Are differences in root growth of nitrogen catch crops important for their ability to reduce soil nitrate-N content, and how can this be measured?

Thorup-Kristensen, Kristian

Published in:
Plant and Soil

DOI:
10.1023/A:1010306425468

Publication date:
2001

Document version
Early version, also known as pre-print

Plant and Soil **230:** 185–195, 2001.

Are differences in root growth of nitrogen catch crops important for their ability to reduce soil nitrate-N content, and how can this be measured?

Kristian Thorup-Kristensen
*Danish Institute of Agricultural Science, Department of Fruit, Vegetable and Food Science, Kirstinebjergvej 10, DK-5792 Aarslev, Denmark**

Received: 11 January 2000; accepted in revised form: 10 November 2000

Key words: cover crop, nitrate leaching, root growth rates, rooting depth, soil nitrate depletion

Abstract

An experiment was made to measure root growth of nitrogen catch crops, to investigate whether differences in root growth among plant species are related to their ability to deplete the soil nitrate-N pool. Large differences were observed in root growth parameters. Monocot species had rooting depth penetration rates in the range of 1.0 to 1.2 mm d^{-1} $°C^{-1}$, whereas the non-legume dicot species had rates between 1.5 and 2.3 mm d^{-1} $°C^{-1}$. Substantial differences were also found in the lag time from sowing until significant root growth was observed. The estimated temperature sum needed for the crops to reach a rooting depth of 1.0 m varied from 750 d °C for fodder radish to 1375 d °C for Italian ryegrass. The depth distribution of the root system varied strongly, and at a depth of 1.0 m the non-legume dicot species generally had root intensities (number of root intersections m^{-1} line on the minirhizotrons) 12 times as high as the monocot species.

The amount of nitrate left in the topsoil (0–0.5 m) was only weakly correlated to a few of the measured plant and root parameters, whereas nitrate left in the subsoil (0.5–1.0 m) was clearly correlated to several root parameters. Subsoil nitrate residues were well correlated to root intensity, but showed even stronger correlations to more simple estimates of rooting depth. In the deepest soil layer measured (1.0–1.5 m), the soil water nitrate concentration was reduced from 119 μg L^{-1} without a catch crop to 61 μg L^{-1} under Italian ryegrass and to only 1.5 μg L^{-1} under fodder radish.

The results show that to identify the important differences in root growth among catch crops, root growth must be measured in deep soil layers. In this study, none of the measurements made aboveground or in the upper soil layers were well related to subsoil nitrate depletion.

Introduction

When catch crops are grown to prevent nitrogen (N) leaching losses, it is important that they are able to deplete the soil nitrate-N pool to very low levels. Therefore, catch crops must grow enough biomass to be an efficient N sink, and they must develop a root system, which can exploit the soil. Thus, to identify the optimal plant species to be grown as catch crops it is necessary to study differences in root growth and root efficiency among relevant species (Lainé, et al., 1993; Thorup-Kristensen, 1993).

Though catch crops have been studied intensively during the last decades, only a few studies have dealt with roots (Grindlay, 1995; Lainé et al., 1993; Thorup-Kristensen, 1993; Vos et al., 1998). Apart from the fact that root studies tend to be very laborious, the lack of root studies could also be due to uncertainties about which root parameters to measure. Which traits of the root system determine its ability to deplete the soil nitrate-N pool?

It is normally found that well growing crops (Macdonald et al., 1989) or catch crops (Thorup-Kristensen, 1994) can deplete the soil inorganic N pool within

* FAX No: 4563904394.
E-mail: Kristian.thorupkristensen@agrsci.dk

their root zone even at a rather high N supply. Therefore, studies of root length density (Burns, 1980; Vos et al., 1998) or N uptake per mm root length (Lainé et al., 1993; Rao et al., 1993) are unlikely to lead to identification of better catch crop species. Even if all relevant species can normally deplete their root zone efficiently, differences may still exist due to differences in rooting depth. Deep-rooted catch crops will have access to a larger soil volume, and can thus deplete parts of the soil volume not available for more shallow-rooted crops.

In accordance with this, the few studies which have shown significant differences in root growth among catch crops (Grindlay, 1995; Thorup-Kristensen, 1993) have focused on differences in rooting depth. In both studies, cruciferous catch crops were found to have deeper rooting than winter rye, and accordingly depleted the soil more effectively.

Vos et al. (1998) found that the rooting depth of catch crops was closely related to aboveground growth, as found by Greenwood et al. (1982) for a number of main crops. Thus, Vos et al. (1998) conclude that differences in rooting depth among catch crops can be studied by measurements of biomass production and root length density in upper soil layers only. However, contrary to Thorup-Kristensen (1993) and Grindlay (1995), no difference in rooting depth was found by Vos et al. (1998) when comparing rye and white mustard using this method.

Differences in N depletion due to differences in rooting depth are of special interest for environmental protection. N in deep soil layers is more prone to leaching loss than N in upper soil layers (Thorup-Kristensen and Nielsen, 1998). Therefore, N taken up from deep soil layers by a deep-rooted catch crop will reduce N leaching losses more than the uptake of a similar amount from the upper soil layers.

The objectives of the present work is to test the hypothesis that (1) highly significant differences in rooting depth exist among catch crops, and (2) that these differences are important for soil nitrate depletion by catch crops. Furthermore, it is attempted to establish which root traits are the most relevant to measure when trying to identify the best catch crops.

Materials and methods

Effects of catch crops on depletion of soil nitrate-N in the autumn were studied during 2 years. The experiment was located at the Research Centre Aarslev (10° 27′ E, 55° 18′ N), on a Typic Agrudalf soil (Table 1).

Weather data were obtained from a weather station situated less than 500 m from the experimental site (Figure 1). Temperature sums (day °C) were calculated as the sum of daily average temperatures.

The experimental design was a randomised complete block, with three replicates. The catch crop plots were 5 by 10 m. The seven catch crop species were winter rye (*Secale cereale*), Italian ryegrass (*Lolium multiflorum*), oats (*Avena sativa*), phacelia (*Phacelia tenacetifolia*), winter rape (*Brassica napus*), fodder radish (*Raphanus sativus*) and hairy vetch (*Vicia villosa*). The seeding rates were 180, 20, 180, 15, 15, 20 and 100 kg seed ha^{-1}, respectively. Apart from these seven catch crop species, a catch crop consisting of a mixture of winter rye and hairy vetch, the seeding rate of each halved compared to pure stand, and a control treatment were included. In the second year, two further species, *Malva sylvestris* and *Agrostemma githago*, were included with seeding rates of 30 kg seed ha^{-1} each.

The experiment was established by sowing catch crops within an organic crop rotation on 31 July 1996 and again 5 August 1997. The catch crops were grown after the harvest of a green pea crop. The pea residues were rotovated into the soil and the soil was ploughed before the sowing of the catch crops.

Plant and soil samples were taken in mid November. Plant material was sampled from one m^2 by cutting the catch crops just below ground level. The plant material was washed to remove soil. Root material was sampled by washing roots from two soil blocks of 0.12 by 0.30 m, and 0.2 m deep excavated from each plot. The root and aboveground plant materials were dried at 80 °C for 20 h and weighed. The plant and root material was then analysed for N content by a dry combustion method (Hansen, 1989), and the sand content was determined as the content of acid insoluble solids.

Soil was sampled as nine samples combined into one bulk sample for each soil layer in each plot. The soil samples were split into sub-samples representing 0.25 m layers, in most cases down to 1.0 m, but in some treatments down to 1.5 m. The soil was analysed for its content of ammonium-N and nitrate-N after extraction for 1 h in a 1 m KCl solution. In the results, only the nitrate-N fraction is shown, as nitrate is the leachable form of nitrogen.

Table 1. Main characteristics of the soil used for the experiment

	% C	% N	% Clay	% Silt	% Sand	pH
0–25 cm	1.8	0.16	14.7	27.1	55.0	7.0
25–50 cm	0.8	0.07	18.2	28.6	51.9	6.4
50–75 cm	0.3	0.04	21.2	28.3	50.0	5.1
75–100 cm	0.2	0.03	20.5	26.5	52.7	5.7

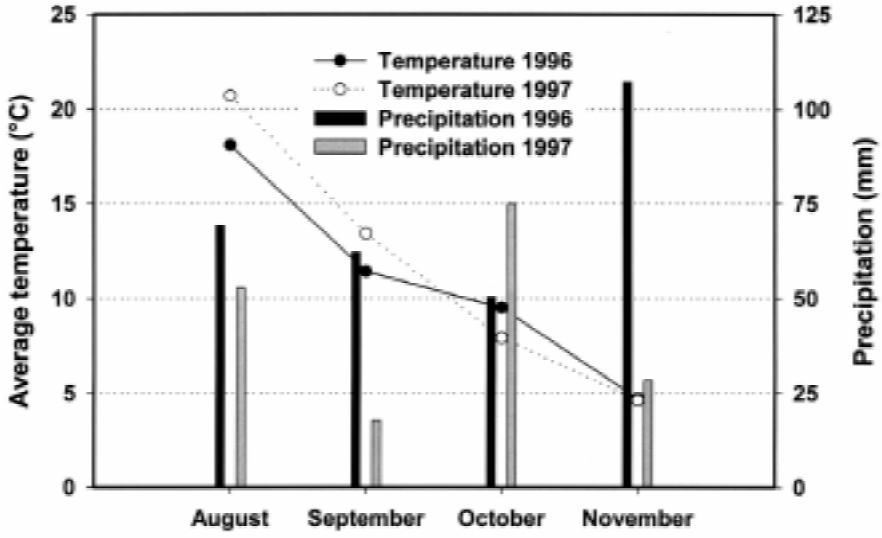

Figure 1. Monthly precipitation (mm) and monthly average temperature (°C) during the experiments.

Root measurements

Directly after the catch crops were sown, two minirhizotron glass tubes (70 mm in outer diameter and 1.5 m long) were inserted into the soil in each plot.

The minirhizotrons were installed at an angle of 30° from vertical, reaching a total depth of approximately 1.0 m in the soil in the first year. After a modification of the drilling equipment, they were installed to reach a total depth of 1.2 m in the second year. The holes for the minirhizotrons were made by drilling twice, first with a spiral auger with a diameter of 60 mm to remove most of the soil, and subsequently with a piston auger with a diameter of 74 mm. The slightly higher diameter of the drilling equipment was necessary due to the plasticity of the moist soil, which also prevented problems with gaps between the glass surface and the soil.

Root intensity was measured on four dates during the autumn each year, with a final measurement at about the time of soil sampling in mid November. Root intensity was measured by counting the number of roots crossing lines painted on the minirhizotron surface. For every 40 mm along each of two 40 mm wide counting areas on the 'upper' surface of each minirhizotron, the number of roots crossing 40 mm of vertical line and the number of roots crossing 40 mm of horizontal line were counted. Due to the angle of 30° from vertical, 40 mm along the minirhizotron surface represent a soil layer of 34.6 mm. Root intensity was calculated as the number of root intersections m^{-1} line in each soil layer. On the same four dates, root frequency was recorded as the fraction of the 40 mm sections along each counting area on the minirhizotrons where roots were observed.

Rooting depth was observed more frequently, and during the early growth phase rooting depth was recorded twice a week. For each of these observation dates, one value for rooting depth was estimated for each plot as the average of four single observations, i.e. the deepest root in each of the two counting areas on each of the two minirhizotrons in the plot. Rates of rooting depth penetration were estimated using data from the period when each crop had reached a rooting

depth of at least 0.15 m until it reached 0.9 m in 1996 or 1.1 m in 1997.

Statistical analyses of the data were performed using the GLM procedure of the SAS statistical package (SAS, 1990). In tables where the data are averaged across 2 years, the data were averaged within each year before calculating SE.

Results

The growth and biomass production of the catch crops varied from 2.5 to more than 5 Mg ha^{-1}, with rye showing the lowest biomass production and fodder radish showing the highest (Table 2). The N content in catch crop biomass varied less, from app. 100 kg N ha^{-1} for rye to more than 160 kg N ha^{-1} for fodder radish.

Root growth

Significant differences among the catch crops were found in most of the root parameters measured, but the ranking of the crops was very different among the root parameters studied. As an example, Italian ryegrass showed the highest root biomass (Table 2), but the lowest root intensity in the subsoil (Figure 2b).

The ranking of the crops also varied during their growing period. At the first date of root observation, the cereal crops and fodder radish had the highest total root intensity (Table 3) and the deepest rooting (Figure 3, Table 4), the rest of the crops showing low values. At the later measurements, fodder radish still showed high root intensity and deep rooting compared to other crops, whereas the root systems of rye and oats developed much more slowly. Winter rape and phacelia showed fast root growth similar to fodder radish, and from six weeks and onwards, their root systems were deeper and they had much higher root intensity than rye and oats (Figure 2).

The rates of rooting depth penetration were found to be very different among the crops. The two cruciferous crops increased their rooting depth with 2 mm d^{-1} °C^{-1} or more (Table 4, Figure 3), followed by phacelia, *M. sylvestris*, and *A. githago* with 1.5–1.7 mm d^{-1} °C^{-1}. The rest of the crops had rooting depth penetration rates within a rather narrow range of 0.9–1.2 mm day^{-1} °C^{-1}. These differences, together with the differences in lag time to initiate root growth, meant that fodder radish used 750 d °C and Italian ryegrass more than 1350 d °C from sowing to reach a rooting depth of 1.0 m (Table 4). Final rooting depths could not be measured, as many of the crops reached the bottom of the minirhizotrons (1.0 m in 1996 and 1.2 m in 1997) well before the end of the measurement period.

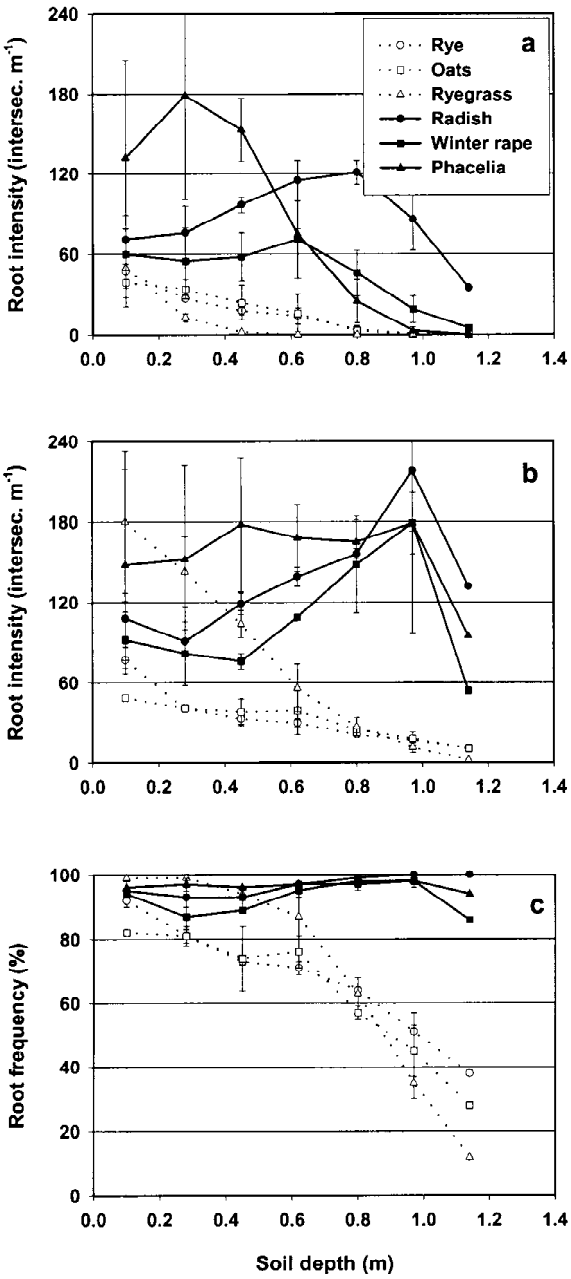

Figure 2. Depth distribution of root intensity (a) 6 weeks after sowing, (b) in November, and (c) root frequency in November.

At the end of the growing season, not only the total root intensity (Table 3), but also the depth distribu-

Table 2. Dry matter production (total and root), total N content in the catch crops and soil nitrate-N residues in the top 1.0 m of the soil in November, average 2 years (figures in brackets are SE, *n*=2)

	Total DM	Root DM	N content	Soil nitrate-N
	Mg ha^{-1}		kg N ha^{-1}	
F. radish	5.6$^{(0.4)}$	0.9$^{(0.4)}$	160$^{(6)}$	15$^{(5)}$
Winter rape	5.4$^{(0.7)}$	1.4$^{(0.0)}$	148$^{(2)}$	9$^{(2)}$
Phacelia	4.7$^{(0.8)}$	0.5$^{(0.2)}$	102$^{(4)}$	26$^{(7)}$
Rye	3.1$^{(0.4)}$	1.0$^{(0.0)}$	91$^{(4)}$	24$^{(12)}$
Oats	3.8$^{(0.6)}$	0.7$^{(0.1)}$	88$^{(19)}$	31$^{(5)}$
Italian ryegrass	5.4$^{(0.1)}$	1.9$^{(0.3)}$	123$^{(13)}$	24$^{(6)}$
Rye/vetch mix.	4.7$^{(1.2)}$	1.4$^{(0.4)}$	143$^{(27)}$	29$^{(9)}$
Hairy vetch	4.3$^{(1.7)}$	0.6$^{(0.1)}$	153$^{(33)}$	51$^{(18)}$
– no catch crop –	–	–	–	129$^{(31)}$
Malva sylvestris[a]	5.6	2.0	105	11
Agrostemma githago[a]	6.3	1.0	132	18

[a] Only included in 1 year.

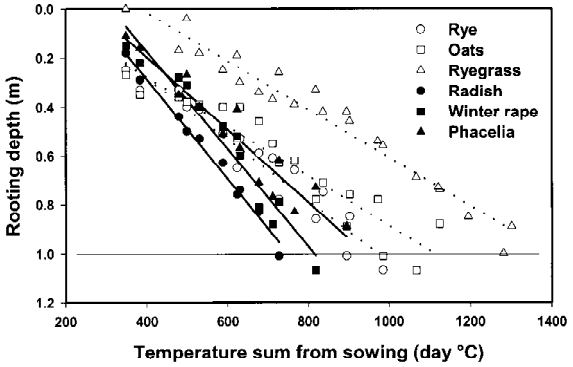

Figure 3. Depth penetration by catch crop roots during the autumn, data from each of the 2 years are shown. The statistics of the regressions are shown in Table 4.

tion of the root systems (Figure 2) were very different among the catch crops. The rye, ryegrass and oats showed clearly declining root intensity with depth, and low root intensities in the deepest soil layers (Figure 2b). With the cruciferous crops and phacelia, the root intensity varied less with soil depth, and the highest root intensity was observed at a depth of 50 cm or more (Figure 2b). Thus, in November the root intensity of fodder radish, winter rape and phacelia were on average 12 times as high as that of rye, oats and ryegrass in the deepest soil layers, though there were little differences between the two groups of crops in the upper soil layers.

Data for root frequency in the deepest soil layers show that fodder radish had roots in every single root observation section (40 mm vertical and 40 mm horizontal line on the minirhizotrons). Phacelia and winter rape also had very high root frequencies in this soil layer (Figure 2c), whereas rye, oats and ryegrass all showed much lower root frequencies than the crucifers and phacelia in the subsoil.

Nitrogen uptake and soil depletion

All catch crops strongly reduced the amount of nitrate-N in the soil in November. In the plot without a catch crop, 129 kg N ha^{-1} was found in the upper 1.0 m of the soil, the non-legume catch crops reduced this to between 8 and 31 kg N ha^{-1}, and hairy vetch left 51 kg N ha^{-1}. Where no catch crop had been grown, much of the nitrate was found in deeper soil layers, but under the catch crops most of the nitrate was generally found in the upper soil layers (Table 5).

The amount of nitrate-N left in the top 1.0 m of the soil was significantly correlated to several factors including N content in the biomass, total root frequency and root intensity (Table 6, Figure 4).

Only few and weak correlations between plant or root parameters and nitrate-N left in the top 0.5 m of the soil were found, and the root measurements made in this soil layer showed no correlation to any of the soil nitrate-N measurements. Much stronger correlations were found when plant and root parameters were

Table 3. Root intensity calculated for the whole depth of the minirhizotrons at four dates shown as number of weeks after sowing and approximate number of day °C after sowing, average 2 years (figures in brackets are SE, *n*=2)

	Root intensity (intersec. m^{-1} line on the minirhizotrons)			
	3 weeks 360 d °C	4 weeks 520 d °C	6 weeks 760 d °C	12 weeks 1320 d °C
F. radish	2.8(1.1)	11.5(0.8)	90(10)	138(4)
Rape	1.3(0.7)	4.8(0.3)	48(14)	108(13)
Phacelia	1.3(0.1)	8.2(1.4)	87(17)	160(29)
Rye	4.1(1.7)	6.9(2.1)	17(3)	35(2)
Oats	2.7(0.6)	5.1(0.1)	18(6)	34(3)
Ryegrass	1.3(1.1)	2.1(1.7)	10(4)	82(3)
Rye/vetch mixt.	2.7(0.1)	5.5(1.2)	16(7)	42(5)
Vetch	1.3(1.0)	2.3(1.2)	6(1)	18(2)
Malva[a]	0.4	2.1	19	58
Agrostemma[a]	0.3	0.6	13	65

[a] Only included in 1 year.

compared only to the amount of nitrate-N left in the subsoil (0.5–1.0 m).

The measurements made in the 1.0–1.5 m soil layer showed the most distinct differences among the crops in their ability to reduce the soil nitrate-N content (Table 5). The nitrate concentration in the soil water in the 1.0–1.5 m layer, (calculated from Table 5) varied from 119 μg nitrate L^{-1} without a catch crop, to 61 μg nitrate L^{-1} under Italian ryegrass, 23 μg nitrate L^{-1} under rye and only 1.5 μg nitrate L^{-1} under fodder radish.

Both years the N uptake by fodder radish and winter rape was higher than the uptake by the three monocot crops (Table 2), in accordance with the observed differences in root growth. The N uptake by rye, ryegrass and oats were not very different from their reduction of nitrate-N in the top 1.0 m of the soil. Contrary to this, winter rape and fodder radish took up 30–40 kg N ha^{-1} more than the observed reduction in nitrate-N content in the top 1.0 m of the soil, and also the nitrogen fixing crops contained more N than what would be expected from their depletion of the soil.

Discussion

Rooting depth

The results confirmed that large differences in rooting depth exist among the catch crops. As previously found (Grindlay, 1995; Thorup-Kristensen, 1993), the crucifer catch crops were faster in developing deep rooting, and obtained a much higher root intensity in the subsoil than rye and other monocot crops. Very fast and deep rooting of crucifer crops has previously been found by Böhm (1974) and Barraclough (1989). They both found a much faster root development for the crucifer crops than they found for winter wheat in other studies (Böhm, 1978; Barraclough and Leigh, 1984).

Other studies have only found small differences in root growth between crucifer and cereal catch crops (Vos et al., 1998; Van Dam and Leffelaar, 1999). However, Vos et al. (1998) made their measurements only in the upper 0.6 m of the soil and Van Dam and Leffelaar (1998) measured rooting depth development only during 40 days from sowing. Within such limited depth or time, also the present results show little difference between cereal crops and crucifer crops; the differences were found later and at larger depth.

The observed differences in rooting depth were the result of differences both in the length of the initial lag-phase until significant root growth started and the subsequent rate of rooting depth penetration. The results indicate that early root growth is related to seed size, as the ranking of species by lag-time and by seed size is similar. Also Zagal (1994) and Whiteley and Dexter (1982) found higher root growth

Table 4. Regression parameters of rooting depth against temperature sum. The lag time is the estimated temperature sum until a rooting depth of 0.1 m is reached. Estimated temperature sum until a rooting depth of 1.0 m is obtained is shown for each crop.

	Lag time d °C	Depth penetration rate mm d^{-1} $°C^{-1}$	R^2	Depth after 1000 d °C M	Time to 1.0 m d °C
F. radish	301	2.0	0.99	1.5	751
Winter rape	397	2.3	0.94	1.5	789
Phacelia	377	1.7	0.99	1.2	908
Rye	222	1.2	0.97	1.0	1001
Oats	200	1.0	0.95	0.9	1134
Ryegrass	532	1.1	0.95	0.6	1375
Rye/vetch mixt.	250	1.1	0.99	0.9	1086
Vetch	342	0.9	0.96	0.7	1356
Malva[a]	431	1.7	0.95	1.1	960
Agrostemma[a]	572	1.5	0.98	0.7	1172

[a] Only included in 1 year.

of large-seeded species than of small-seeded species when measured approx. 2 weeks after sowing.

The rates of rooting depth penetration which were observed for rye, oats and ryegrass were lower than previously observed for wheat by Barraclough and Leigh (1984), who estimated a rate of 1.8 mm d^{-1} $°C^{-1}$. However, Barraclough and Leigh (1984) also estimated a longer lag-phase of 680 d°C to initiate root growth. Thus, calculating the predicted rooting depth using their equation yields similar estimates of rooting depth as the present equations for winter rye and oats for the period between 600 d°C and 1200 d°C, covering most of the measurements in both experiments.

The measured rates of rooting depth penetration were remarkably constant within botanical groups. As an example, the three monocot crops, rye, oats and ryegrass showed rates of 1.0–1.2 mm d^{-1} $°C^{-1}$, and the two crucifer species had rates of 2.0–2.3 mm d^{-1} $°C^{-1}$. The roots of hairy vetch grew at a rate of 0.9 mm d^{-1} $°C^{-1}$, the same rate as previously determined for a number of pea genotypes grown as a main crop (Thorup-Kristensen, 1998).

The depth distribution pattern of the root system was very different among the crops, and this characteristic also seems to be related to botanical groups (Figures 2a and 1b). Materechera et al. (1993) found similar differences in depth distribution between four monocot species (barley, oats, wheat and ryegrass) and the dicot crop safflower. The studies of root systems of many plant species made by Kutschera and Lichtenegger (1982a,b) also show that the monocot species have high root densities in the upper soil layers but clearly declining densities with depth, whereas, among dicot species many examples exist where the highest root density is found in deeper soil layers.

N uptake and soil depletion

It would be obvious to assume a strong negative correlation between N content in the catch crops, and N residues left in the soil, but this relationship was not found to be straightforward. The reason may be that the sum of catch crop N and nitrate-N in the top 1.0 m of the soil does not include all the variables relevant for the N budget. Some N was assimilated from below 1.0 m as demonstrated for ryegrass, rye and fodder radish, and roots from below 0.2 m were not included in the estimate of crop N content. Furthermore, some of the crops had lost significant amounts of leaves before the November sampling, which was especially true for oats and phacelia, as well as for rye due to severe leaf diseases.

The amount of nitrogen left in the upper 0.5 m of the soil did not vary as much among the crops as the amount left in deeper soil layers and it did not correlate to any of the root measurements. This indicates that the amount of nitrate-N left in the upper 0.5 m must be the result of factors not measured in the present

Table 5. Depth distribution of nitrate-N (kg N ha^{-1}) in the soil under catch crops in November (figures in brackets are SE, *n*=2)

	Soil layer (m)		
	0–0.5	0.5–1.0	1.0–1.5
F. radish	13(4)	1.3(0.9)	0.4(0.0)
Winter rape	8(2)	0.7(0.3)	
Phacelia	22(7)	4(0)	
Rye	18(8)	6(4)	8
Oats	20(3)	11(2)	
Ryegrass	10(6)	14(0)	20(1)
Rye/vetch mixt.	20(6)	8(3)	
Vetch	19(0)	32(18)	
– no catch crop –	46(18)	83(49)	41(14)
Malva[a]	6	5	
Agrostemma[a]	5	13	

[a] Only included in 1 year.

Table 6. F values for the estimated slope of the regression lines for soil nitrate-N residues against various plant and root parameters. A statistical model allowing separate intercepts for the 2 years but estimating one slope covering both years was used. *, ** and *** shows significance levels of $p < 0.05$, $p > 0.01$ and $p < 0.001$, respectively, for the estimated slope. Data from the two treatments containing legumes were not included in this analysis

	kg nitrate-N ha^{-1} $layer^{-1}$		
	0–1.0 m	0–0.5 m	0.5–1.0 m
Biomass	4	7*	0
Aboveground biomass	1	1	0
Root biomass	2	9*	1
N uptake	11**	7*	2
%N in catch crop DM	7*	0	1
Depth after app. 40 days	4	0	65***
Depth after 1000 d °C	10**	0	76***
Temp. sum to reach 1.0 m	6*	0	65***
Root int. 0–1.0 m	2	0	4
Root int. above 0.5 m	0	0	0
Root int. below 0.5 m	5*	0	15**
Root freq. 0–1.0 m	6*	0	11**
Root freq. above 0.5 m	1	1	0
Root freq. below 0.5 m	7*	0	20***

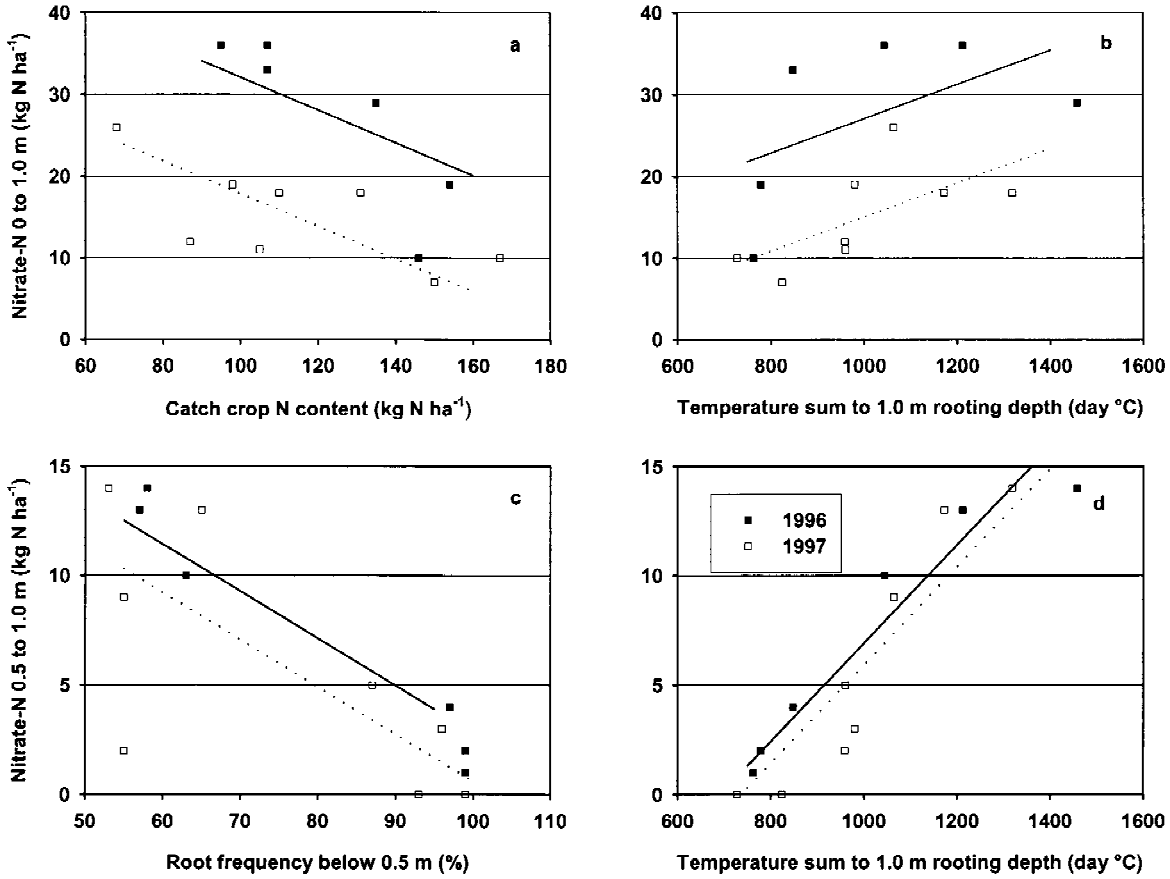

Figure 4. Four examples of the relationships between soil nitrate-N content in the 0–1.0 or 0.5–1.0 m soil layers in November and various factors. (a) and (b) shows examples of the weaker correlations found when considering the whole 0–1.0 m soil layer, whereas (c) and (d) shows the much closer correlations obtained when considering only the 0.5–1.0 m soil layer. F values for the slope of the regressions are shown in Table 6.

experiment. One of these factors could be the ability of the plants to remain viable and active in late autumn.

The strongest correlations between measured plant and root parameters and soil nitrate-N residues were found between some of the root growth parameters and the nitrate-N content in the 0.5–1.0 m soil layer. This result shows that whereas the total amount of nitrogen left in the soil in the autumn may depend on many factors, the amounts left in the soil layers below 0.5 m is strongly dependent on differences in root growth.

The observed differences in the depletion of soil layers below 1.0 m were more distinct than differences among crops in the top 1.0 m which is most frequently considered. For the crucifer catch crops, roots were clearly not limiting subsoil nitrate depletion, and under winter rape and fodder radish the 0.5–1.5 m soil layer was virtually devoid of nitrate. Rye and ryegrass also reduced the nitrate content even in the 1.0–1.5 m soil layer, but they were clearly less effective than fodder radish. Crucifer catch crops have previously been found to deplete subsoil N reserves more efficiently than monocot crops as rye or ryegrass (Aufhammer et al., 1992; Thorup-Kristensen, 1994). Substantial N uptake from soil layers below 1.0 m has previously been found by Strebel and Duynisveld (1989) and Daigger and Sander (1976).

The large differences found in the N depletion of the deepest soil layers show that differences in root growth among catch crops are very important for their environmental effect, as nitrate in deeper soil layers are highly prone to leaching loss (Thorup-Kristensen and Nielsen, 1998). Therefore, catch crop uptake of nitrogen from deep soil layers will have a larger effect on total leaching loss than the uptake of similar amounts from the upper soil layers.

What to measure

The results show that it is important to study root growth of catch crops. As root studies are often restrained by very laborious methods, it is important to find simple methods that will allow root studies to be included in more catch crop experiments. The methods should be relatively easy to use, but still give the relevant information about the ability of the catch crops to deplete the soil.

The results of the present study showed very strong correlations between some of the measured root parameters and soil nitrogen depletion. The strongest correlations were found using some of the less laborious methods e.g. rooting depth measured approximately 40 days after sowing. When the minirhizotrons were installed, this measurement took only 5–10 min per plot to perform. More detailed measurements of depth development rates require that such measures are repeated, but this is still easy to do compared to other methods for studying roots.

Attempts to simplify root measurements by measuring only in upper soil layers, as done by Sainju et al. (1998) or Vos et al. (1998), will only identify the important differences among catch crops, if root density in the upper soil layers is well correlated to root density and nitrate depletion in deeper soil layers. In the present study, no such correlations were found, and only the root measurements made in deeper soil layers correlated to soil nitrate depletion. Thus, for screening purposes, root measurements may be simplified by measuring only in deeper soil layers.

Measurements of root intensity or root frequency are more laborious than measurements of rooting depth, but they give more information about the root system. The measurement of root intensity, which is comparable to root length density (Merrill and Upchurch, 1994), is especially time consuming. Much of the time used for measuring root intensity is spent on counting very high root intensities mostly found in the topsoil. Based on the absence of correlation between topsoil root data and soil N depletion, these data may not be very relevant for the study of soil nitrate-N depletion by crops or catch crops.

Data for root frequency showed better correlation to soil nitrate depletion than data for root intensity, though root frequency is a much simpler analysis to make. The better correlations obtained may be due to the different nature of the two measures. Many roots at a few sites in a soil layer can give a high average estimate of root intensity, but high estimates of root frequency are only obtained where roots are more evenly distributed in the soil. Due to the high mobility of nitrate, high root densities are not needed to enable to crops to deplete a specific soil layer (Robinson et al., 1991; Robinson, 1996).

In spite of the high mobility of nitrate, some studies have indicated that quite high root length density (RLD) is needed for N depletion of the soil (e.g. Wiesler and Horst, 1994). This may be due to the methods used for measuring the root system, rather than to a real need for high RLD. The results show an average RLD for each soil layer, not whether the roots were well distributed or concentrated in a smaller part of the soil volume. Measurements of root frequency or other methods showing root distribution rather than root length may be better suited to estimate the ability of a root system for N depletion of a soil layer.

Final rooting depth of a catch crop is not the only important parameter determining its effect on subsoil nitrate-N content at the end of the growing season. For at least two reasons, fast early root growth and N uptake from the soil is also important. N depletion of deeper soil layers has been found to be slower than N depletion of upper soil layers (Strebel and Duynisveld, 1989). Therefore, it can be important that the catch crop roots reach the deep soil layers early, as this will allow more time for efficient N depletion. Further, under Northwest European climate conditions, the autumn is a normally period with surplus precipitation, and therefore downward movement of nitrate. Early N uptake from the upper soil layers will thus reduce the downward movement of nitrate during the autumn, and thereby reduce the nitrate concentration in deeper soil layers. In this way, catch crops can reduce nitrate concentrations even below their rooting depth, and this may be the reason why Italian ryegrass reduced the nitrate content in the 1.0–1.5 m soil layer by approximately 50% even though it had very few roots below 1.0 m.

Conclusion

Large differences in root growth were observed, and as previously found, crucifer crops had fast and deep rooting compared to cereal crops. To obtain deep rooting when grown as a catch crop, a plant species must show fast establishment and a high rooting depth penetration rate. Species with fast depth penetration are most likely to be found among non-legume dicot species.

The differences in root growth were important for the ability of the catch crops to deplete deep soil layers of their nitrate content. The use of catch crops that can take up nitrate from deep soil layers can increase the environmental and agronomic value of catch crops considerably.

Significant N uptake from soil layers below 1.0 m by catch crops and main crops may question previous results on nitrogen leaching, as they are generally based on the assumption that N leached to below 1.0 m is lost. Significant N uptake from below 1.0 m could have consequences for both agronomic and political strategies for reducing nitrogen leaching losses.

By using the minirhizotron method, it was relatively easy to obtain relevant data about root growth of catch crops. Other methods, which can reveal differences in rooting depth, could be equally useful, but measurements of crop N content or root growth in upper soil layers are not likely to give the relevant information.

Acknowledgements

I thank the Danish Research Centre for Organic Farming for financial support for this study, and Astrid Bergman for doing the root measurements on the catch crops.

References

Aufhammer W, Stützel H, Kübler E and Figenbaum A 1992 Interplanting of non-legumes into faba bean (*Vicia faba* L.) to reduce the risk of nitrate contamination of the ground water. Eur. J. Agron. 1, 59–69.

Böhm W 1974 Mini-Rhizotrons for Root Observations under Field Conditions. Z. Acker- und Pflanzenbau 140, 282–287.

Böhm W 1978 Untersuchungen zur Wurzelentwicklung bei Winterweizen. Z Acker- und Pflanzenbau 147, 264–269.

Barraclough P B 1989 Root growth, macro-nutrient uptake dynamics and soil fertility requirements of a high-yielding winter oilseed rape crop. Plant Soil 119, 59–70.

Barraclough P B and Leigh R A 1984 The growth and activity of winter wheat roots in the field: the effect of sowing date and soil type on root growth of high-yielding crops. J. agric. Sci. 103, 59–74.

Burns I G 1980 Influence of the spatial distribution of nitrate on the uptake of N by plants: A review and a model for rooting depth. J. Soil Sci. 31, 155–173.

Daigger L A and Sander D H 1976 Nitrogen availability to wheat as affected by depth of nitrogen placement. Agron. J. 68, 524–526.

Greenwood D J, Gerwitz A, Stone D A and Barnes A 1982 Root development of vegetable crops. Plant Soil 68, 75–96.

Grindlay D J C 1995 Rooting depth in cover crops and its relation to shoot size. Principles governing the ability of cover crop species to trap nitrate: 230–278. Phd thesis, University of Nottingham.

Hansen B 1989 Determination of nitrogen as elementary N, an alternative to Kjeldahl. Acta Agric. Scand. 39, 113–118.

Kutschera L and Lichtenegger E 1982a Wurzelatlas mitteleuropäischer Grünlandpflanzen. Band I. Monocotyledoneae. Gustav Fischer Verlag, Stuttgart, New York. pp 517.

Kutschera L and Lichtenegger E 1982b Wurzelatlas mitteleuropäischer Grünlandpflanzen. Band II. Dicotyledoneae. pp ??? Gustav Fischer Verlag, Stuttgart, New York.

Lainé P, Ourry A, Macduff J, Boucaud J and Salette J 1993 Kinetic parameters of nitrate uptake by different catch crop species: Effects of low temperatures or previous nitrate starvation. Phys. Plant. 88, 85–92.

Macdonald A J, Powlson D S, Poulton P R and Jenkinson D S 1989 Unused fertilizer nitrogen in arable soils – its contribution to nitrate leaching. J. Sci. Food Agric. 46, 407–419.

Materechera S A, Alston A M, Kirby J M and Dexter A R 1993 Field evaluation of laboratory techniques for predicting the ability of roots to penetrate strong soil and of the influence of roots on water sorptivity. Plant Soil 149, 149–158.

Merrill S D and Upchurch D R 1994 Converting root numbers observed at minirhizotrons to equivalent root length density. Soil Sci. Soc. Am. J. 58, 1061–1067.

Rao T P, Ito O and Matsunga R 1993 Differences in uptake kinetics of ammonium and nitrate in legumes and cereals. Plant Soil 154, 67–72.

Robinson D 1996 Resource Capture by Localized Root Proliferation: Why Do Plants Bother? Ann. Bot. 77, 179–185.

Robinson D Linehan D J and Caul S 1991 What limits nitrate uptake from soil? Plant Cell Environ. 14, 77–85.

Sainju U M, Singh B P and Whitehead W F 1998 Cover crop root distribution and its effects on soil nitrogen cycling, Agron. J. 90, 511–518.

SAS 1990 SAS/STAT User's Guide. Version 6, 4th edn. Cary: SAS Institute Inc.

Strebel O and Duynisveld W H M 1989 Nitrogen supply to cereals and sugar beet by mass flow and diffusion on a silty loam soil. Z. Pflanzenernär. Bodenk. 152, 135–141.

Thorup-Kristensen K 1993 Root development of nitrogen catch crops and of a succeeding crop of broccoli. Acta Agric. Scand., Sect. B, Soil Plant Sci. 43, 58–64.

Thorup-Kristensen K 1994 Effect of nitrogen catch crop species on the nitrogen nutrition of succeeding crops, Fert. Res. 37, 227–234.

Thorup-Kristensen K 1998 Root development of green pea (*Pisum sativum* L.) genotypes, Crop Sci. 38, 1445–1451.

Thorup-Kristensen K and Nielsen N E 1998 Modelling and measuring the effect of nitrogen catch crops on nitrogen supply for succeeding crops. Plant Soil 203, 79–89.

Van Dam A M and Leffelaar P A 1998 Root, soil water and nitrogen dynamics in a catch crop–soil system in the Wageningen Rhizolab. Neth. J. Agric. Sci. 46, 267–284.

Vos J, Van Der putten P E L, Hussein M H, Van Dam A M and Leffelaar P A 1998 Field observations on nitrogen catch crops. II. Root length and root length distribution in relation to species and nitrogen supply. Plant Soil 201, 149–155.

Whiteley G M and Dexter A R 1982 Root development and growth of oilseed, wheat and pea crops on tilled and non-tilled soil. Soil Till. Res. 2, 379–393.

Wiesler F and Horst W J 1994 Root growth and nitrate utilization of maize cultivars under field conditions. Plant Soil 163, 267–277.

Zagal E 1994 Carbon distribution and nitrogen partitioning in soil-plant system with barly (*Hordeum Vulgare* L.), ryegrass (*Lolium perenne*) and rape (*Brassica Napus* L.) grown in a $^{14}CO_2$-atmosphere. Plant Soil 166, 63–74.

Section editor: J. Lynch