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The effect of nitrogen catch crop species on the nitrogen nutrition of succeeding crops

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Abstract

Ten widely different plant species were compared for their ability to reduce soil mineral nitrogen levels in the autumn and their ability to improve the nitrogen nutrition of the succeeding crop. The species included monocots and dicots, crops that survived the winter (persistent) or were winter killed (non-persistent) as well as legumes and non legumes. Their ability to reduce soil mineral nitrogen content was dependent on both root depth and persistency of the crops in the autumn. For non-persistent catch crops most of the mineralization of plant nitrogen occurred during the winter, and for some of these so early as to allow leaching of some mineralized nitrogen. For persistent crops most of the mineralization occurred shortly after incorporation in the spring. The effect of the catch crops on nitrogen uptake by the succeeding barley crop varied from 13 to 66 kg N ha^{-1} and the differences between the crops could not be related to any single character, but to a combination of root depth, persistency, plant nitrate accumulation, and depletion of the soil mineral nitrogen pool in spring.

Introduction

In intensive cropping systems, as in vegetable production, large amounts of nitrogen may remain in soil at harvest. This situation may lead to considerable losses of nitrogen from the soil before the next crop is established. Under North European conditions winter rainfall will often induce leaching of considerable amounts of nitrogen to the environment.

One possible method for reducing this problem is to grow catch crops after the main crop. Catch crops then take up nitrogen from the soil and thereby reduce the nitrogen concentration in water percolation from the soil.

After being incorporated into the soil, decomposition of the catch crop plant material will lead to mineralization of its nitrogen. This mineralized nitrogen may be utilized by the succeeding crops, and thereby reduce the demand for fertilizer nitrogen input. The nitrogen mineralization can be expected to be high in the first year, but what is not mineralized this year will mineralize very slowly over the succeeding years (Jensen, 1991; 1992; Ladd *et al.*, 1983).

To reduce long term total nitrogen losses from the soil to the environment, catch crops have either to increase the amount of nitrogen stored in the soil, increase the amount harvested, or to reduce the fertilizer nitrogen inputs. Catch crops neither seem to add much to the organic nitrogen pool in the soil (Linden *et al.*, 1987; Paustian *et al.*, 1992), nor are they likely to increase crop yield very much. Most commercial crops are at present fertilized with close to optimal amounts of nitrogen fertilizer, and increased soil supply due to previous catch crops will allow reduced nitrogen fertilization rather than further improve yield. Such a reduction in nitrogen fertilization will be necessary if catch crops shall effectively reduce the total nitrogen losses from the soil. If catch crops reduce leaching in the season when they are grown, but do not improve the long term nitrogen balance of the system they will just have altered the time course (Jäggeli, 1978; Thorup-Kristensen, 1993b) or pathway of nitrogen losses.

To make it possible for farmers to reduce fertilization as a consequence of catch crops, the nitrogen effect of catch crops must be high and predictable (Bowden *et al.*, 1988).

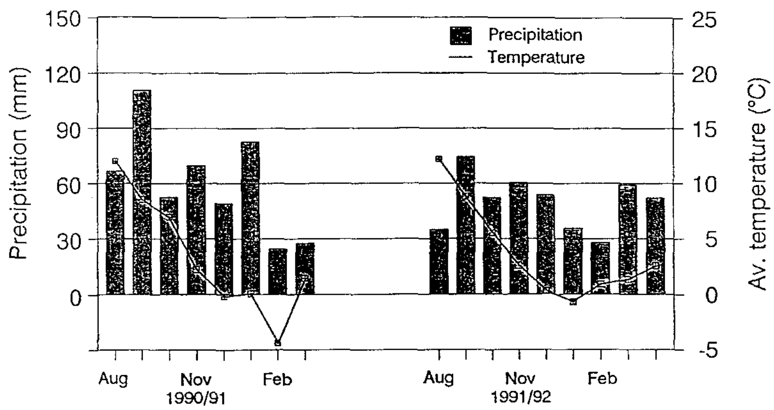

Fig. 1. Average monthly temperature and precipitation during the growth periods of the catch crops.

Previous results have indicated that species of catch crops may differ in their effects on soil mineral nitrogen even when they assimilate approximately the same amount of nitrogen into organic matter with approximately the same C/N ratio (Sørensen and Thorup-Kristensen, 1993). Characterizing the influence of catch crop species on the nitrogen dynamics of the soil should facilitate the choice of the most suitable catch crop for a specific situation. Such work is important because if the best species is not chosen it may increase the nitrogen fertilizer need of the succeeding crop (Martinez and Guiraud 1990; Jensen 1991; 1992), and reduce the environmental effect of the catch crop.

The objective of the present work was to clarify some main reasons for the large differences found in the effect of different catch crops on nitrogen supply for a succeeding crop. The present paper deals with field performance of catch crops on soil nitrogen content and nitrogen uptake by a succeeding crop. Additionally, the root growth of some of the species has been measured (Thorup-Kristensen, 1993a), and their chemical composition and nitrogen mineralization under controlled conditions have been measured and will be published later.

Methods

The experiment was located at the Horticultural Research Centre Aarslev, on a Typic Agrudalf soil. The upper 40 cm contains 2% organic matter, 11% clay, 14% silt, and 73% sand. The 40 to 100 cm layer contains 0.2% organic matter, 19% clay, 13% silt, and 67% sand. The experiment was performed twice, in 1990/91 and 1991/92. The climatic conditions during the experiment are shown in Figure 1.

The catch crop of species included in the experiment were winter rape (*Brassica napus*), Italian ryegrass (*Lolium multiflorum*), winter rye (*Secale cereale*, var 'Multicaule'), winter barley (*Hordeum vulgare*), oats (*Avena sativa*), phacelia (*Phacelia tenacetifolia*), white mustard (*Sinapis alba*), fodder radish (*Raphanus sativus*), hairy vetch (*Vicia villosa*), and narrow leafed lupin (*Lupinus angustifolia*).

To simulate the situation after harvest of a vegetable crop, a crop of Brussels sprouts (*Brassica oleracea* var *gemmifera*) was sown in the spring, and fertilized with a total of 200 kg N ha^{-1}. One to two weeks before sowing the catch crops, the Brussels sprouts were cut at a height of 25 cm, the tops removed and the residues were incorporated into the soil. On 1 August the catch crops were sown. Both catch crop and bare soil plots were fertilized with 50 kg N ha^{-1} each year, in the first year the fertilizer was applied one month after sowing, in the second it was applied shortly before sowing.

The plots were 2.5 × 10 m and there were two replicates each year. In the second year two extra replicates were included for measuring root growth of some of the catch crops (Thorup-Kristensen, 1993a). Where possible these plots were included in the measurements of the present experiment to give four replicates of these measurements.

Plant samples were taken on one m^2 in mid November and again just before 1 April in the following year. The November samples were analysed for dry matter, nitrogen, nitrate-nitrogen, carbon, and lignin content. Samples from the spring of 1991 were only analysed for dry matter and nitrogen content whereas samples from the spring of 1992 were further analysed for nitrate, carbon, and lignin content.

Soil samples were taken on the same dates as the plant samples. In November samples were taken of the soil layers 0–50 cm, 50–75 cm and 75 to 100 cm, and in the spring 0–25, 25–50 and 50–100 cm. The soil samples were analysed for content of nitrate and ammonium nitrogen.

Immediately after the spring sampling of soil and plant material the catch crops were incorporated, in 1991 by rotovation followed by ploughing, but in 1992 only by deep rotovation. On 1 April spring barley was sown, in 1992 the barley was undersown with Italian ryegrass. As the purpose was to measure the nitrogen supply as dependent on catch crops, the barley crop was not fertilized. Barley was sampled from one m^2 twice during its growth and analysed for dry matter production and nitrogen content. The first sampling was made at the beginning of heading (21 June 1991 and 9 June 1992) and the second when nitrogen assimilation was assumed to have ceased around two weeks before maturity (17 July 1991 and 16 July 1992). In 1992 the ryegrass growing after the barley had been harvested, was fertilized with 40 kg N ha^{-1} and was sampled from one m^2 on 15 September and analysed for dry matter production and nitrogen content.

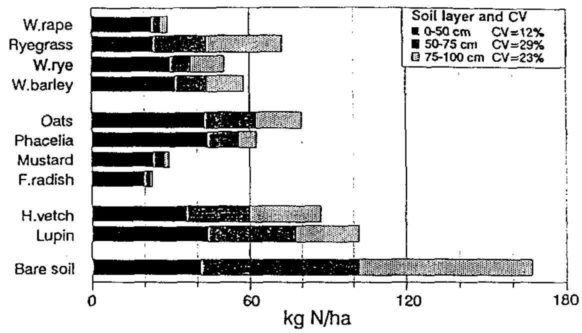

Fig. 2. Soil mineral nitrogen (N_{min}) in the autumn under catch crops. Coefficient of variance (CV) of N_{min} in individual soil layers are indicated with legends.

Results

The results from the two years of the experiment were in good agreement, and are therefore not presented separately. Figures given are averages for the two years unless stated otherwise.

The catch crops reduced soil mineral nitrogen content (N_{min}) in the autumn with quantities between 65 and 144 kg N ha^{-1} as compared to bare soil (Fig. 2); the cruciferous catch crops were the most efficient, and the legumes the least efficient.

The catch crops differed not only in their effect on the amount of soil mineral nitrogen in mid November, but also in their effect on its vertical distribution (Fig. 2). The subsoil (50–100 cm soil layer) had the lowest nitrogen content under non legume dicot crops, and in several situations contained virtually none. The legumes also reduced subsoil N_{min}, but not as effectively as the other catch crops. The topsoil N_{min} (0–50 cm soil layer) was higher below legumes, phacelia and oats than below the other crops. In the autumn of 1991 it was even higher under these crops than in the bare soil plots.

By mid November the catch had taken up between 75 and 167 kg N ha^{-1} in above-ground plant parts (Table 1). The highest uptake was measured in the dicotyledonous crops, with fodder radish showing the highest uptake both years. Not all plant nitrogen was reduced and incorporated into organic compounds; phacelia, mustard, and oats contained between 10% and 25% of their nitrogen as nitrate (Table 2).

The total amount of nitrogen found as N_{min} and within the plants was very different among the crops (Table 1). For several crops, this sum was approximately the same as N_{min} in the bare soil plots, but for winter cereals it was lower and for the legumes, fodder radish, and phacelia it was higher.

Dry matter production varied almost threefold among species, with fodder radish giving the highest yield of 5.7 t ha^{-1} whereas the winter cereals gave only about 2 t ha^{-1}. The nitrogen uptake of the winter cereals was not as low as could be expected from the dry matter yields, as they had rather low C/N ratios (Table 2). This compensation through nitrogen concentration did not occur in other species with low dry matter production.

During the winter most catch crops lost both nitrogen (Table 2) and dry matter. The non-persistent crops (narrow leafed lupin, fodder radish, white mustard, phacelia, and oats) lost between 50% and 80% of their nitrogen, persistent monocotyledonous crops showed almost no change in nitrogen content whereas winter rape increased its nitrogen content significantly. Vetch was special in that it was non-persistent in the first year, but persistent in the second.

Among the non-persistent crops, the chemical composition of the plant material still present in the spring had been changed dramatically during the win-

Table 1. Dry matter, nitrogen content, C/N ratio, nitrate and lignin contents in aboveground plant parts and total nitrogen by mid November. Total nitrogen is calculated as the sum of aboveground catch crop nitrogen and mineral nitrogen within the top meter of the soil. Average of two years

	Dry matter	Nitrogen uptake	Nitrate content	Soil+plant nitrogen	C/N ratio	Lignin %
	t/ha	kg N ha^{-1}				
Bare soil	-	-	-	167^{def}	-	-
Non-persistent catch crops						
F.radish	5.7^{a}	167^{a}	15^{bc}	190^{bcd}	13^{b}	3^{cd}
Mustard	5.5^{ab}	144^{ab}	23^{ab}	173^{cde}	14^{a}	8^{a}
Phacelia	4.7^{b}	147^{ab}	33^{a}	210^{ab}	9^{d}	8^{a}
Oats	3.2^{cd}	85^{cd}	10^{cd}	165^{ef}	15^{a}	3^{d}
Persistent catch crops						
W.barley	2.0^{f}	75^{d}	3^{f}	133^{gh}	10^{cd}	5^{bc}
W.rye	2.2^{ef}	80^{cd}	3^{f}	131^{h}	10^{c}	6^{b}
Ryegrass	2.8^{def}	85^{cd}	5^{f}	158^{f}	12^{b}	2^{e}
W.rape	3.8^{c}	127^{b}	7de	156^{fg}	10^{c}	4^{bcd}
Legume catch crops						
Lupin	2.9^{de}	97^{c}	1^{f}	199^{bc}	12^{b}	4^{bc}
Hairy vetch	2.9^{cde}	140^{ab}	3de	227^{a}	9^{d}	7^{a}

Values followed by the same letter are not significantly different by LSD test. The LSD tests were performed on log transformed data, except for the dry matter and plant+soil N values.

ter (Table 2), both C/N ratios and lignin content rose during winter.

N_{min} in the bare soil plots fell by more than 110 kg N ha^{-1} during the winter. Under catch crops the development in N_{min} varied strongly among species, and during winter fell by 45 kg N ha^{-1} under ryegrass and increased by 70 kg N ha^{-1} under fodder radish (Fig. 2 and 3). The total amount of nitrogen (N_{min} and plant N) in the spring was between 46 and 139 kg N ha^{-1} higher in the catch crop plots than in the bare soil plots. During winter the amount of total nitrogen fell in all plots except winter rape where it rose with 40 kg N ha^{-1} (Table 1).

The effect of different catch crops on N_{min} in spring varied greatly, below persistent crops N_{min} was lower, and below non-persistent crops N_{min} was higher than in the bare soil plots (Fig. 3). In 1992 spring N_{min} varied 4–5 fold, from 27 kg N ha^{-1} after Italian ryegrass to more than 120 kg N ha^{-1} after fodder radish and phacelia, but in 1991 the variation was less.

Barley grown after catch crops in all treatments contained more nitrogen than barley grown after bare soil (Table 3). Its nitrogen uptake was higher than N_{min}

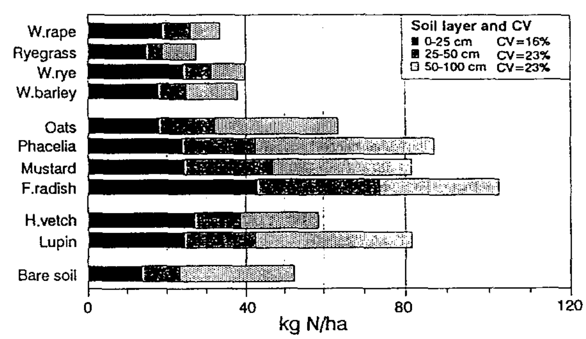

Fig. 3. Soil mineral nitrogen (N_{min}) in the spring under catch crops. Coefficient of variance (CV) of N_{min} in individual soil layers are indicated with legends.

found after the persistent catch crops even at the first harvest. By the second harvest the barley had taken up between 1.7 and 2.7 times the amount of nitrogen found as N_{min} before sowing of the crop. At the same time barley after bare soil took up 85% of N_{min} and barley after non-persistent catch crops took up between 91% and 108% of N_{min}.

Table 2. Dry matter, nitrogen content, C/N ratio, nitrate and lignin contents in aboveground plant parts and total nitrogen by late March. Total nitrogen is calculated as the sum of aboveground catch crop nitrogen and mineral nitrogen within the top meter of the soil. C/N ratios and lignin content from, spring of 1992 only. The other data are average of two years

	Dry matter	Nitrogen uptake	Soil+plant nitrogen	C/N ratio	Lignin %
	t/ha	kg N ha^{-1}			
Bare soil	-	-	53^{c}	-	-
Non-persistent catch crops					
F.radish	1.9^{b}	51^{c}	153^{b}	14^{c}	12^{c}
Mustard	2.5^{b}	40^{d}	121^{cd}	29^{a}	31^{a}
Phacelia	2.0^{b}	39^{d}	126^{bcd}	22^{b}	25^{ab}
Oats	2.0^{b}	40^{d}	104^{d}	20^{b}	8^{d}
Persistent catch crops					
W.barley	1.6^{b}	61^{b}	99^{d}	10^{ef}	4^{fg}
W.rye	2.0^{b}	82^{b}	122^{cd}	10^{de}	5^{ef}
Ryegrass	2.2^{b}	76^{b}	103^{d}	12^{cd}	3^{fg}
W.rape	3.6^{a}	159^{a}	192^{a}	9^{ef}	3^{g}
Legume catch crops					
Lupin	1.7^{b}	41^{d}	123^{cd}	18^{b}	18^{b}
Hairy vetch	1.9^{b}	86^{b}	144^{bc}	8^{f}	5^{de}

Values followed by the same letter are not significantly different by LSD test. The LSD tests were performed on log transformed data, except for the dry matter and plant+soil N values.

Correlating nitrogen uptake in barley to N_{min} showed that for the persistent crops the uptake before heading was not correlated to N_{min}, but for the non-persistent catch crops uptake before heading was strongly correlated to topsoil (0–50 cm) N_{min} (1991: r^2=0.77, slope 0.96, ***, 1992: r^2=0.90, slope 0.90***). Nitrogen uptake between first and second growth analysis (analysis made for all experimental treatments) showed no correlation to topsoil N_{min} but was correlated to subsoil N_{min} (50–100). In the first year where subsoil N_{min} was low, this correlation was weak, but in the second year with higher levels, the correlation was highly significant (1991: r^2=0.14, slope=0.26, P=0.9, 1992: r^2=0.53, slope=0.48***).

The nitrogen uptake by barley was not found to be correlated to the autumn nitrogen uptake of the catch crops. The nitrogen uptake of barley was increased with 15% of the autumn nitrogen uptake in the previous ryegrass catch crops, whereas residual effects of over 40% of catch crop nitrogen uptake in the autumn was found after lupin, fodder radish and winter rye.

An estimate of the nitrogen supplied by mineralization from the catch crop residues (minN) during the time between incorporation and the first growth analysis of barley was calculated as:

$$\mathrm{minN} = (N_b - N_{bo}) - (tsN - tsN_o) \qquad (1)$$

where N_b is nitrogen uptake in barley, tsN is topsoil N_{min} and N_{bo} and tsN_o are the barley nitrogen uptake and topsoil N_{min} in the bare soil plots.

This estimate was close to 30% of nitrogen in the incorporated plant material of winter barley, winter rye, winter rape, and ryegrass (Table 3). The slightly lower value for vetch is due to a low value in the first year when it was non-persistent and a high value in the second when it was persistent (39% for vetch against approximately 25% for the other persistent crops this year).

Catch crops also increased the nitrogen uptake at the final harvest of the subsequent crop of ryegrass

Table 3. Dry matter production and nitrogen uptake by barley and ryegrass following catch crops. Results of barley average of two years, results of ryegrass are from 1992 only

Catch crop	Until heading	Total	Uptake until heading	Uptake after heading	Total Uptake	Uptake in ryegrass	Early mineralization %*
	Barley dry matter prod., t ha^{-1}		kg N ha^{-1}				
Bare soil	1.1^{e}	4.0^{e}	20^{f}	25^{de}	45^{h}	40^{c}	-
Non-persistent catch crops							
F.radish	2.8^{ab}	8.3^{ab}	73^{a}	39^{ab}	112^{a}	47abc	4^{bc}
Mustard	1.9^{cd}	6.1^{cd}	41^{d}	34^{bc}	75^{def}	43^{abc}	-7^{c}
Phacelia	1.8^{cde}	6.4^{cd}	39^{d}	43^{a}	81^{cde}	46^{abc}	-1^{c}
Oats	1.7^{de}	6.7^{bcd}	33^{e}	39^{ab}	72^{e}	47^{ab}	12^{abc}
Persistent catch crops							
W.barley	2.1^{bcd}	5.8^{d}	41^{cd}	23^{de}	65^{fg}	42^{bc}	33^{a}
W.rye	2.2^{abcd}	6.6^{bcd}	50^{bc}	30^{cd}	80^{cde}	46^{abc}	27^{a}
Ryegrass	1.9^{cd}	5.1^{de}	39^{de}	19^{e}	58^{g}	46^{abc}	31^{a}
W.rape	2.9^{a}	8.2^{ab}	68^{a}	22^{de}	90^{bc}	50^{a}	29^{a}
Legume catch crops							
Lupin	2.3^{abcd}	7.5^{abc}	41^{cd}	45^{a}	86^{bcd}	45^{abc}	5^{bc}
Hairy vetch	2.5^{abc}	8.6^{a}	56^{b}	42^{ab}	98^{b}	42^{bc}	25^{ab}

Values followed by the same letter are not significantly different by LSD test. The LSD tests on data for nitrogen uptake until heading were performed on log transformed data, other tests on non-transformed data;
* Increased uptake until heading as % of incorporated plant nitrogen, assuming that topsoil N_{min} was utilized with 100% efficiency.

with which the barley was undersown in the second year (Table 3), but the effect was not high.

Discussion

The effects of the catch crops on N_{min} in the late autumn, i.e. in the early part of the leaching period, suggest that all catch crops reduced the leaching risk substantially. Still, there were large differences between the crops both in amount and distribution of N_{min} in the soil.

Under some crops the N_{min} was mainly found in the topsoil, but under others it was mainly found in the subsoil (Fig. 2). The finding that subsoil N_{min} was higher under monocots than under (non-legume) dicots is consistent with the finding that subsoil root density was significantly higher under three catch crops of dicot plant species than under three catch crops of monocot species (Thorup-Kristensen, 1993a). The very efficient depletion of the 75–100 cm soil layer by some catch crops indicates that they must also have had a significant effect on soil layers below 100 cm. The legumes reduced N_{min} considerably, but not as efficiently as the other crops. The results support those of Jäggeli (1978) who found that a legume catch crop reduced leaching by 70% but a cruciferous catch crop by almost 100%.

The variations in topsoil N_{min} under catch crops in the autumn were not well explained by any of the measured parameters. The highest values were found under legumes and under phacelia and oats. Phacelia and oats contained considerable amounts of unreduced nitrate, and in the field the decay of the plant material of these crops had started by mid November when the soil sampling was made. High autumn topsoil N_{min} under catch crops of phacelia was also found by Sørensen (1992) and Thorup-Kristensen (1993b).

The observed difference in vertical distribution of N_{min} at the start of the leaching period may be important, as autumn subsoil N_{min} during the winter is almost certainly leached to below the rooting zone of the succeeding crop. Topsoil N_{min}, on the other hand, may still be present within the rooting zone in the spring if leaching is not too intense.

The differences among species in total nitrogen in the autumn (N_{min} and plant N) may be due to several factors. In the winter cereals, the low amount is likely to be due to a significant fraction of their nitrogen content being present in roots and stubble, and thus present but not measured. The higher levels of total nitrogen in some of the none legume dicot crops shows that soil samples should have been extended to more than one meter to represent the affected soil volume.

The reductions of total nitrogen during winter can have occured by two processes, either leaching of mineral nitrogen to below one meter or transfer of nitrogen from the plant nitrogen pool to the soil organic nitrogen pool by leaf drop and crop decay. Increased storage in roots and stubble can also have contributed for the persistent crops. Denitrification is not likely to have played a significant role under the prevailing temperatures.

The rise in the total amount of nitrogen in winter rape plots during the winter is in accordance with the fact that is was the only crop that had the possibility of absorbing nitrogen from below 100 cm during the winter. None of the other persistent crops had any significant root growth at such depths (Thorup-Kristensen, 1993a).

When incorporating catch crops in the spring just before establishment of the succeeding crop, the N_{min} after persistent catch crops was very low whereas it was high after non-persistent crops. In spite of this, the persistent catch crops were found to lead to a high uptake of nitrogen in the barley crop until heading, but a low uptake after heading, and almost no effect on nitrogen uptake by ryegrass growing after the second harvest of barley. This suggest that initial mineralization is very fast, but that mineralization soon drops to a low level. Others have found mineralization (at 25°C) from low C/N ratio plant material to be high only within the first 25 days after incorporation (Marstorp and Kirchmann, 1991; Oglesby *et al.*, 1992). Results of incubation of the present plant materials showed high mineralization for about 60 days at 15°C (results to be published later).

Late in the growing season of barley, the mineralization thus supplied only low levels of nitrogen, and the supply of barley after all treatments was then mainly dependent on the subsoil supply, as suggested by the regressions, and by the low effect on nitrogen uptake in the ryegrass succeeding the barley crop in 1992.

The regressions of nitrogen uptake of barley to spring N_{min}, where non-persistent catch crops were incorporated, was close to one, which indicates that almost all the nitrogen available to the barley had been mineralized during the winter before incorporation. N_{min} under fodder radish rose by 80 kg N ha^{-1} during the winter, this rise was equivalent to almost 50% of its total autumn nitrogen content. As the total loss of nitrogen from the plant material during the same period was about 120 kg N ha^{-1} this indicates a surprisingly high mineralization from unincorporated plant material during the winter.

The mineralization of about 30% of added nitrogen from the incorporated catch crop material (persistent crops) is in accordance with other results on low C/N ratio plant material (Marstorp and Kirchmann, 1991). The estimated relative mineralization was quite uniform among the crops, and this means that the amount of nitrogen they have assimilated becomes an important determinant of their effect on early uptake of nitrogen. The uniformity of the estimated mineralization rates is in accordance with the low and quite similar C/N ratios of these crops.

Though the mineralization was found similar among the persistent crops, their effect on the nitrogen supply for the barley crop was quite different due to differences in the N_{min} below these crops before their incorporation. As an example, ryegrass had depleted the soil more efficiently than winter rye, and showed a similar mineralization from the crop residues. Still the nitrogen supply for the barley crops was significantly higher after winter rye than after ryegrass. Spring nitrogen uptake by catch crops will occur in a pre emptive competition with the succeeding crop (Thorup-Kristensen, 1993b). It will lead to a "loss" of available soil mineral nitrogen into unavailable organic form, only some of which will become mineralized again in time to be used by the succeeding crop.

The difference between the effects of the non-persistent crops seems to have other causes. Especially phacelia and mustard, but also oats and lupin, were fast to enter the reproductive phase, and were all flowering by the beginning of October. Fodder radish only set few flowers, and only very late in the autumn. Flowering is normally accompanied by reduced root activity, and a beginning of senescence of non reproductive plant parts. Delaying the onset of flowering (as with fodder radish relative to the other non-persistent crops) can therefore be expected to improve the catch crop by extending the duration of its nitrogen uptake and delaying the onset of mineralization.

The lack of correlation between the autumn nitrogen uptake by catch crops and the nitrogen uptake by the succeeding barley crop shows that though catch crop nitrogen uptake may give a rough estimate of their effect on leaching risk, it is not useful as an estimate of their residual effect.

The results show that high nitrogen recycling can be achieved by growing catch crops. By growing fodder radish the nitrogen balance of the system could on average have been improved by at least 67 kg N ha^{-1} per year, even assuming a 100% utilization of added fertilizer nitrogen, as the real value of fertilizer nitrogen is below 100% the real effect could have been even higher.

The finding that catch crops not only alter the total nitrogen supply but also the time course of its availability means, that apart from reducing nitrogen fertilization, timing of the fertilizer application should be adjusted.

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