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ORIGINAL PAPER

Effect of deep and shallow root systems on the dynamics of soil inorganic N during 3-year crop rotations

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Abstract Unused inorganic nitrogen (N_{inorg}) left in agricultural soils will typically leach to deeper soil layers. If it moves below the root zone it will be lost from the system, but the depth of the root zone depends on the crop species grown. In this experiment we studied the effect of 3-year crop sequences, with different combinations of deep-rooted and shallow-rooted crops, on soil N_{inorg} dynamics to 2.5 m soil depth and the possibility of crop utilization of N leached to deep soil layers. We grew ten different crop sequences for 3 years. The crops and catch crops grown were selected to allow different sequences of deep-rooted and shallow-rooted crops. Very different rooting depths were obtained, from only 0.5 m (leek), to ~1.0 m (ryegrass and barley), 1.5 m (red beet), 2.0 m (fodder radish and white cabbage) and more than 2.5 m by the chicory catch crop. The results showed a significant retention of N_{inorg} within the 2.5 m soil profile from one year to the next, but the retained N had leached to deeper parts of the profile during the winter season. Only little N_{inorg} was retained over two winter seasons. The retention in the deeper soil layers allowed N_{inorg} to be taken up by succeeding deep-rooted main crops or catch crops. The effects of crop rooting depth on N_{inorg} in the subsoil layers from 1.0 to 2.5 m were striking. White cabbage reduced N_{inorg} below 1.0 m with up to 113 kg N ha^{-1} during its growth. Grown after catch crops, leek and red beet left on average 60 kg N ha^{-1} less below 1.0 m than leek and red beet grown without a preceding catch crop. We conclude that it is possible to design crop rotations with improved nitrogen use efficiency by using the differences in crop rooting patterns; deep-rooted crops or catch crops can be used to recover N_{inorg} leached after previous crops, and catch crops can be grown before shallow-rooted crops to lift the deep N_{inorg} up to layers where these crops have their roots.

Keywords Vegetables · Barley · Catch crops · Root growth · Rooting depth · Nitrogen leaching · Cropping system · Crop rotation · Cover crop

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Introduction

In all arable cropping systems, there will be instances of a significant risk of nitrogen (N) leaching loss. Inorganic nitrogen (N_{inorg}) left in the soil will then typically leach downwards with surplus precipitation. However, downward leaching of N is not in itself a loss process; the loss occurs only when N is leached beyond the root zone of the crop. The N left in the field may therefore either be lost by leaching or retained within the root zone although leached to a larger depth in the soil.

Although some data show increased N_{inorg} contents in the subsoil in situations where leaching has occurred previously (Gass et al. 1971; Sainju et al. 1999), few data show for how long N_{inorg} may be retained in deeper soil layers or how much of it may actually be recovered by subsequent crops.

Before a deep-rooted crop, it will take more precipitation and consequently more time to leach N out of the root zone than before crops with shallow rooting. Growing deep-rooted crops will therefore allow more time for the recovery of the leached N as illustrated by the results of Addiscott and Darby (1991). This makes studies of crop root growth and function important for understanding soil N dynamics, losses and options for reducing leaching losses.

Studies of root growth and function comprise only a small part of the large volume of studies of field N dynamics and losses made during the last decades. Still, there is increasing evidence of large differences in rooting depth among crop species (Kristensen and Thorup-Kristensen 2004a; Smit and Groenwold 2005) and evidence that several important crops may have significant rooting to well below 1.0 m (Daigger and Sander 1976; Peterson et al. 1979; Barraclough 1989; Addiscott and Darby 1991; Stone et al. 2002). Significant N uptake from soil layers between 1.0 and 3.0 m have also been shown (Gass et al. 1971; Daigger and Sander 1976; Peterson et al. 1979; Kristensen and Thorup-Kristensen 2004a). The need to consider differences in crop rooting depths when simulating soil N dynamics was stressed by Delgado et al. (2000).

In most experimental and model simulation studies of N leaching losses, the bottom of the rooting zone has been assumed to be generally located at 0.8–1.0 m depth, and it has been assumed that N leached below this depth is lost (e.g. Webster and Goulding 1995; Askegaard et al. 2005). Results showing N uptake from well below 1 m soil depth clearly questions this assumption and some of the results and conclusions based on it.

If some crops can take up significant amounts of N from deep soil layers below 1.0 m, it is also an important question whether such deep-rooted crops can be used actively to reduce N leaching losses from farming systems. Growing deep-rooted main crops or catch crops in the season following a high-leaching risk situation, may allow the recovery of N which would be lost if more shallow-rooted crops are grown.

Farmers will also grow shallow-rooted crops in their rotations, but in order to optimize soil N utilization these should preferably be grown when little N_{inorg} is found in the deeper soil layers. This situation may occur after extended periods with limited N leaching from the topsoil or where deep-rooted crops have removed N from deep soil layers already. Catch crops may be used to create situations ideal for shallow-rooted crops, as they concentrate N_{inorg} in the uppermost soil layers (Thorup-Kristensen 2006).

In this experiment we wanted to study such strategies and interactions and in general to study the effect of rooting depth on soil N dynamics. To do this, we had to study several factors at once; crop root growth, crop N uptake, crop depletion of soil N_{inorg} and retention versus leaching of N_{inorg} in the soil during time. However, the focus of the experiment was the interaction between these factors, not on each of the topics themselves.

The objective of this work was (1) to test whether deep-rooted crops can take up substantial amounts of N from soil layers below 1 m, (2) to examine for how long N leached from the topsoil can still be found in the deep soil layers and (3) to test whether different strategies for growing either deep-rooted main crops or combining shallow-rooted main crops with deep-rooted catch crops can be used to recover N leaching down the soil profile. For this purpose, we studied the effect of deep or shallow-rooted crops or catch crops within ten 3-year crop sequences, on N_{inorg} dynamics in the soil to a depth of 2.5 m.

Materials and methods

The effects of deep versus shallow-rooted crops during a cropping sequence were studied in a

Table 1 Main characteristics of the experimental soil to 2.5 m depth

Soil layer (m)	Sand	Silt	Clay (%)	Organic C	pH
0.0–0.25	70.3	15.3	12.1	1.41	6.4
0.25–0.5	69.0	14.9	14.7	0.82	6.2
0.5–1.0	67.6	13.2	18.8	0.25	5.4
1.0–1.5	68.2	13.1	18.4	0.18	6.4
1.5–2.0	68.7	12.9	18.3	0.10	6.9
2.0–2.5	66.5	15.5	17.7	0.24	7.1

3 years experiment repeated twice; the first replicate ran from year 2000 to 2003 and the second from 2001 to 2004. The experiment was located on organically grown fields at Research Centre Aarslev (10°27′E, 55°18′N), on a Typic Agrudalf soil (Table 1). Weather data (Fig. 1) was obtained from a weather station situated less than 500 m from the experimental site. All operations in the field are shown in Table 3.

The experiment was laid out in a randomized complete block design, with two replicates and ten experimental treatments. The field plots were 7.5 × 10 m.

The experiment was made within an existing organic crop rotation on fields, which had been grown organically since 1996. Before the start of the experiment, a green manure crop was grown. It was established by undersowing in spring barley 1 year earlier, and was allowed to grow into the spring before it was ploughed under. The experimental treatments were initiated in August in the first year of the cropping sequences.

Each season of the cropping sequences we attempted to obtain three very different rooting depths (Table 2). With three treatments in each of three seasons, there are 27 possible combinations, but to limit the size of the experiment we selected only ten of those, namely the combinations which would most critically test the hypothesis. During the first season, the sequences were initiated with different autumn catch crops: fodder radish (*Raphanus sativus* L. var. *oleiformis*), Italian ryegrass (*Lolium multiflorum* Lam.) or no catch crop. In the second season we grew different vegetable crops: white cabbage [*Brassica oleracea* L convar. *capitata* (L) Alef.], red beets (*Beta vulgaris* L. var. *esculenta* L.) and leek (*Allium porrum* L.). In the third season spring barley (*Hordeum vulgare* L.) were grown with different undersown catch crops: chicory (*Cichorium intybus* L.), perennial ryegrass (*Lolium perenne* L.) and no catch crop.

The operations of the experiment are summarized in Table 3. No herbicides or pesticides were used in any of the crops. Only the vegetable crops in the second season were fertilized by an addition of 2,000 kg dried chicken manure per

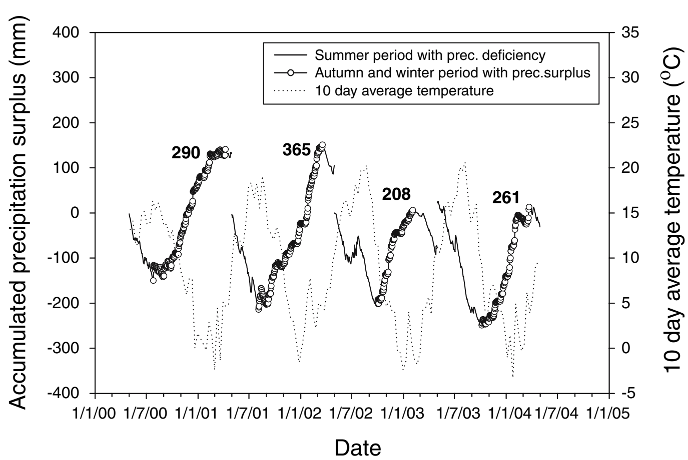

Fig. 1 Weather data for the 4 years of the experiments. Precipitation surplus accumulated from 1 May each year, and 10 days average air temperatures (2 m height) are shown. The summer period, where precipitation deficits accumulated are shown with a *plain line*, whereas, the autumn and winter period each year with precipitation surplus is shown with *open symbols*. The maximum accumulated precipitation surplus during each autumn and winter period is written above the curve

Table 2 The ten crop sequences

Treatment number	First season catch crop	Second season vegetable crop	Third season barley and undersown catch crop	Rooting sequence
1	No catch crop	Leek	Barley—no catch crop	L L L
2	No catch crop	Leek	Barley—ryegrass	L L M
3	No catch crop	Leek	Barley—chicory	L L D
4	No catch crop	Red beet	Barley—no catch crop	L M L
5	No catch crop	White cabbage	Barley—no catch crop	L D L
6	Ryegrass	Leek	Barley—no catch crop	M L L
7	Ryegrass	Red beet	Barley—no catch crop	M M L
8	Ryegrass	White cabbage	Barley—no catch crop	M D L
9	Fodder radish	Leek	Barley—no catch crop	D L L
10	Fodder radish	White cabbage	Barley—no catch crop	D D L

In the last column the sequence during the three seasons of limited (L), medium (M) or deep (D) root exploitation of the soil is shown

hectare, containing 100 kg total N ha^{-1}. The vegetable crops in the second season were irrigated when necessary to avoid severe water stress. This did not occur in 2001 and the crops were not irrigated this year, but in 2002 in experiment 2 they were irrigated three times with a total of 105 mm during the late summer, which was very dry.

Plant sampling and analysis

The catch crops were sampled from a 1 m^2 area in November in the first and third season by cutting just below ground level. The plant material was washed to remove the attached soil and air dried at 80°C for 20 h to determine dry weight and N content by the combustion method. The sand content was determined as acid insoluble material. As undersown catch crops tend to have a high root to shoot ratio, root matter was sampled as well from the catch crops in the third season. This was done by digging out soil samples of 0.036 m^2 to a depth of 0.2 m from each plot, and washing out the root material. Dry matter, N content and sand content were determined by the same procedure as used for the aboveground plant material. At harvest, the vegetable crops were sampled (leek and red beet from a 2.25 m^2 area, cabbage from 4.5 m^2) to determine yield, dry matter and N accumulation by the same procedure as for the catch crops. Total aboveground biomass of the vegetables was sampled, though for red beets also the storage roots were included in the sample.

Root measurements

Root growth of the crops was determined by using minirhizotrons with a diameter of 70 mm and a total length of 3 m, installed at an angle of 30° from the vertical. More details on minirhizotrons installation are given by Thorup-Kristensen (2001). The maximum observation depth was 2.4 m. In the catch crops grown during the first season, two minirhizotrons were installed in each plot, but in the second and third seasons three minirhizotrons were installed in each plot. The vegetables grown in the second season were grown as row crops with a row spacing of 0.5 m. In the row crops, the minirhizotrons were installed along the crop rows, 0.1 m from the row (Table 3).

Roots were observed by lowering a mini-video camera into the minirhizotrons and recording visible roots on the minirhizotron surface. Roots were recorded before the harvest of each main crop or incorporation of catch crops in the first and third season. Roots were recorded for every 40 mm along each of two 40 mm wide grids on the ‘‘upper’’ surface of each minirhizotron. For each of these observation units, it was observed whether any roots were crossing the gridlines (40 mm of vertical line and 40 mm of horizontal line). Root frequency was then calculated as the fraction of observation units where roots were observed within each soil layer. Root frequency was used rather than a calculation of the total root density observed on the minirhizotrons, as it has previously been shown to correlate well to

Table 3 Overview of crops and operations during the experiment

	Treatment dates	
	First experiment	Second experiment
First season catch crops		
Incorporation of green manure	30 May 2000	30 April 2001
Sowing catch crops	8 August 2000	31 July 2001
Installation of minirhizotrons	15 August 2000	3 August 2001
Catch crop sampling	6 November 2000	13 November 2001
Soil sampling	6 November 2000	14 November 2001
Catch crop incorporation	15 November 2000	16 November 2001
Ploughing	28 March 2001	2 April 2002
Second season vegetable crops		
Vegetable planting	Cabage 10 May 2001	Cabage 27 May 2002
	Beet 24 May 2001	Beet 28 May 2002
	Leek 30 May 2001	Leek 29 May 2002
Manure application	7 June 2001	24 May 2002
Installation of minirhizotrons	All crops 8 June 2001	Leek 6 June 2002
		Cabbage and beet 5 July 2002
Soil sampling	18 May 2001	16 May 2000
Vegetable crop harvest and sampling[a]	Cabage 29 October 2001	Cabage 1 October 2002
	Beet 24 October 2001	Beet 1 October 2002
	Leek 29 October 2001	Leek 1 October 2002
Soil sampling	31 October 2001	30 October 2002
Crop residue incorporation	Rotovated 26 November 2001	Rotovated 8 November 2002
	Ploughed 2 April 2002	Ploughed 27 March 2003
Third season barley with catch crops		
Barley and catch crop planting	11 April 2002	4 April 2003
Installation of minirhizotrons	18 April 2002	16 April 2003
Soil sampling	27 May 2002	12 May 2003
Barley harvest[b]	1 August 2002	4 August 2003
Soil sampling	13 November 2002	19 November 2003
Cover crop sampling	12 November 2002	12 November 2003
Cover crop incorporation	13 March 2003	12 March 2004
Fourth season carry over effect		
Soil sampling	12 May 2003	11 May 2004

Sampling during the four seasons were moved around the plots, and not made at the same part of the plot twice, to avoid effects of previous sampling to affect the results

[a] Total plant biomass and N was determined from the sampled subplot. At the rest of the plot, crops were harvested ‘‘as normal practice’’. With leek and red beet all crop material was removed; with cabbage the saleable part was harvested while the residues containing c. 100 kg N ha^{-1} were left on the soil and incorporated

[b] Grain and straw removed from the entire plot

soil N depletion (Thorup-Kristensen 2001) and it is much faster to record. Due to the angle of 30° from vertical, 40 mm along the minirhizotron surface represents a soil layer increment of 34.6 mm.

Soil sampling and analysis

Soil N_{inorg} was determined once each autumn and each spring (Table 3), on a total of six dates during each experiment. On each date soil was sampled to a depth of 2.5 m. Subsamples for each 0.5 m soil layer were frozen immediately after sampling. For analysis, the frozen soil samples were thawed and 100 g of soil was immediately shaken with 1 M KCl for 1 h (soil:solution ratio 1:2). The soil extract was filtered and analysed for NH_4^+ and NO_3^- concentration by flow injection (Lachat 8000).

Statistical analysis of the data were performed using the GLM procedure of the SAS statistical package. Root data obtained from many observation fields on two or three minirhizotrons per plot was averaged to give one figure per plot before statistical analysis. Only significant differences ($P < 0.05$) are mentioned unless otherwise stated.

Results

Root growth

Clear differences in rooting depth among the crops were obtained in all three seasons. In the first season the ryegrass catch crop had root frequencies exceeding 30% only in the top 0.75 m and practically no roots below 1.0 m (Fig. 2a). The fodder radish grew much deeper and had root frequencies exceeding 30% down to 2.25 m.

In the second season, the vegetables showed even greater differences in rooting depth, as leek had root frequencies exceeding 30% only in the top 0.5 m of the soil with very few roots below that depth (Fig. 2b), whereas cabbage had high-root frequencies in most of the soil profile and values exceeding 30% down to 2.25 m. Also red beet had a deep root system, but the root frequencies were lower than for cabbage in all soil layers below 0.5 m, and root frequencies exceeding 30% were recorded only down to 1.5 m.

In the third season, the barley crop had root frequencies exceeding 30% down to 0.75 m, and at the time of barley harvest, the root frequencies were practically unaffected by the undersown

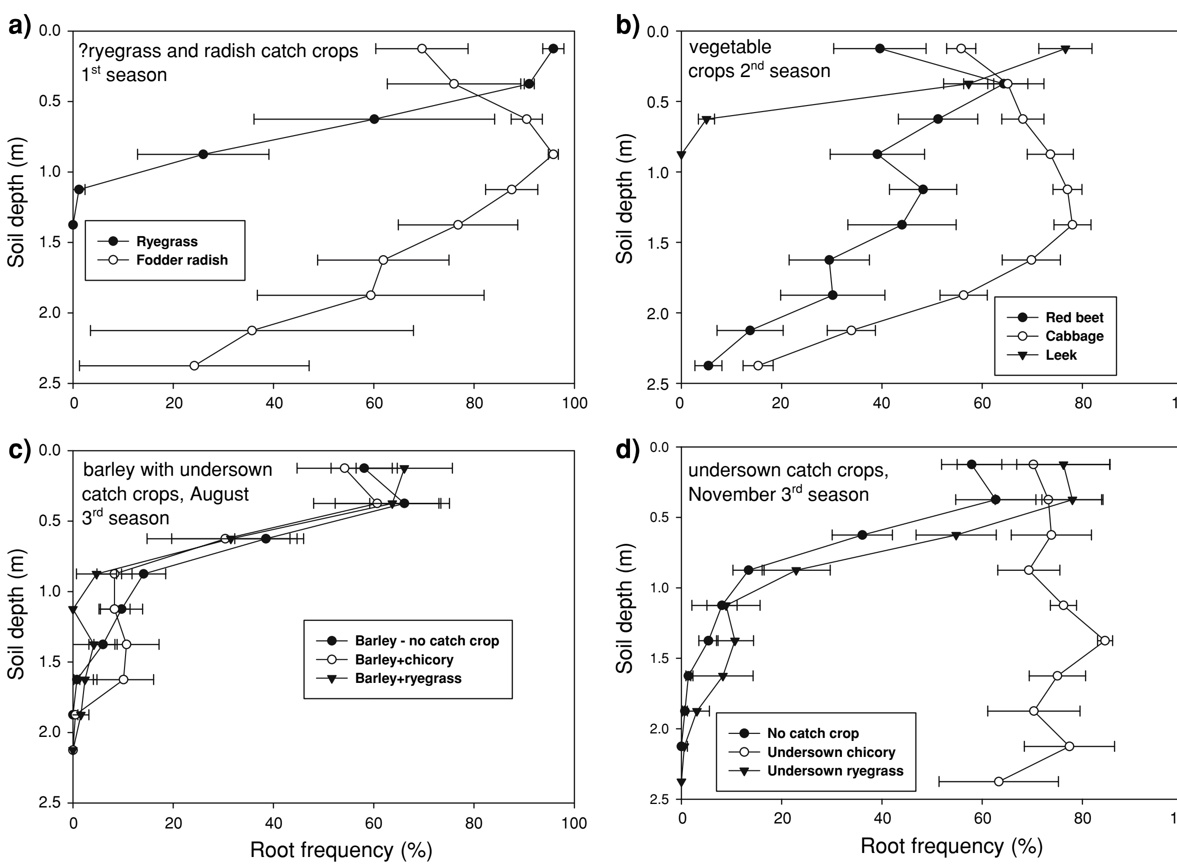

Fig. 2 Root frequency (percentage of minirhizotron counting grid fields in each soil layer showing roots) of the crops grown in the three seasons. All measurements were made at the end of the growing season of each crop. For statistics, one value for root frequency was calculated for each soil depth and each plot, based on the observations obtained from the two grids on each of the two minirhizotrons (first season) or three minirhizotrons (second and third season). *Bars* show SE (n = 4)

catch crops (Fig. 2c). During autumn the roots of the barley crop stayed visible on the minirhizotrons and even without a catch crop, only a slight decrease in root frequency was observed from barley harvest till November. In the ryegrass plots a clear increase in root frequency during autumn was observed, but only in the soil layers already rooted. The increase did not change the overall root pattern much, and root frequencies exceeding 30% were still only found down to 0.75 m (Fig. 2d). The undersown chicory catch crop continued to develop its root system strongly during the autumn, and in November root frequencies exceeding 60% were recorded in all soil layers.

Retention of N_{inorg} in the soil

Inorganic nitrogen left in the soil was retained in the soil for some time and still evident in subsequent soil analyses. This was seen from the autumn of the first to the spring of second season and again from the second to the third season. In the first season much N was left in the soil where no catch crop was grown (Fig. 3a). In the subsequent spring N_{inorg} below 1 m was 120 kg N ha^{-1} where no catch crop had been grown (Fig. 3b), but only 49 and 60 kg N ha^{-1} where catch crops of fodder radish or ryegrass had been grown. In the second season much N_{inorg} were left especially after leek (Fig. 4). In the spring of the third season N_{inorg} below 1 m was on average 71 kg N ha^{-1} after leek (Fig. 5a, treatment LL, ML and DL) but only 33 kg N ha^{-1} after cabbage (LD, MD and DD). In both cases, high autumn N_{inorg} led to high spring N_{inorg} in the soil layers below 1 m. Contrary to the increase in the subsoil, spring topsoil N_{inorg} values tended to be low where autumn N_{inorg} had been high (Figs. 3b, 5a).

The differences in N_{inorg} measured below 1 m in the spring were partly conserved until the autumn measurements. Where N_{inorg} below 1 m had been high before leek or red beet in the second season, it was still at around the same level in the autumn after the harvest of these crops (Fig. 4). Where it had been low in the spring, it was also still relatively low-after harvest, though some increase had occurred during the season. The exception from this pattern was seen after cabbage, where autumn subsoil N_{inorg} was low irrespective of whether it had been high or low in the preceding spring (Fig. 4).

A similar effect was observed in the third season, where subsoil N_{inorg} was relatively high in the spring after leek (treatments LL, ML and DL) and low after cabbage (LD, MD and DD, Fig. 5a). These differences were generally still present in the soil below 1 m at the autumn measurements (Fig. 5b). Only where barley with an undersown chicory catch crop had been grown, N_{inorg} in the subsoil was significantly reduced during the growing season (Fig. 6).

The data also indicate some retention of N_{inorg} across two seasons. In the spring of the third season N_{inorg} in the subsoil after the sequence L M (no catch crop followed by red beet) was

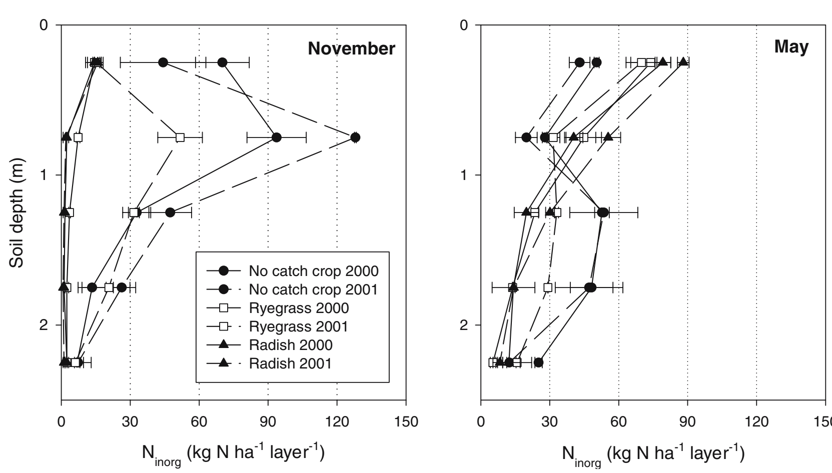

Fig. 3 Soil inorganic N (N_{inorg}) in November under the first season catch crops and in May in the next spring before establishment of the second season vegetable crops. The effect of ryegrass varied clearly between the two experimental years, therefore, results from each year is shown separately. *Bars* show SE (n = 2)

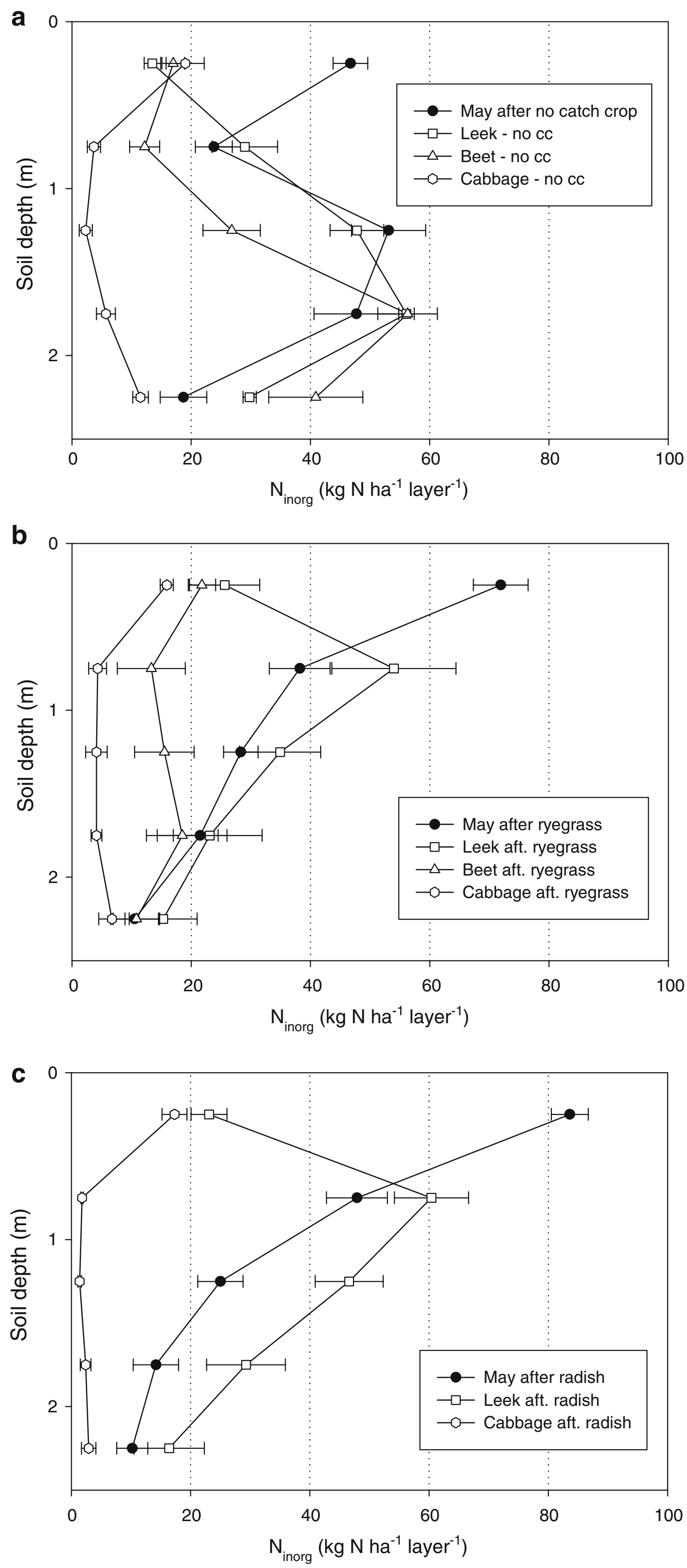

Fig. 4 Soil inorganic N (N_{inorg}) measured at harvest of the second season vegetable crops, **a** after no catch crop, **b** after ryegrass catch crop and **c** after a fodder radish catch crop. Data for N_{inorg} at vegetable establishment in May are shown for comparison. *Bars* show SE (n = 4)

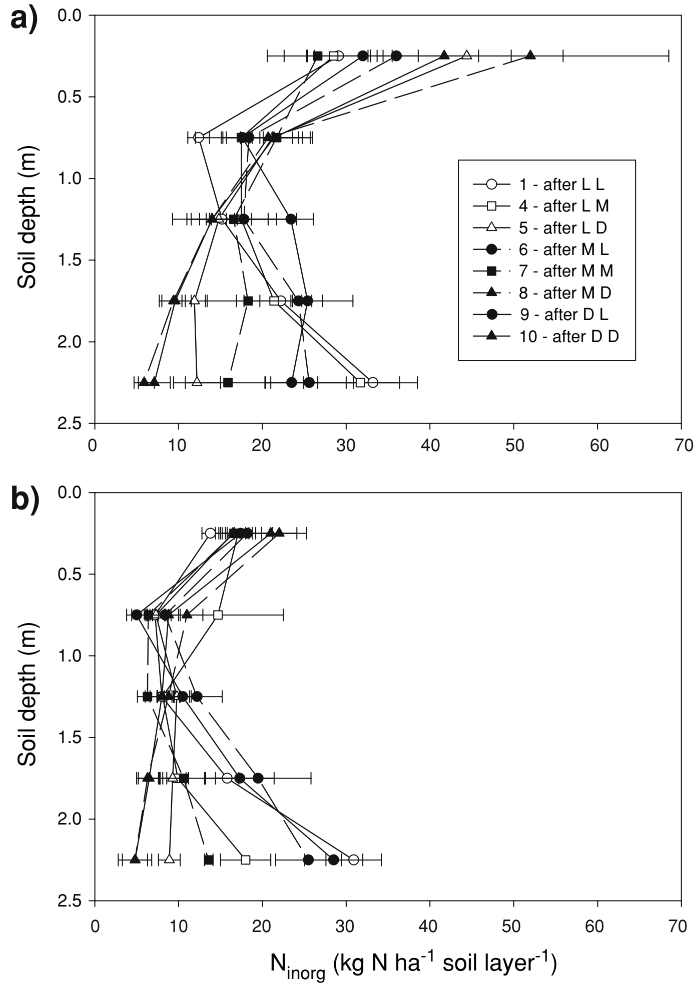

Fig. 5 Soil inorganic N (N_{inorg}) in the third season, **a** in May shortly after sowing of barley and **b** at the end of the season in November. The capital letters in the legends show the sequence of limited (L), medium (M) and deep (D) root exploitation in the first two seasons preceding the measurements. Only data from treatments without catch crops are shown here. *Bars* show SE (n = 4)

71 kg N ha^{-1} whereas after M M or D M (ryegrass or radish followed by red beet) it was only 51 kg N ha^{-1}. The similar second year effect of the catch crops was a reduction of 1 and 9 kg N ha^{-1} after leek and cabbage, respectively. Where no catch crop had been grown in the first season, it was especially in the deepest soil layer (2–2.5 m) that increased N_{inorg} was found in the third spring Fig. 6.

Also in the Fourth season, an indication of N_{inorg} retention from the second season was indicated, but differences were small (data not shown). After leek, which left much N_{inorg} in the soil in the second season, N_{inorg} below 1 m in the spring of the fourth season was 46 kg N ha^{-1} compared to 34 and 35 kg N ha^{-1} after red beet and cabbage, respectively. Although the data show indications of retention of N_{inorg} across two seasons, from the first to the third season and from the second to the fourth season, the effects are small, in the range of 1–20 kg N ha^{-1}. They are mainly found in the very deep soil layer below 2 m and they are generally not statistically significant.

In this experiment we wanted to study retention of N_{inorg} in the soil, but the catch crops in the first season also affected the retention of N in organic form in the soil. This was seen by significantly increased barley N uptake (see below) in the third season and even by increased N_{inorg} in the spring of the fourth season. N_{inorg} was higher where catch crops were grown in the first season (average 119 kg N_{inorg} ha^{-1}) than where no catch crop had been grown in the first year (103 kg N_{inorg} ha^{-1}). This difference was found mainly in the upper part of the soil profile.

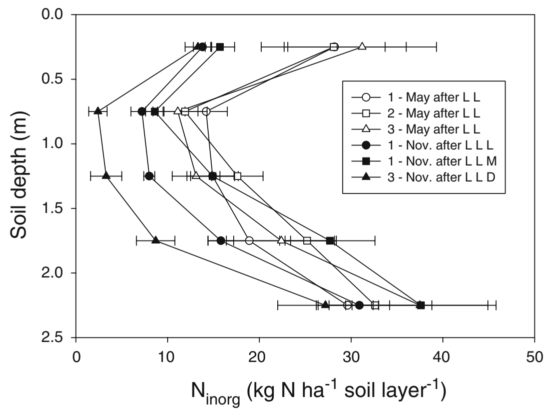

Fig. 6 Effect of ryegrass versus chicory catch crops grown in the third season on N_{inorg} measured in November in the late autumn. The capital letters in the legends show the preceding sequence of limited (L), medium (M) and deep (D) root exploitation in the two seasons or three seasons preceding the measurements. Data for N_{inorg} measured in the same plots in May shown for comparison. *Bars* show SE (n = 4)

The total water holding capacity of this soil at field capacity has been measured to be 259 mm in the top 1.0 m. During the four autumn and winter periods included in this experiment, the maximum accumulated net precipitation during any period varied between 208 and 365 mm (Fig. 1), with an average of 281 mm. This maximum accumulated precipitation surplus compares well to the conclusion that N_{inorg} is moved roughly 1.0 m down the soil profile during each winter season.

Soil N_{inorg} depletion during crop growth

Soil N_{inorg} depletion during crop growth was clearly related to the rooting depth of crops and catch crops in all three seasons. After the catch crops in the first season an effect of rooting depth was found, but there was not much deep N present in any case, so the catch crop could not create any large differences. In one year (2000) there was a significant difference between N_{inorg} under ryegrass and fodder radish in all soil layers below 0.5 m (Fig. 3a). In 2001 a significant difference was found in the 0.5–1 m soil layer, but the subsoil N_{inorg} levels were very low, and in the soil layers below 1 m practically no N_{inorg} was found under either catch crop.

After the vegetables in the second season, the difference in subsoil N_{inorg} was highly significant and clearly followed the rooting depth of the three vegetables. Without a preceding catch crop, 133 kg N_{inorg} ha^{-1} were found in the soil layer 1–2.5 m after harvest of leek, 125 kg N ha^{-1} after red beet, but only 20 kg N ha^{-1} after cabbage (Fig. 4).

In the third season with barley followed by undersown catch crops, N_{inorg} was significantly reduced in November after chicory in all soil layers down to 2.5 m depth (treatment LLD), and it was lower than after ryegrass or without a catch crop (LLL and LLM, Fig. 6). In total 55, 105 and 77 kg N_{inorg} ha^{-1} was found in the soil in the three treatments, respectively. With ryegrass and without a catch crop a reduction in N_{inorg} from spring to autumn was only observed in the upper 1 m (ryegrass) or 1.5 m (no catch crop). The effect of chicory was clear and significant, but N_{inorg} was not reduced to the same low levels as after cabbage in the second season.

N uptake

In the first season, ryegrass and fodder radish took up 124 and 162 kg N ha^{-1}, respectively (Table 4). Among the vegetable crops grown in the second season highly significant differences in N uptake were found. Without a preceding catch crop, leek on average took up 114 kg N ha^{-1}, red beet took up 170 kg N ha^{-1} and cabbage took up 251 kg N ha^{-1} (Table 5).

In the third season, the barley crop generally took up little N, but it had a higher yield and N uptake when following cabbage than when following the other vegetables (Table 6). There were no differences in barley rooting depth at

Table 4 Dry matter production and N uptake by the catch crops grown in the first season

	Dry matter (Mg ha^{-1})	N uptake (kg ha^{-1})	(%) N in dry matter
Italian ryegrass	4.1^{a}	124^{a}	3.0^{b}
Fodder radish	4.6^{a}	162^{a}	3.5^{a}
LSD	1.1	43	0.5

Numbers followed by the same letter are not significantly different

Table 5 Dry matter production, N uptake and N content of the three vegetable crops in the ten experimental treatments

Experimental treatment	Crop	Dry matter (Mg ha^{-1})	N uptake (kg ha^{-1})	(%) N in dry matter
1-L L	Leek after bare soil	7.3^{c}	112^{e}	1.6^{e,f}
2-L L	Leek after bare soil	8.1^{c}	114^{e}	1.4^{f}
3-L L	Leek after bare soil	7.7^{c}	115^{e}	1.5^{f}
4-L M	Beet after bare soil	9.9^{b}	170^{b,c}	1.7^{d,e}
5-L D	Cabbage after bare soil	11.6^{a}	251^{a}	2.2^{a}
6-M L	Leek after ryegrass	7.3^{c}	130^{d,e}	1.8^{c,d}
7-M M	Beet after rygrass	10.2^{b}	193^{b}	1.9^{b,c}
8-M D	Cabbage after ryegrass	11.4^{a}	236^{a}	2.1^{a}
9-D L	Leek after fodder radish	8.2^{c}	151^{c,d}	1.9^{b,c,d}
10-D D	Cabbage after fodder radish	11.4^{a}	229^{a}	2.0^{a,b}
LSD	LSD	1.0	25	0.2

Numbers followed by the same letter are not significantly different

Table 6 Yield, dry matter production, N uptake and N content by barley in the third season

Experimental treatment	First season catch crop	Second season vegetable crop	Dry matter (Mg ha^{-1})	Cereal yield (Mg ha^{-1})	N uptake (kg ha^{-1})	(%) N in dry matter
1-L L	Bare soil	Leek	4.3^{c,d}	3.0^{b,c}	45^{e}	1.07^{d}
2-L L	Bare soil	Leek	4.0^{d}	2.7^{d}	40^{f}	1.00^{e}
3-L L	Bare soil	Leek	4.2^{c,d}	3.0^{c,d}	46^{d,e}	1.09^{c,d}
4-L M	Bare soil	Beet	4.3^{c,d}	3.0^{c,d}	46^{d,e}	1.08^{c,d}
5-L D	Bare soil	Cabbage	5.6^{a}	3.8^{a}	61^{b}	1.11$^{b–d}$
6-M L	Ryegrass	Leek	4.6^{b,c}	3.2^{b,c}	51^{c}	1.13$^{a–c}$
7-M M	Ryegrass	Beet	4.3^{c,d}	3.1^{b,c}	50^{c,d}	1.17^{a}
8-M D	Ryegrass	Cabbage	6.0^{a}	4.1^{a}	69^{a}	1.16^{a,b}
9-D L	Radish	Leek	4.8^{b}	3.4^{b}	54^{c}	1.13$^{a–c}$
10-D D	Radish	Cabbage	6.0^{a}	4.0^{a}	66^{a}	1.12$^{a–d}$
LSD			2.1	0.3	5	0.06

Numbers followed by the same letter are not significantly different

harvest, and accordingly it did not respond with increased N uptake where deep N was available, e.g. after leek. The effects of the catch crops in the first season were still significant, and barley after cabbage or leek took up an extra 7 and 9 kg N ha^{-1}, respectively, where there had been a catch crop in the first season compared to where there had not. A similar effect was seen after red beet, but it was not significant.

Table 7 Dry matter production, N uptake and N content in catch crops grown in the third season following bare soil in the first season and leek in the second season

Experimental treatment	Catch crop	Dry matter (Mg ha^{-1})	N uptake (kg ha^{-1})	(%) N in dry matter
1-L L L	None	1.1^{b}	22^{b}	2.0^{a}
2-L L M	Ryegrass	3.7^{a}	56^{a,b}	1.6^{b}
3-L L D	Chicory	4.7^{a}	67^{a}	1.4^{b}
LSD		2	37	0.3

Among the catch crops undersown in the barley crop, the difference in N uptake was quite small, as chicory took up only 11 kg N ha^{-1} more than ryegrass, and this difference was not significant (Table 7). The difference in N uptake among these two catch crops is much smaller than the difference measured in their depletion of soil N_{inorg}, where chicory left 60 kg N ha^{-1} less in the soil than ryegrass (Fig. 6a).

Catch crop N effect on vegetables

Although all of the vegetables were able to deplete topsoil N_{inorg}, and thus to take up all available N from the soil layers where N miner-

Table 8 Effect of preceding catch crops (N_{eff}) on spring soil N_{inorg} within the vegetable root zone and on N uptake by vegetables calculated as the N content (in vegetables or soil) after catch crops minus N content without preceding catch crops

Treatment	Crop	kg N ha^{-1}	
		N_{eff} soil	N_{eff} crop
6-M L	Leek after ryegrass	25^{a,b}	17^{a}
7-M M	Beet after ryegrass	15$^{a–c}$	23^{a}
8-M D	Cabbage after ryegrass	–20^{c}	–15^{b}
9-D L	Leek after radish	37^{a}	38^{a}
10-D D	Cabbage after radish	–9^{b,c}	–23^{b}
	LSD	38	29

N_{eff} in the soil was calculated based on N_{inorg} to 0.5 m before leek, to 1.5 m before red beet and to 2.5 m before white cabbage. Numbers followed by the same letter are not significantly different

alization from the catch crops occurred, only leek and red beet responded positively to catch crops, while cabbage with its deeper root system responded negatively to the catch crops. The effect of the catch crops on N supply (N_{eff}) can be calculated as the increased amount of N_{inorg} in the soil or N in the vegetable crops when grown after catch crops (Table 8). The N_{eff} in the soil depends on the depth to which it is calculated. When calculated to 0.5 or 1.5 m, roughly corresponding to the rooting depth of leek and red beet, respectively, positive N_{eff} values in the range of 15–37 kg N ha^{-1} were found, and N_{eff} measured as the effect on N uptake in leek or red beet varied from 17 to 38 kg N ha^{-1} (Table 8). The N_{eff} values calculated for white cabbage were negative whether they were calculated based on N_{inorg} (to a depth of 2.5 m) or based on cabbage N uptake. In either case it was significantly lower than the N_{eff} values calculated for leek and red beet.

Discussion

Root growth and soil N depletion

Large differences in rooting depth among the crops and catch crops grown in the 3 years were observed, largely in line with the planned and expected differences. The crucifer species were deep-rooted as previously found (Barraclough 1989; Thorup-Kristensen 2001; Kristensen and Thorup-Kristensen 2004a, b) showing significant root density to more than 2.0 m depth. The deepest rooting was observed for chicory, which is in line with studies showing that several species of *Compositae* growing under natural conditions develop rooting depths of more than 2.0 m (e.g. Sun et al. 1997). Ryegrass and barley had more moderate rooting depths of 1 m or less as also found previously (Burns 1980; Thorup-Kristensen 2001; Kristensen and Thorup-Kristensen 2004a; Smit and Groenwold 2005). With a rooting depth of only 0.5 m, leek had a very superficial root growth as previously found for *Allium* crops (Burns 1980; Smit and Groenwold 2005; Thorup-Kristensen 2006).

Soil depletion of N_{inorg} by the crops was in accordance with their rooting depth in most cases. Cabbage and radish with very deep rooting left little N_{inorg} even at 2.5 m in the soil. Leek could not reduce N_{inorg} in layers below 0.5 m during its growth period, and ryegrass in the third season could not reduce N_{inorg} below 1.0 m. These observations are in accordance with previous studies showing a similar relationship between root observations and ^{15}N uptake (Kristensen and Thorup-Kristensen 2004a, b).

However, there were also examples where the root data and soil N_{inorg} data did not match quite so well. In one of the two experimental years, ryegrass grown in the first season reduced N_{inorg} to well below its recorded rooting depth, while in the second and third seasons red beet and chicory did not deplete the deeper part of their root zone efficiently.

The N_{inorg} depletion below the rooting depth of ryegrass in the first season was probably due to N leaching during the autumn. In north-western Europe, the main precipitation surplus, and thereby downwards N movement, occurs during the autumn while catch crops are growing. As catch crops take N from the upper soil layers during their early growth, this will reduce the leaching of N to deeper soil layers, and consequently N_{inorg} in the subsoil. Therefore, it is often found that shallow-rooted catch crops reduce N_{inorg} also below their rooting depth (Thorup-Kristensen 2001).

It is not clear why red beet and chicory did not deplete the deeper parts of their root zone as efficiently as the two crucifer species. Red beet depletion of N_{inorg} may have been limited by its relatively low-root density in the subsoil layers. This cannot be the case with chicory, which showed high-root density all the way down to 2.5 m.

A possible explanation of the limited efficiency of the deep roots of red beet and chicory is that their uptake capacity may be limited during the last part of the growing season. In the later stages of their growth, red beet and chicory approach winter dormancy and they will therefore primarily produce carbohydrates for storage in their root systems, while they start loosing their leaves. These processes demand very little N, and with low N demand, the N uptake rate by the roots will go down (Robinson 1996). As the roots reach the deepest soil layers only when N demand is declining at this late stage of growth, it is not surprising that the deepest soil layers were not effectively depleted. Contrary to red beet and chicory, white cabbage stores its reserves by a continuing leaf growth, and fodder radish developed no storage organ but continued to produce new leaves during the autumn. Thereby, these two crops maintain higher N demands during the late growth stages.

The results show N uptake from deep soil layers to be very important. In the different comparisons between deep-rooted and shallow-rooted crops in this experiment; the deep-rooted crops left 30–113 N ha^{-1} less in the soil layer between 1 and 2.5 m than the shallow-rooted crops. It is clear that omitting such large effects of rooting depths would lead to serious errors in an N balance calculation. The results also question many conclusions from other experiments based on the assumption that the depth of the root zone is typically 0.8–1 m. If some crops can take up high amounts of N from below 1 m depth, this assumption may lead to overestimation of real N leaching losses, to other errors in N balance calculations and to misleading comparisons between crops.

While the present experiment adds to the few studies showing significant N uptake from below 1 m in the soil (Gass et al. 1971; Daigger and Sander 1976; Peterson et al. 1979; Kristensen and Thorup-Kristensen 2004a), we do not know how important this is in agriculture in general. How many crop species can grow this deep, how many soils will allow this, and how much N can be taken up from the deep soil layers in ordinary agricultural practice?

Retention time of N_{inorg}

The results show that N_{inorg} was retained within the top 2.5 m of the soil for up to a year, but only to a small extent for 2 years. A few other experiments showing effects of "previous N loss" on N_{inorg} in deep soil layers have been published. Both Sainju et al. (1999) and Gass et al. (1971) found that high-fertilizer applications in one year led to increased subsoil N_{inorg} in the subsequent spring, whereas topsoil N_{inorg} was not affected.

The observation that N_{inorg} moved down roughly 1 m during the autumn and winter season in agreement with the weather data showing an average net precipitation surplus during the winter season of 281 mm corresponding to the estimated water holding capacity of 259 mm in the top 1 m of the soil. Little retention was observed in the top 1 m of the soil, so the retention could only be observed if the soil layers below 1 m were included in the measurements.

The fact that N_{inorg} is retained for a longer time when a deeper soil layer is considered is obvious when the main loss process is downwards leaching. Previous studies have also shown, that depending on winter precipitation and soil type, N_{inorg} may be retained in the soil during winter leaching, and that the retained N is then mainly found in the subsoil in the spring (Burns 1984; Thorup-Kristensen and Nielsen 1998; Thorup-Kristensen et al. 2003), even though these studies did not include soil layers under 1 or 1.5 m. Addiscott and Darby (1991) showed that because of N movement in the soil, N_{inorg} in the top 1 m of the soil in January gave a good estimate for the N_{inorg} available to wheat within the top 1.5–2 m soil depth in April.

While N_{inorg} was leached roughly 1 m downwards during each winter season in our experiment, it moved little during summer. The N_{inorg}

profile found in the subsoil in spring was still roughly the same in the autumn measurements, unless deep-rooted species such as cabbage or chicory were grown. This shows that the N_{inorg} can be retained for at least 1 year in the soil, if it is not taken up by crops.

Retention of N_{inorg} across two winter seasons was also indicated in the results, but it was too small to be of significant value in practical farming. In agricultural fields, the amount of retained N and the depth in which it is retained will vary strongly with soil type (water holding capacity) and precipitation (Burns 1984; Thorup-Kristensen and Nielsen 1998). Under conditions with high-leaching intensity there may be little chance of recovering any leached N even from one season to the next, whereas under dry land conditions there may be significant retention for longer periods than observed here.

While a significant fraction of N_{inorg} was retained for only 1 year, the data show retention of N in organic form for a longer time. The effect of first season catch crops on N uptake in barley in the third season was in the order of 5% of the catch crop N content in the first season, this effect is slightly higher than the effects, which have previously been measured for second year effects of catch crops using ^{15}N techniques (Thomsen 1993). Effects of first season catch crops were even indicated in the N_{inorg} data from the spring of the fourth season.

Using deep roots to reduce N losses

The results show that deep-rooted crops or catch crops could be used to develop new strategies for reducing N leaching losses. In the first season, catch crops were used in the conventional way to reduce leaching losses in a high-leaching risk situation, and accordingly they strongly reduced soil N_{inorg} and leaching risk during this winter season.

However, the data also show that if a catch crop is not grown, and N is allowed to leach down the soil profile, some of the leached N can be recovered later by growing deep-rooted crops. This was observed both with the white cabbage as a main crop in the second season and with the chicory grown as a catch crop in the third season.

The results also show that catch crops or other deep-rooted crops may preferentially be grown before shallow-rooted crops. Leek and red beet left 40–80 kg N ha^{-1} less in the subsoil at harvest when following a catch crop than where no catch crop had been grown. In the third season barley left c. 30 kg N ha^{-1} less in the subsoil when grown after cabbage than when grown after leek.

It was also found that catch crops had a positive effect on N availability for leek and red beet whereas the effect on N availability for the deep-rooted cabbage crop was negative. This confirms that catch crops may preferentially be grown before shallow rooted crops. It has been shown several times that catch crops may have positive as well as negative effects on N availability for succeeding crops (e.g. Vyn et al. 1999). The negative effect on cabbage was caused by the catch crop taking up N that would otherwise have been available for the main crop. The catch crops had mineralized N and increased topsoil N_{inorg}, and this increased N availability for all three vegetable crops, but the reduction of subsoil N_{inorg} by catch crops was even stronger, and this affected mainly N availability for the cabbage crop. This effect has previously been termed pre-emptive competition (Thorup-Kristensen 1993; Thorup-Kristensen et al. 2003) and mainly affects deep-rooted crops as catch crops especially reduce N_{inorg} in the deeper part of the soil.

All in all, this suggests new strategies for reducing N leaching losses in crop rotations. It is possible to use deep-rooted main crops in such strategies, but this possibility will often be limited by economic and practical considerations by the farmers. Therefore, new possibilities for using catch crops are maybe more obvious.

Even when catch crops cannot be grown directly in a high-leaching risk situation, e.g. because of a late main crop harvest, they can still be used in other ways. They can be grown in the year before a shallow-rooted crop to lift N to upper soil layers and reduce the leaching risk created after harvest of the shallow-rooted crop. Alternatively, deep-rooted catch crops can be grown in the autumn after a high-leaching risk has occurred in order to recover some of the leached N still present in deep soil layers, as shown with the chicory catch crop in the third season in this experiment.

Conclusions

There are large differences in rooting depths among crops and catch crops, some crops reaching rooting depths of more than 2 m. Soil N_{inorg} depletion from below 1 m depth can be considerable, in this experiment it was estimated to be in the range of 30–113 kg N ha^{-1}.

It was found that the N_{inorg} left in the topsoil in the autumn was retained for one winter season, where it was leached roughly 1.0 m downwards. Little displacement of N_{inorg} occurred during summer. Thereby, significant retention was shown within the top 2.5 m soil profile for a whole year. Some retention across 2 years was also indicated in the data, but the amounts were small.

With a displacement of ~1 m during the winter season, N_{inorg} left in the soil in one autumn, was retained and still available in the soil for the next year. However, it was only available to deep-rooted species with rooting depths of 2 m or more. If more shallow-rooted crops were grown, the retention time of N_{inorg} was shorter, as it was already lost from the root zone by the displacement during the first winter season.

The rate of movement of N_{inorg} in the soil depends on soil type and precipitation, and the interpretation of the results should be related to these factors. On sites with fast leaching, even deep-rooted crops may not allow uptake of much N_{inorg} left from the previous season. On sites with slower N movement than in our experiment, recovery by deep-rooted crops after more than one year could be possible.

Deep root growth and retention of N_{inorg} in deep soil layers allow new strategies for reducing N leaching losses from cropping systems to be developed based on the use of deep-rooted catch crops and main crops.

Catch crops can be used in a broader range of strategies than previously assumed. Normally we try to grow them at high-leaching risk situations, but they can also reduce N leaching risk when grown before a shallow-rooted main crop, or deep-rooted catch crops can be grown in the year after high N leaching has occurred.

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