as percent of the residue N input. Bars represent 2 x SE.

declined gradually during the following decomposition period (Fig. 1). Inorganic N derived from barley residues never exceeded 10% of the soil inorganic N pool whereas inorganic N from green pea residues constituted more than half of the inorganic N 30 DAI (Fig. 1). After 3 years, 3–5% of the total inorganic N was derived from the barley, pea x 1 and indeterminate pea residues.

The decline in residue-derived organic N showed a 2 phase pattern: a rapid decline from 0–216 DAI, with higher decline rates for the pea than for the barley residue N, followed by a slower decline (216–1099 DAI) with similar decline rates for all residues (Fig. 2A and 2B). In the middle of April (216 DAI) 72% of the barley, 63% of the pea x 2, 57% of the pea x 1 and indeterminate pea and 45 of the green pea residue N remained in the topsoil in organic N forms. During the 1–3 year period of decomposition the residue-derived organic N declined with decay constants of 0.13–0.21 yr^{-1} and the N derived from residue had an average half life of 4.1 year (Table 4). After 3 years, a signifi-

Table 4. Decline constant (k) and half lives ($T\frac{1}{2}$) for residue-derived organic N in the depth of 0–10 cm during the 1–3 year decomposition period

Treatment	k (yr^{-1})	$T\frac{1}{2}$ (yr)	r^2
Barley	0.13	5.3	0.91
Pea x 1	0.16	4.3	0.81
Pea x 2	0.18	3.9	0.84
Green pea	0.20	3.5	0.95
Arvense pea	0.21	3.3	0.99
Mean	0.176	4.1	

Table 5. Dry matter production and N accumulation from soil and ^{15}N-labelled crop residues by perennial ryegrass after 2 years of growth

Parameter	Crop residue		Level of significance in ANOVA
	Pea	Barley	
Shoot DM ($g\ m^{-2}$)	975	889	NS
Root DM ($g\ m^{-2}$)	840	895	NS
Shoot N ($g\ m^{-2}$)	10.5	10.1	NS
Root N g (m^{-2})	7.2	7.6	NS
Residue-derived N[a] ($g\ m^{-2}$)	1.91	1.04	$p< 0.001$
Residue N recovery[a] (%)	14.3	15.2	NS
Soil N uptake[a] ($g\ m^{-2}$)	15.8	16.7	NS

[a] Root + shoot N; NS: Non-significant.

cantly higher proportion of the barley residue N (45% of the input) than of the pea residue N (average of pea treatments: 32%) was stabilized in soil organic matter, but the amount stabilized was larger after pea residue incorporation, due to the higher amount initially added. Green pea residues N had the greatest proportion of N being released after 3 years (Fig. 2B).

Fate of residue N in planted soil

The uptake of residue- and soil-derived N in perennial ryegrass was low in the first autumn/winter period (0–214 DAI), but increased during the spring and summer (214–347 DAI, Fig. 3). The low uptake of N in the first autumn/winter period was presumably due to the slow development of the perennial ryegrass established in that autumn.

The uptake of residue-derived N in the ryegrass shoots was significantly larger after pea than after barley residues at all harvest (Fig. 3). The total uptake of residue-derived N in shoots during 2 years of growth after pea and barley residues, were 1.25 and 0.54 g N m^{-2}, respectively.

At the first 2 harvests the amount of soil-derived N taken up in ryegrass shoots was higher after pea than after barley residues, although only significantly ($p< 0.01$) at the first harvest (Fig. 3). However, from the harvest at 347 DAI the soil-derived N uptake was higher after barley than after pea residues (Fig. 3). Consequently, the cumulative uptake of soil-derived N, including N in harvested roots, was not significantly different between the 2 residue treatments after 2 years (Table 5). Neither was the total dry matter production nor the total N uptake in the ryegrass shoots and roots significantly influenced by the type of crop residue incorporated. Over the 2 years a total of 10.8% and 5.9% of the ryegrass were derived from pea and barley residues, respectively.

After one year of growth the cumulative recovery of residue N in ryegrass shoots was 6.8% for pea and 4.6% for barley residues. Harvested roots contained 5.1% of the pea and 7.7% of the barley residue N after 2 years of growth. Consequently, the total recovery of residue N in shoots and roots of ryegrass after 2 years was not significantly different in the two residue treatments; 14.3% for pea and 15.2% for the barley residue N (Table 5). At the final harvest the topsoil (0–8 cm) contained 51.0 ± 0. 6% and 61.1 ± 2. 6%

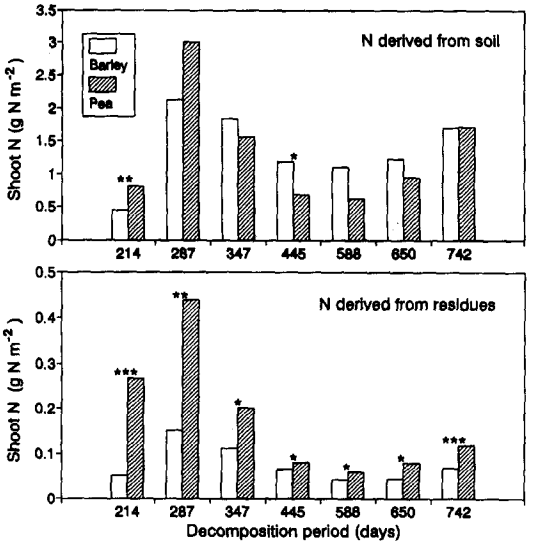

Figure 3. Uptake in perennial ryegrass shoots of N derived from residues and soil at 7 harvests. Asterisks indicate the significance for the effect of residue treatment. *: $p<0.05$; **: $p>0.01$; ***: $p>0.001$. If asterisks are absent the difference between treatments is not significant.

(± SD) of the residue-derived N for the pea and barley residue treatments, respectively. Consequently, 35% of the pea and 24% of the barley residue N could not be accounted for in the plants and topsoil.

Discussion

Mineralization-immobilization of N during initial residue decomposition

The mineralization-immobilization of N during the initial stage of decomposition is known to be significantly influenced by the chemical composition of residues. Chemical characteristics, such as the % total N, % lignin and soluble C and N concentrations and C/N ratios of residues used in the present study, varied considerably (Tables 1 and 2).

Net immobilization of inorganic N was observed after barley residue incorporation. The maximum net immobilization of N in the top 10 cm soil layer (difference between inorganic N concentrations in soil with residue amendment and the control treatment) due to residue incorporation was observed in the barley residue treatment. The immobilization was estimated to 11.8 μg N g^{-1} soil or 8.5 mg N g^{-1} added C after 30 days, assuming no leaching of nitrate and denitrification. Christensen (1986) reported that barley straw immobilized similar amounts of N in a sandy loam soil, so did Powlson et al. (1985) for wheat straw in a silty clay loam.

The potential for immobilization of soil N by cereal straw has been reported to be much higher: ca. 40 mg N g added C (Recous et al., 1995), and depends, among other factors, on the availability of straw N to the soil microbial biomass, the soil temperature, straw particle size and the concentration of inorganic N in the soil (Ambus and Jensen, 1995 ; Mary et al., 1995; Ocio et al., 1991; Recous et al., 1995). Net mineralization of N occurred during the initial decomposition of pea residues. Maximum net mineralization 30 DAI was found in the green pea residue treatment, where the amount of inorganic N in the top 10 cm soil had increased with 33 μg N g^{-1} soil compared to the control.

The effect of crop residues (excluding the pea x 2 treatment) on net mineralization of N was found to be more strongly correlated with the concentrations of soluble N and C in residues than with the C/N ratio and lignin concentration in residues (Table 6). The positive correlation found between soluble matter and the net mineralization of N is in contrast to the observation by Reinertsen et al. (1984), who found a negative correlation between the amounts of soluble N and C in wheat straw residues and the net mineralization of N.

Table 6. Correlation coeffients (r^2) for linear regressions of some residue characteristic and the net mineralization of N 30 DAI and the % of residue N input remaining in the soil after 216 days and 3 years of decomposition (excl. the pea x 2 treatment)

Residue characteristic	Net mineralization at 30 DAI	% residue N remaining	
		216 days	3 years
% N	0.52	0.80	0.96
% C	0.18	0.40	0.71
C/N	0.50	0.79	0.90
% soluble N	0.91	0.99	0.92
% non sol. N	0.31	0.61	0.84
% soluble C	0.99	0.84	0.61
sol C/sol N	0.03	0.21	0.43
% lignin (L)	0.25	0.04	0.00
L/N	0.97	0.91	0.79
L/sol N	0.95	0.99	0.88
L/non sol. N	0.96	0.89	0.78

The lignin/N ratio or the lignin+polyphenol/N ratio have been reported to be much better indicators of initial net mineralization rates than the C/N ratio, lignin concentration and total N concentration (Becker et al., 1994; Fox et al., 1990). This study also showed that the lignin/N ratio was more strongly correlated to early net mineralization than the C/N ratio, %N and % lignin of residues (Table 6).

The pool of N in residues being readily-available to the soil microbial population and perhaps assimilated as organic N (Hadas et al., 1992) may stand proxy to soil-derived inorganic N. Consequently, the higher the amount of readily-available N (soluble N) in residues the lower one could expect the net immobilization of soil-derived inorganic N to be. This effect, termed "apparent added nitrogen interaction" can only be observed in ^{15}N-tracer studies (Jenkinson et al., 1985). After 30 DAI the inorganic soil-derived N pool was larger in the treatments were the higher amounts of soluble N was added (data not shown), indicating that more residue-derived N were immobilized, in favour of soil-derived inorganic N, with the higher amount of soluble N added.

Decline in residue-derived organic N

The decline in residue-derived organic N during decomposition in the topsoil is due to net mineralization of residue N and the transport of residue materials to deeper soil layers by percolating water and by soil faunal activity. Analysis of residue-derived organic N in soil at 10 and 30 DAI were highly variable. The first samplings were probably not as representative as the later, due to the small auger used. With time, the residue particles were gradually reduced in sized and became homogenously distributed in the soil by faunal activity. Sampling the whole plot would have reduced this variability during early decomposition.

The rapid decline in residue-derived organic N for barley and mature pea residues (Fig. 2A), which were not accompanied by an increase in soil inorganic N, may have several causes. Approximately 17–22% of the barley and mature pea residue N was water-soluble (Table 2), but the amounts of soluble pea residue N was higher, due to the higher total N content of these residues. A proportion of this N could have been leached to deeper soil layers. Jensen (1994a) found that 12–18% of the pea residue N incorporated in the top 10 cm soil was present as inorganic and organic N in the 10–45 cm soil layer after 90 days of decomposition in the same soil. Christensen (1986) reported that about 40% of the N in barley straw with a C/N of 50 was leached during the first months of decomposition. However, even if net N-immobilization prevailed initially after the incorporation of barley residues, residue N may have been mineralized and lost by leaching and denitrification.

The decline rate of about 30% observed for barley residue-derived organic N after 216 days is higher than reported for wheat (*Triticum aestivum* L.) residue N after 180 days in a series of Australian soils (Amato et al., 1987) and in Canadian soils (Voroney et al., 1989). However, several of the Australian and the Canadian soils studied had much higher clay contents, which may have increased the early stabilization of residue-derived N. The decline in mature determinate pea residue N from incorporation to 216 DAI was similar to those reported by Jensen (1994a). Norman et al. (1990) similarly reported that 40% of the soybean N incorporated in the autumn was mineralized in the spring. In contrast Bremer and van Kessel (1992) found that only a few percent of the lentil (*Lens culinaris* Medikus) and wheat straw incorporated in the autumn was mineralized until the subsequent spring under Canadian conditions.

The faster decline of pea than of barley residue-derived organic N, up to the sampling at 216 DAI, is most likely due to the higher concentrations of N and water-soluble (labile) substances in the pea residue, since the lignin concentration was higher in mature pea than in barley residues (Table 1). Regressions of the percent (of input) residue N remaining in the top soil after 216 days of decomposition on various residue characteristics showed that the strongest correlation (r^2) was found with the concentration of soluble N, the lignin/N and lignin/sol. N ratios (Table 6). The best two-parameter model, found using the RSQUARE procedure in SAS (1990), included % soluble C and % soluble N (R^2 0.99), whereas the model including %N and lignin/N as suggested by Vigil and Kissel (1991) had a R^2 of 0.94.

The more rapid decline in green pea residue N than of mature pea residue N is in agreement with Bremer and van Kessel (1992) and Jans-Hammermeister et al. (1994). They also found that the younger the lentil or pea material the higher was the release of N during the first year of decomposition.

Ladd et al. (1983) reported that a greater percentage of residue-derived organic N was retained in soil the lower the amount of residues incorporated. It was suggested that this was partly due to a better protection of the microbial biomass formed during decomposition of the lower levels of residue addition. During the initial 3 months of decomposition in my experiment the decline rate of residue-derived organic N tended to be higher for the pea x 2 treatment than for the pea x 1 treatment, but the differences were not significant. After 216 DAI no clear trend could be observed and after 3 years the percentages of mature determinate pea residue-derived N retained in soil were similar after the 2 levels of residue addition, indicating that the amount of pea residue N stabilized was proportional to the amount added.

Stabilization of residue-derived N

The decline in proportion of residue-derived residual organic N during the second and slower phase of residue decomposition was lower for barley than for pea residue (Table 4). This indicates that the remaining barley residue N was stabilized to a higher degree than the pea N. However, the amount of pea residue N stabilized was higher than of barley residue N, due to the difference in amounts added.

The amount of residue N added varied from 26 to 65 μg N mg^{-1} added C, with the lowest amount for

barley and the highest for the green pea residues (Table 1). The amount of residue N stabilized in the soil per unit C added after 3 years showed that this ratio was very similar for the pea residues (18–20 μg residue-N remaining mg^{-1} added C), despite differences in C/N, soluble N and C and lignin concentrations. The ratio was much lower for barley (12 μg residue-N remaining mg^{-1} added C), indicating that relatively less barley residue N was stabilized per unit added C. There can be several explanations to this difference. A higher amount/proportion of residue N (pea residues) being available to the soil microbial biomass during early decomposition will result in a higher amount of residue N being stabilized per unit C metabolized. For barley relatively more non–labelled soil N was being used (immobilised) than in the pea residue treatments and microbial cell synthesis in the barley residue treatment was probably N-limited during early decomposition (Table 3). The C use efficiency may therefore have been low (Ladd and Foster, 1988). It could be speculated that during later stages of decomposition, where a major part of the barley C have been metabolized, the barley residue N was then mineralized and relatively less barley residue N per unit added C was humified. However, also the type and chemical nature of the decomposer microflora may have been influenced by the type of residue incorporated, causing differences in the C and N use efficiencies of the decomposer populations (Ladd and Foster, 1988). Broder and Wagner (1988) reported that bacterial populations associated with soybean residues (2.2% N) were higher than for wheat (0.9% N) and corn residue (1.0%, N), and that this difference was due to the relative levels of soluble components. Consequently, a relatively higher activity of bacteria than of fungi in the decomposition of pea residues, due to higher amounts of soluble matter compared to the barley residue, could also influence the ratio of remaining residue N per unit added C, since bacteria have a higher N requirement for cell synthesis than fungi. However, the stabilized residue N (residue N present in soil after 3 years) as a proportion of added N was higher (45%) for barley than for mature pea residues (average 34%) and lowest for green pea residues (28%).

The stabilization of residue-derived N was also evaluated using the ratio (% residue-derived N in the inorganic N-pool)/(% residue-derived N in the organic N-pool). This ratio is similar to the availability ratio (Broadbent and Nakashima, 1967) and indicates the lability of the residue-derived N relatively to the indigenous soil organic N. The closer the ratio is to

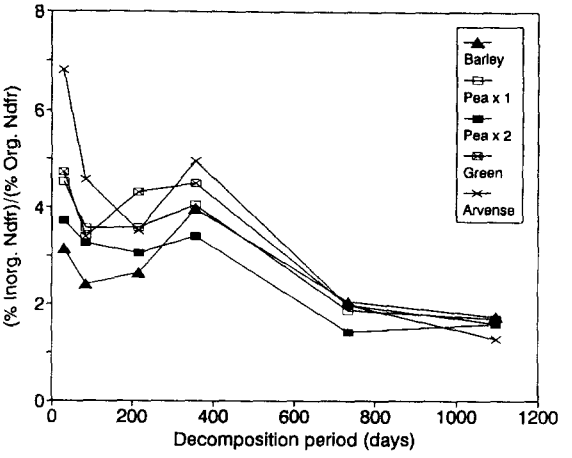

Figure 4. Rate of residue N stabilization in soil using the ratio of the percentage residue-derived N in the inorganic N pool (% Inorg. Ndfr) over the percentage residue-derived N in the organic N pool (% org. Ndfr) in the 0–10 cm soil layer in unplanted plots.

1 the more similar is the lability of residue-derived N to the lability of the indigenous soil N pool. The lability of residue derived N declined during the initial 3 months of decomposition, but increased during the subsequent spring and growing season (Fig. 4) After 2 and 3 years the average ratio were 1.9 and 1.6, respectively, which indicate that the major part of the residue N was stabilized after 2 years of decomposition.

Plant uptake of residue- and soil-derived N

The recoveries of barley and pea residue N in ryegrass shoots after one year were 5 and 7%, respectively. These recoveries are similar to those previously reported, e.g. by Bremer and van Kessel (1992) for wheat and lentil residues. Assuming that most roots in the top soil were formed during the first year, the total recovery of residue N in my experiment was 12% for barley and 14% for pea. These recoveries were similar to previous reports, e.g. Powlson et al. (1985) for wheat straw N in and Jensen (1994b) for pea residue N.

After 2 years the total uptake of N derived from indigenous N sources was not significantly different between residue treatments. However, at the first 2 cuts, the soil N uptake was higher after pea than after barley residue incorporation, although at later harvests more indigenous soil N was taken up after barley residue incorporation. This difference in pattern of indigenous soil N uptake could be due to the differential effects of crop residues on mineralization-immobilization processes during early decomposition.

Table 7. Balances of residue N (% of residue N input) as organic + inorganic N in the 0–10 cm soil depth or in plants after 216 days and 2 years of decomposition

Treatment	216 days		2 years		
	Soil	Plant	Soil	Plant	Unaccounted
Unplanted soil					
Barley residues	72	NA	49	NA	51
Pea residues	57	NA	47	NA	53
Planted soil					
Barley residues	ND	7	61	15	24
Pea residues	ND	9	51	14	35

NA: Not available; ND: Not determined.

The lower uptake after barley during the first part of growth and the higher uptake at later harvests, could be due to the immobilization of N during early decomposition. The immobilized N may then have been temporarily stored in the microbial biomass until the second year. This argument is in accord with the observation that the barley amended soil contained more inorganic N than the other treatments, when sampled 2 years after residue incorporation (Table 3).

Balances and losses of residue N

After 2 years, 49% of the barley and 47% of the pea residue N were recovered in the unplanted topsoil, whereas the corresponding figures for planted soils were 61% and 51% respectively (Table 7). Looking at the shapes of the curves in Fig 2B, the recovery of residue N in the pea x 1 treatment is anomalously high at the 2-year sampling, so the difference in the recovery of pea residue N between in the planted and unplanted soil may actually have been greater. Nevertheless, the higher recovery of residue N in the cropped soil is in agreement with the observations by Janzen and Radder (1989), that cropping reduce the net N-mineralization, perhaps due to immobilization of N in the rhizosphere or simpler due to dead roots not being recovered. However, competition for N by ryegrass could have reduced the amount of N available to the soil microbial biomass and the water uptake by ryegrass could have reduced soil moisture in the planted plots compared to unplanted plots, hereby causing the apparent lower net mineralization of residue N in the planted plots (Dormaar, 1990; Merckx et al., 1987; Sparling et al., 1982).

After 2 years of decomposition 35% of the pea and 24% of the barley residue N could not be accounted for in the 0–10 cm layer of the soil and in ryegrass plants (Table 7). However, since much more pea residue N was incorporated, the amount of residue N not accounted was about 3 times higher for pea than for barley residues. A part of the pea residue N was probably leached during the first autumn and winter. In an experiment, also initiated in September 1987 and using similar pea residues, Jensen (1994c) found that 11% of the residue N was leached as nitrate during the first autumn and winter period in soil planted with ryegrass. Jensen (1994c) also found that the newly sown ryegrass only recovered 0.7% of the residue N, and decreased the total leaching of residue and soil-derived N over this period by only 15% compared to unplanted soil.

Since the apparent losses of pea and barley residue N were comparable to almost twice the amounts of residue N taken up by the perennial ryegrass crop, there seems to be a potential for improved crop residue management in order to conserve residue nutrients in the soil-plant system.

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