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REGULAR ARTICLE

Winter wheat roots grow twice as deep as spring wheat roots, is this important for N uptake and N leaching losses?

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Abstract Cropping systems comprising winter catch crops followed by spring wheat could reduce N leaching risks compared to traditional winter wheat systems in humid climates. We studied the soil mineral N (N_{inorg}) and root growth of winter– and spring wheat to 2.5 m depth during 3 years. The roots of the winter and spring wheat penetrated the soil at a similar rate (1.3 mm $^{o}C\ day^{-1}$) and by virtue of its longer growing period, winter wheat reached depths of 2.2 m, twice that of spring wheat (1.1 m). The deeper rooting of winter wheat was related to much lower amounts of N_{inorg} left in the 1 to 2.5 m layer after winter wheat (81 kg N_{inorg} ha^{-1} less). When growing winter catch crops before spring wheat, N content in the 1 to 2.5 m layer after spring wheat was not different from that after winter wheat. The results suggest that due to its deep rooting, winter wheat may not lead to as high levels of leaching as it is often assumed in humid climates. Deep soil and root measurements (below 1 m) in this experiment were essential to answer the questions we posed.

Keywords Catch crops · Cover crops · Leaching · Nitrogen · Organic farming · Root depth

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Introduction

Wheat is one of the most widely cultivated crops, and in many areas winter wheat is preferred by farmers rather than spring wheat. Winter wheat is sown in the autumn and develops slowly during the cold period. High precipitation during this time is common in humid regions, and in most cases the precipitation surplus during winter will exceed the water holding capacity of the top 1 m of the soil. Therefore, water will move through this soil layer, and nitrate will move with it to deeper layers or out of the soil profile (Addiscott and Darby 1991). This drainage of soil water after the start of the winter rainfall makes nitrate under winter wheat crops prone to leaching, especially if they have been grown after a pre-crop leaving much inorganic N in the soil (Anderson et al. 1998a). Estimated amounts of N leached from winter wheat vary depending on precipitation and on the soil type and fertility management, ranging from 4.2–12 kg ha^{-1} in a Red Kandosol with a high clay content (20–60%) (Smith et al. 1998) to 34–59 kg ha^{-1} (Anderson et al. 1998b) and 30–70 kg ha^{-1} (Thomsen et al. 1993) in sandy soils.

In most experimental and modeling work on N leaching it has been assumed that the bottom of the rooting zone was at 1 m depth or even less, and that N leached to below this depth is lost (Karlen et al. 1996; Smith et al. 1998; Watson et al. 1993). However, if winter wheat has significant root activity and N uptake from soil layers between 1 and 2 m depth, its effect on N leaching losses may be significantly better than often assumed. Growth of wheat roots has been observed to more than 1.8 m (Gregory et al. 1978; Kirkegaard and Lilley 2007; Sauer et al. 2002). N placed in different depths up to 1.5 m, gradually affected N uptake from winter wheat (Daigger and Sander 1976), suggesting presence of roots in deeper layers, though maybe not sufficient for taking all N from these soil layers.

From current literature there is little evidence whether deep root development by winter wheat can prevent that mineral N moved downwards during autumn will finally be lost from the system by leaching to below the rooting depth. As winter wheat roots can grow well below 1 m depth, measurements to 1 m soil depth might not be sufficient when N leaching is to be calculated, or for the comparison of N management strategies (Sauer et al. 2002).

To minimize N leaching losses from wheat cropping systems, one possibility is to shift from growing winter wheat to growing spring wheat preceded by catch crops. Catch crops sown in late summer under high precipitation conditions have been found to be an efficient method to prevent the residual nitrogen from a previous crop being leached during winter (Thorup-Kristensen et al. 2003), and catch crops grown before spring barley have proved to reduce N leaching compared to winter wheat (Thomsen et al. 1993). Incorporation of the catch crop grown before spring wheat can then be delayed until winter or early spring, to allow catch crop N to be mineralized and become available for the spring wheat, rather than being lost by leaching.

In most areas, farmers prefer to grow winter wheat because it gives higher yields. However, in organic systems and high precipitation regimes, a catch crop preceding spring wheat might supply N to the wheat crop. This is N that would otherwise have been leached from the soil profile under winter wheat, and spring wheat yields similar to those reached by winter wheat might be achieved with much less N leaching loss. Depletion of N at deep soil layers by brassica catch crops has previously been reported (Kristensen and Thorup-Kristensen 2004; Thorup-Kristensen 2001, 2006), as well as positive effects of rotations with brassicas on wheat yields (Kirkegaard et al. 1994).

Studies of root and mineral N to 2.5 m soil depth, and spring wheat rotations with catch crops, could therefore improve our understanding of the effect of winter wheat on N leaching losses, and on the possibilities for improving N management in wheat cropping systems. Based on this, the objectives of this study were: (i) To study differences in root depth and distribution of spring wheat and winter wheat, (ii) to quantify differences in soil N content below 1 m depth under winter wheat compared to spring wheat, and the reduction of subsoil N content that can be achieved by growing catch crops before spring wheat, (iii) to test whether maximum wheat yield can be achieved when growing spring wheat preceded by catch crops instead of winter wheat in an organic system, and (iv) to test whether soil and root measurements below 1 m depth are important for understanding N dynamics of wheat crops and strategies to reduce nitrate leaching.

Materials and methods

Field site and experimental design

A 3-year field experiment was performed with winter wheat and different catch crops preceding spring wheat to study root growth, soil N_{inorg} and wheat yield. The experiment was carried out in organically grown fields at the University of Aarhus, Department of Horticulture in Aarslev, Denmark (10°27'E, 55°18'N). The soil is a sandy loam Agrudalf soil (Table 1). Weather data was obtained from a meteorological station situated less than 500 m from the experimental field (Fig. 1). Accumulated yearly precipitation ranged from 500 to 729 mm from 2002 to 2005. Surplus precipitation was calculated as daily precipitation minus potential evapotranspiration. Temperature sums (day °C) were calculated as the sum of daily average temperatures.

Table 1 Clay, silt, sand content and chemical compostion (pH, C, P and K) of the soil profile to a depth of 2.5 m. Averaged for the 3 years

Depth (m)	Clay (%)	Silt (%)	Sand (%)	pH ($CaCl_2$)	C (%)	P* (mg kg^{-1})	K** (mg kg^{-1})
0–0.5	12.6	15.9	69.5	6.9	1.16	22.7	125.5
0.5–1	18.6	13.8	67.2	5.8	0.25	20.7	98.7
1–2.5	18.0	13.1	68.5	7.3	0.22	15.6	102.6

*extracted with 0.5 M $NaHCO^3$

**extracted with CH^3 $COONH^4$

The experimental design was a randomized complete block, with three replicates. Plot size was 5 by 10 m. The treatments consisted of different wheat cropping systems: winter wheat (*Triticum aestivum* L.), spring wheat after bare soil during winter, and spring wheat after winter catch crops. Catch crops were sown in August and left in the soil until plowing before spring wheat sowing. Sowing and plowing dates for every year are summarized in Table 2. During the first year of the experiment, there were three different treatments with catch crops before spring wheat: winter rye (*Secale cereale*), fodder radish (*Raphanus sativus*) and common vetch (*Vicia sativa*). For the second year, cover crops where oats (*Avena sativa*), turnips (*Brassica rapa* subs., *rapa*) and hairy vetch (*Vicia villosa* Roth.). In the third year only the fodder radish catch crop was studied, but a new treatment consisting of an earlier sown winter wheat in August was included. Seeding densities for wheat, fodder radish, turnip, vetch, oats and rye were 300 seeds m^{-2}, 16, 10, 80, 100 and 100 kg ha^{-1}, respectively. No N fertilizer was applied to wheat or the cover crops.

During the summer before the start of the experiment, the field had been covered by a green pea crop. The pea residues were rotovated into the soil in July, and the soil was ploughed before starting the experiment.

Root measurements

Root depth and distribution was measured using minirhizotron glass tubes of 70 mm outer diameter, inserted at an angle of 30° up to a depth of 2.5 m. Two minirhizotrons where installed at every plot. Along each minirhizotron, two replicate counting grids (rows of 40 x 40 mm ^{2}) were painted along the left–and right sides of upper surface of the minirhizotron. A mini-video camera was used to record the roots at the minirhizotron surface along the counting grids. From these recordings two

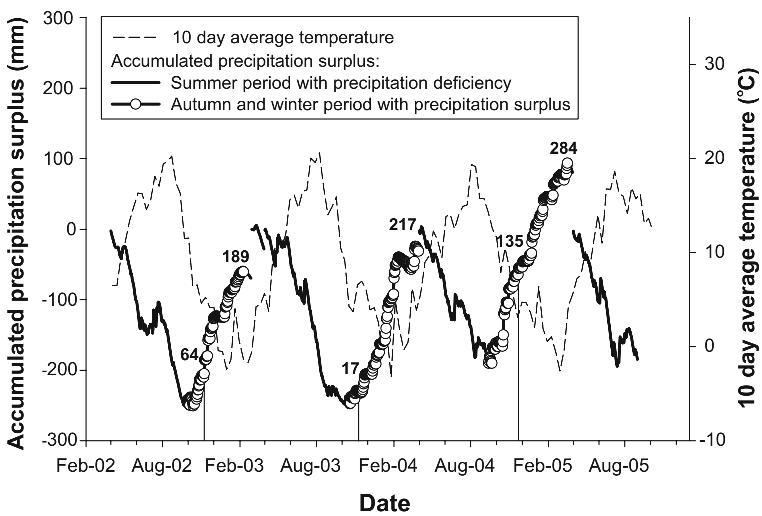

Fig. 1 Weather data for the 3 years of the experiment. 10 days average air temperature (°C) and precipitation surplus (*mm*) accumulated from 1 April each year. The summer period, where precipitation deficits accumulated are shown with a plain line, whereas the autumn and winter period each year with precipitation surplus is shown with open symbols. Numbers indicate maximum precipitation surplus accumulated and precipitation surplus accumulated up to the November soil measurement

Table 2 Sowing time, date of catch crop plowing, wheat harvest and dates of root growth and soil N_{inorg} measurements for every year of the experiment

	Year 1	Year 2	Year 3
Catch crop sowing	08/08/2002	08/08/2003	05/08/2004
Early winter wheat sowing	-	-	25/08/2004
Winter wheat sowing	16/10/2002	10/09/2003	10/09/2004
Catch crop plowing	08/03/2003	03/03/2004	25/03/2005
Spring wheat sowing	31/03/2003	13/04/2004	19/04/2005
Winter wheat heading stage	16/06/2003	14/06/2004	24/06/2005
Spring wheat heading stage	16/06/2003	13/06/2004	30/06/2005
Winter–and spring wheat harvest	11/08/2003	23/08/2004	24/08/2005
Root growth measurements	13/11/2002*	22/10/2003	12/10/2004
	12/02/2003	12/11/2003*	16/11/2004*
	28/05/2003*	19/02/2004*	16/02/2005*
	19/06/2003	25/05/2004*	21/03/2005
	07/08/2003*	22/06/2004	26/05/2005*
		16/07/2004	14/07/2005
		26/08/2004*	23/08/2005*
Soil samplings	17/09/2002	10/09/2003	25/08/2004
	11/11/2002	11/11/2003	26/11/2004
	15/03/2003	21/03/2004	26/05/2005
	06/08/2003	07/09/2004	24/08/2005

* Root measurements shown in Fig. 5

different measures of root growth were obtained: root depth and root intensity. Root depth was registered as the deepest root observed in each of the two counting grids on each minirhizotron. Root intensity was calculated as the total number of root crossing the grid lines in each 40 x 40 mm cross (total of 80 mm line). This was calculated as number of cross intersections per meter line (intersection m^{-1}) in a soil layer of 36.4 mm depth (=cos(30°) x 40 mm) due to position of the tube 30° from vertical. The 2 by 2 measurements obtained for each plot (two tubes with two grids each) were averaged to one value for each plot before statistical analysis. Roots where recorded several times during the growing season, and the measurement dates are summarized in Table 2. Root depth penetration rates (mm d^{-1} $°C^{-1}$) were calculated following Barraclough and Leigh (1984), as the slope of regression lines of the average root depth versus accumulated average daily temperature from sowing day, using a base temperature of 0°C.

Plant and soil sampling

Plant material was sampled at harvest from sub-plots of 1 m^2 by cutting the wheat crops just above ground level. The plant material was separated in grain and the rest of the aboveground plant, dried at 80°C for 20 h, weighed and analyzed for N content by a combustion method (thermal conductivity detector, vario-MAX CNS).

Soil was sampled using a soil piston auger with an inner diameter of 14 mm. Nine replicate samples were combined into one bulk sample for each soil layer and plot. The samples were divided into 0.5 m depth intervals to 2.5-m depth. The soil samples were frozen until being thawed and 100 g fresh weight were weighed and extracted in 1 M KCl for 1 h (soil/solution ratio 1:2). The soil extract was centrifuged and the supernatant was analyzed for NH_4 and NO_3 content by standard colorimetric methods using an AutoAnalyzer 3 (Bran +Luebbe, Germany). N_{inorg} was determined as the sum of N in the form of NH_4^+ and NO_3^-. Plant and soil samplings dates are summarized in Table 2.

Statistical analysis

Significant differences in soil N_{inorg}, wheat yield, and plant N content were tested by analysis of variance (F test), followed by pairwise comparisons by Tukey's student range test (Proc GLM, SAS Institute Inc., Cary, NC, USA). Values of soil N_{inorg} were transformed prior to analyses by the function y=log(x) to obtain homogeneity of variance. Relationships between root depth and accumulated average daily temperature were investigated by simple linear regression modeling and test of homogeneity of slopes. In assessing differences between results, tests with P<0.05 were considered statistically significant.

Results

Root depth and intensity

Large differences were observed between spring wheat and winter wheat root depth and distribution. Average root depth was twice as high for winter wheat (2.2 m) than for spring wheat (1.1 m) at the end of the season, though little root development was observed in winter wheat during autumn and winter (Fig. 2). Roots of winter wheat were confined to the top 1 m of the soil during this time, except for the third year when autumn temperatures where higher (Fig. 3 a, b, c). When winter wheat was sown already in August, it showed a much deeper root development by November compared with winter wheat sown in September (Fig. 3 c). By the spring measurement in May, winter wheat had reached the maximum measurement depth of the minirhizotrons in two of the 3 years, whereas spring wheat sown at the end of March had roots up to 0.75 m. During early growth stages, wheat showed its highest root intensities in the topsoil, but in the 2nd and 3rd year, winter wheat showed its highest root intensities below 1 m soil depth in May and at harvest. Roots of spring wheat did not penetrate below 1.5 m in any case, but root intensities in the upper soil layers (0–0.75 m) were usually higher than those of winter wheat (Fig. 3 d-i). Root depth up to the date of heading stage in wheat showed almost the same linear relationship to temperature sum for both winter wheat and spring wheat (Fig. 4).

Catch crops sown in August showed root depths in November ranging from less than 1 m for oats and hairy vetch, to 1.8 m for winter rye and more than 2 m for the brassica crops. At the same time winter wheat had reached root depths of around 0.5 m (Fig. 2). Some catch crops died in the late autumn or during winter, but winter rye, hairy vetch, and turnip survived the winter, and still had active root systems until their incorporation in March.

Soil mineral Nitrogen

Initial soil inorganic N (N_{inorg}) in August was similar for the 3 years of the experiment, with most of the N_{inorg} in the top soil layer (values from 110 to 145 kg N_{inorg} ha^{-1}) (Fig. 5). In the November measurement, N_{inorg} in the bare soil had moved down the soil profile, depending on the surplus precipitations up to that time. For instance, in the 2nd year, when surplus precipitation was only 25 mm, N remained in the upper soil layer (Fig. 5 b). At this time, winter wheat had little effect on N_{inorg} in the soil, except in the 2nd year and when sowing winter wheat in August in the 3rd year. In these cases N_{inorg} in the top 1 m soil layer under wheat was 129 and 64 kg N_{inorg} ha^{-1} lower than in bare soil plots respectively (Table 3), whereas no difference were observed in the 1–2.5 m layer.

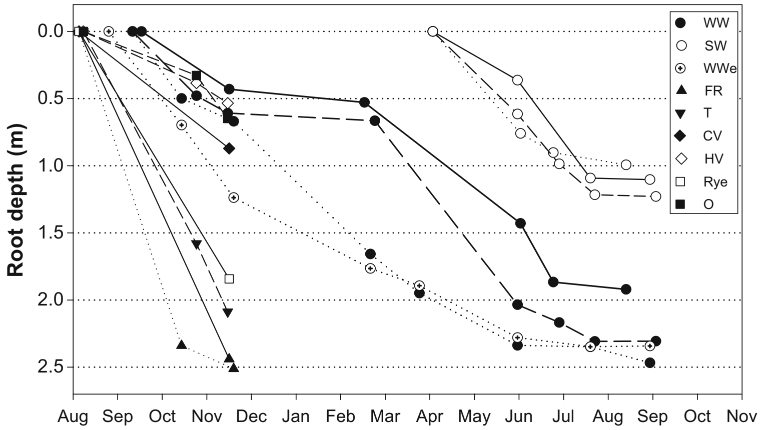

Fig. 2 Depth penetration over time by winter wheat, spring wheat and catch crop roots. Data from the 1st (*solid lines*), 2nd (*dashed lines*) and 3rd year (*dotted lines*) are shown. Abbreviations: WW, winter wheat; WWe, early sown winter wheat; SW, spring wheat; FR, fodder radish; HV, hairy vetch; T, turnip; CV, common vetch; O, oats; BS, bare soil

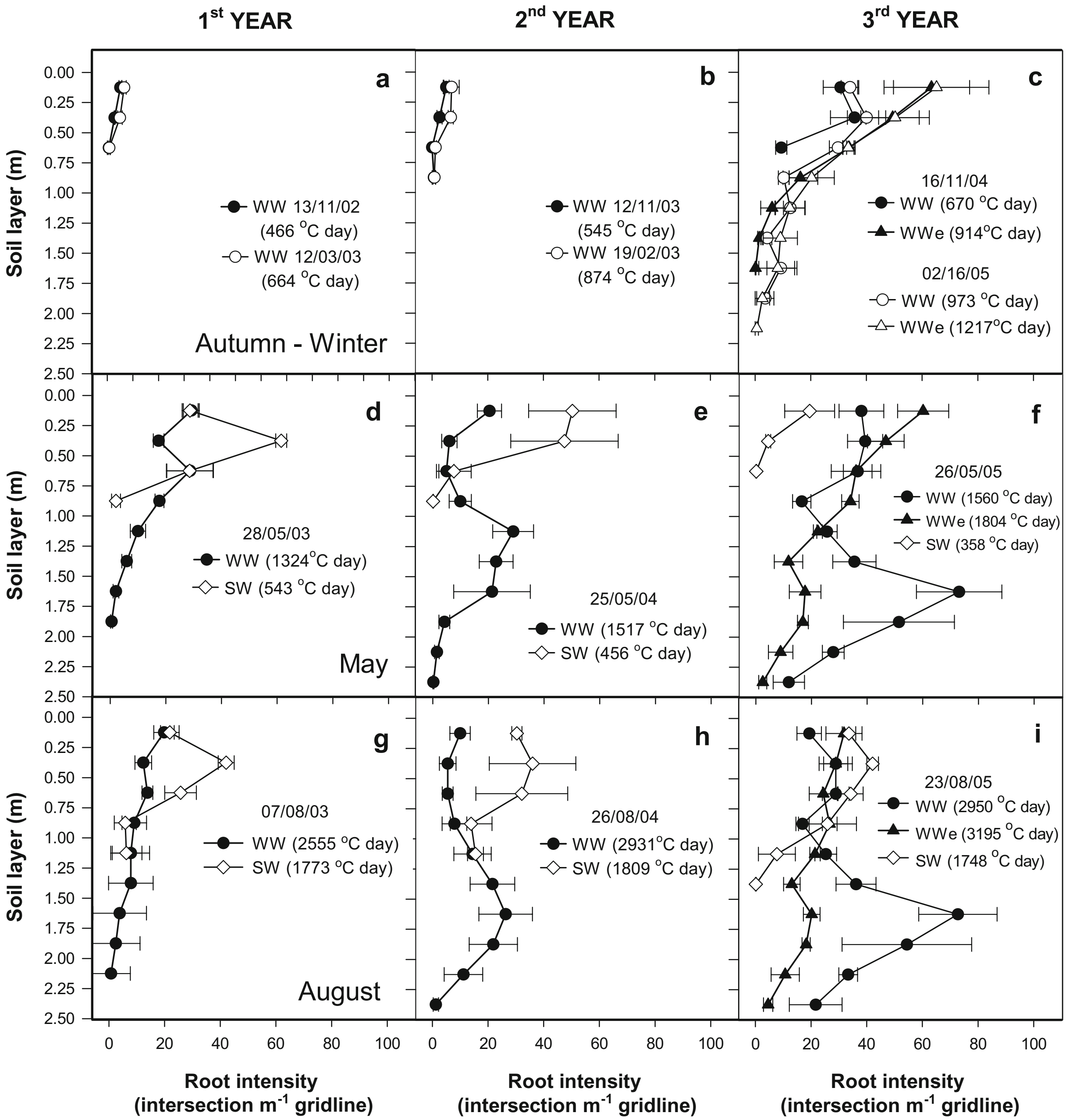

Fig. 3 Depth distribution of root intensity for winter wheat (*WW*), spring wheat (*SW*) and early sown winter wheat (*WWe*). Data from the 1st (**a**, **d**, and **g**) 2nd (**b**, **e** and **h**) and 3rd (**c**, **f** and **i** year) of the experiment are shown. Dates in the graphs indicate the moment of measurement, and the corresponding accumulated temperature sum from sowing day is shown between brackets for each treatment. Error bars represent standard error (n=3)

By the April measurement, reductions in the soil N_{inorg} were observed to 2.5 m under winter wheat compared to the bare soil plots where spring wheat had just been sown. The reductions were on average 50 and 81 kg N_{inorg} ha^{-1} in the 0–1 and 1–2.5 m layers, respectively. At harvest, no differences were found between spring wheat and winter wheat in the top 1 m, with a content of 40 kg N_{inorg} ha^{-1} for both wheat types. However, large differences were found in the 1–2.5 m layer, with on average 81 kg N_{inorg} ha^{-1} more after spring wheat alone than after winter wheat (Fig. 5 g, h, i and Table 3).

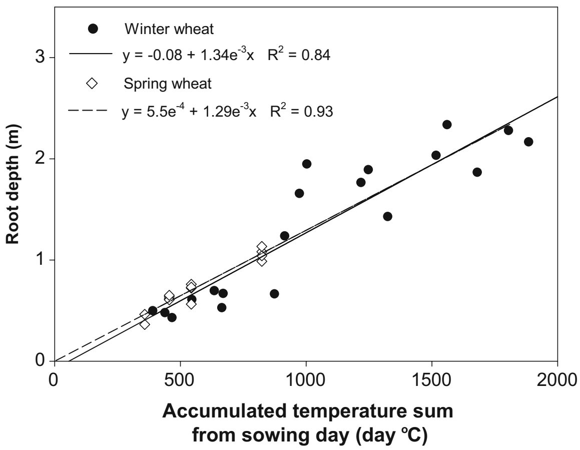

Fig. 4 Depth penetration by winter wheat and spring wheat vs. temperature sum. Data from the 3 years of the experiment are shown. ****P*<0.0001

When using catch crops, soil N_{inorg} in November was significantly lower than in the bare soil (Fig. 5 a, b, c and Table 3), reductions ranging from 156 to 318 kg N_{inorg} ha^{-1} among all the catch crops. The largest reductions in soil N_{inorg} were observed after fodder radish and turnip. Catch crops redistributed N_{inorg} in the soil in spring: Where catch crops had been ploughed in, increased N_{inorg} was seen in the top 0.5 m soil layer in spring, while N contents below 1 m continued to be consistently lower (56 to 110 kg N_{inorg} ha^{-1}) than in bare soil plots. However, at the time of wheat harvest, the differences in soil N_{inorg} in the top 1 m layer between the catch crop treatments and spring wheat alone observed in April had disappeared, but a large difference was still seen in the soil below 1 m.

When comparing the catch crop-spring wheat rotation with winter wheat, the winter wheat showed higher N_{inorg} below 1 m in autumn and spring, but at harvest no significant differences were observed. Only spring wheat after fodder radish in the first year led to significantly lower subsoil N_{inorg} at harvest than winter wheat.

Through the 3 years of experiment, large differences in N_{inorg} were observed in the subsoil, differences that were consistently significant for all years (Table 3). Clear effects were also seen in the topsoil, but only in the November and April measurements, when there was active plant growth on some plots but not on others. By August, when spring or winter wheat had been grown on all plots, there were no significant differences in the topsoil.

Wheat yield and N content

Winter wheat showed higher grain yields, aboveground biomass and N content than spring wheat grown without catch crops (Table 4), but no significant differences were observed in N concentration in grain. When using catch crops before spring wheat, all catch crops but rye had a positive effect on spring wheat grain yields, aboveground biomass and N, and grain N content, however these effects were not always significant (Table 4). Positive effects of catch crops on spring wheat grain yields ranged from 1 to 1.7 Mg ha^{-1}, without significant differences among the different catch crops.

In the 1st and 3rd year, catch crops increased grain yields of spring wheat, total aboveground biomass and N content to values as high as those of winter wheat or not significantly different (Table 4). On average for all years, brassica catch crops increased spring wheat yields with 1.3 Mg ha^{-1}, but these yields were still 1 Mg ha^{-1} lower than winter wheat yields.

Catch crop effect of N supply for the next crop (N_{eff}) was estimated based on soil N_{inorg} and on crop N measurements. N_{eff} calculated from spring wheat N uptake varied from 66 to −31 kg N ha^{-1}, whereas N_{eff} estimated by on soil N_{inorg} showed larger variation from 70 to −148 kg N ha^{-1} (Table 5). N_{eff} declined when deeper soil layers were included in the calculation, from on average 45 kg N ha^{-1} in the top 0.5 m to −83 kg N ha^{-1} when the full 2.5 m soil layer was considered. Crop based estimates of N_{eff} were most closely related to N_{eff} calculated to 1 m soil depth, and in all cases crop based N_{eff} was intermediate to soil based N_{eff} to 1 and 1.5 m (Table 5), whereas to N_{eff} calculated only to 0.5 m or to 2 or 2.5 m were not well related to crop based N_{eff}.

Discussion

Root differences in spring wheat and winter wheat

The pattern of rooting depth development vs. accumulated temperature followed what Kirkegaard and Lilley (2007) found, with a phase of linear development of rooting depth ending at around the time of

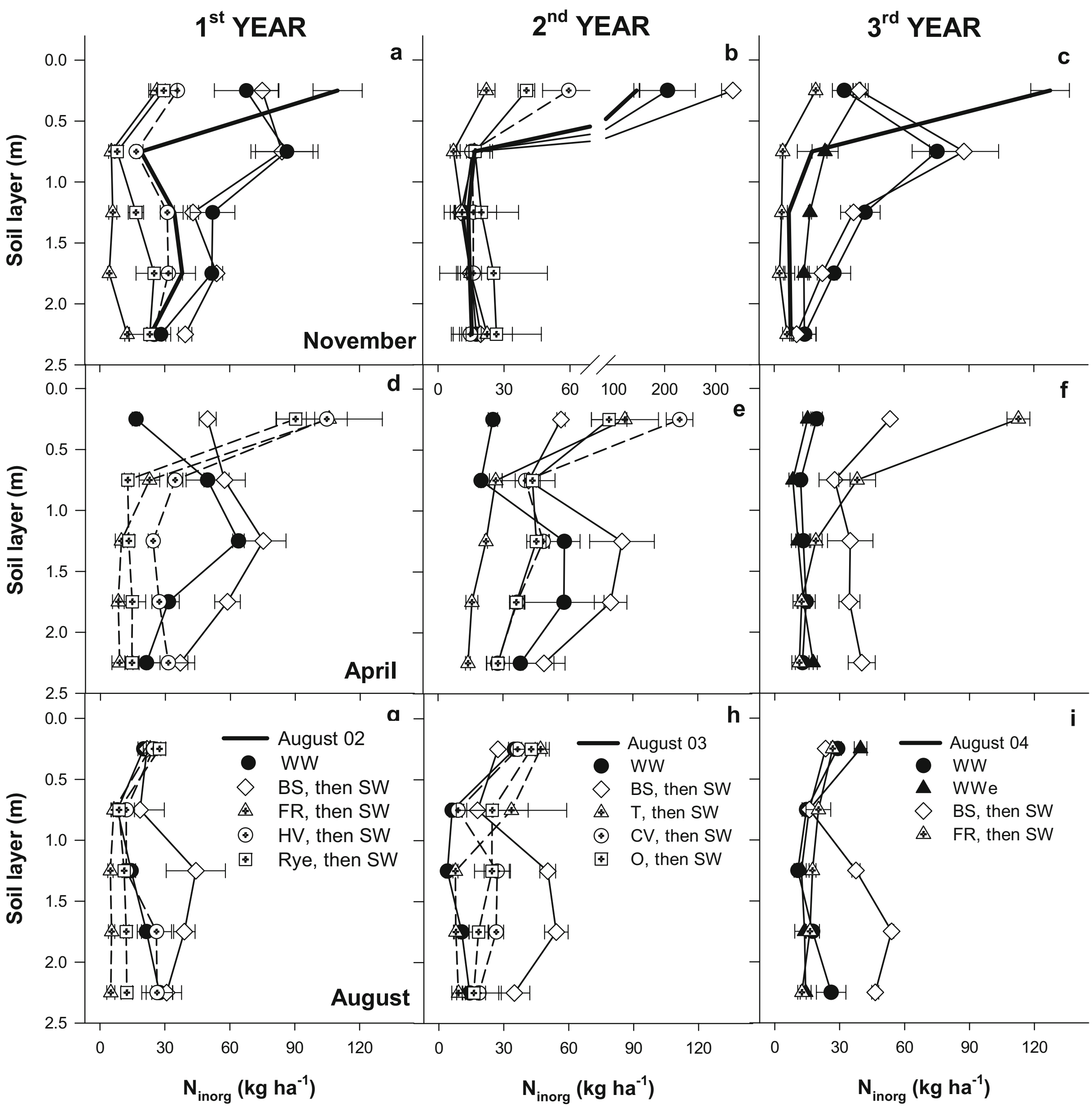

Fig. 5 Soil N_{inorg} content in November (**a**, **b** and **c**), in April (**d**, **e** and **f**), and in August after wheat harvest (**g**, **h** and **i**). Soil N_{inorg} at the start of the experiment in August, before catch crops where sown, is shown in the November measurement. Error bars indicate standard error (*n*=3). Abbreviations: WW, winter wheat; WWe, early sown winter wheat; SW, spring wheat; FR, fodder radish; HV, hairy vetch; T, turnip; CV, common vetch; O, oats; BS, bare soil

anthesis. We estimated root depth penetration rates of approximately 1.3 mm °C day^{-1} for both spring and winter wheat, close to some of the rates found by Kirkegaard and Lilley (2007) in kandosol soils, but higher than those found by Gregory and Eastham (1996) and Tennant (1976) on duplex sands over clay soils. Lower rates of rooting depth can be related to soil compaction (Dracup et al. 1992; Unger and Kaspar 1994) or not fully wetted soil profiles (Kirkegaard and Lilley 2007).

Winter wheat rooting depth at harvest was around 2 m, twice the depth we found for spring wheat. Similar depths of winter wheat have previously been shown (Gregory et al. 1978) whereas Kirkegaard and Lilley

Table 3 Available soil soil N_{inorg} (kg N_{inorg} ha^{-1}) measured in winter, before spring wheat sowing, and at harvest, averaged in 0–1 m layer and 1–2.5 m layer. Values followed by different letters are statistically different (P<0.05)

	Mid November				Before SW sowing				Harvest			
	0–1 m		1–2.5 m		0–1 m		1–2.5 m		0–1 m		1–2.5 m	
1st YEAR												
Winter wheat	154	ab	132	a	65		116	a	28		63	ab
Bare soil, then spring wheat	159	a	136	a	106		170	a	40		114	a
Fodder radish, then spring wheat	31	c	23	c	128		26	c	29		15	c
Common vetch, then spring wheat	52	b	87	ab	138		82	ab	36		64	ab
Rye, then spring wheat	37	bc	64	ab	102		42	bc	36		35	bc
Pr > F	0.0001		0.0002		0.0968		0.0003		NS		0.0008	
2nd YEAR												
Winter wheat	221	a	44		45	b	154	ab	40		28	b
Bare soil, then spring wheat	350	a	44		98	a	213	a	45		139	a
Turnip, then spring wheat	28	c	48		113	a	51	c	80		24	b
Hairy vetch, then spring wheat	74	b	46		152	a	112	b	49		83	ab
Oats, then spring wheat	56	b	71		122	a	109	b	67		58	b
Pr > F	<0.0001		NS		0.0004		0.0003		NS		0.0011	
3rd YEAR												
Early sown winter wheat	63	ab	44		31	c	40		55		46	b
Winter wheat	107	a	83		23	c	41		43		54	b
Bare soil, then spring wheat	127	a	69		80	b	109		39		138	a
Fodder radish, then spring wheat	24	b	16		150	a	42		46		46	b
Pr > F	0.0137		0.0089		<0.0001		0.0504		0.0982		0.0005	
Average between years												
Winter wheat	161		87		45		104		38		49	
Bares oil, then spring wheat	212		83		95		165		42		130	
Brassica CC, then spring wheat	29		29		131		40		52		29	
Leguminous CC, then spring wheat	64		67		146		98		43		74	

(2007) and Anderson et al. (1998a) found lower depths of around 1.6–1.8 m. Root depths of spring wheat were similar to those found by Kirkegaard and Lilley (2007). Rooting depth differences can depend on the rate of root depth penetration and the accumulated temperature up to the time of anthesis. In this way, we found lower rooting depth of winter wheat in the 1st year than in the 2nd and 3rd year (1.9 m vs. 2.3 m) and this is partially explained by the lower accumulated temperature in the first year at the time of heading (1618 vs. 1780°C day^{-1}). This difference in accumulated temperature corresponds to a difference of 0.24 m in rooting depth. The deeper rooting of winter wheat than of spring wheat also relates to the much higher accumulated temperature available for winter wheat development before anthesis, and this is in agreement with the results of Kirkegaard and Lilley (2007), who also found that the duration of growth was important for determining final rooting depth of wheat.

The finding that wheat had its highest root intensity in the upper soil layers during early growth but at later stages often showed higher intensity in deeper soil layers may be related to soil N distribution. A hypothesis to explain this is the high wheat root densities found by some authors in soil layers where N had been available earlier in the season (Belford et al. 1987, Diggle and Bowden 1990, Gao et al. 1998). Precipitation was high in our experiment in the second and third winter, moving large amounts of N to between 1 and 2.5 m depth, and this was associated with higher root intensities below 1 m soil depth later in the season. Our results indicate that the winter wheat root system has the ability to respond to high soil N availability in soil layers down to 2 m.

Early sown winter wheat in our experiment allowed a deeper root penetration before winter. This advantage of early sown wheat was reported by Barraclough and Leigh (1984) as well. Also winter

Table 4 Grain yield, dry matter, % N in grain, grain N content and total aboveground N content for every treatment and experimental year. Values followed by different letters are statistically different (P<0.05)

	Grain yield (Mg ha^{-1})		Dry matter (Mg ha^{-1})		% N grain		Grain N content (kg ha^{-1})		Plant N content (kg ha^{-1})	
1st YEAR										
Winter wheat	4.9	a	8.0	a	1.8		87	a	97	a
Bare soil, then spring wheat	3.5	ab	6.8	ab	1.9		66	ab	74	b
Fodder radish, then spring wheat	4.8	a	9.6	a	1.7		79	a	90	a
Common vetch, then spring wheat	4.7	a	9.2	a	1.8		85	a	99	a
Rye, then spring wheat	2.3	b	4.5	b	1.6		37	b	42	b
Pr>F	0.0012		<0.0001		NS		0.0168		<0.0001	
2nd YEAR										
Winter wheat	5.0	a	9.3	a	1.8		89	a	126	a
Bare soil, then spring wheat	2.6	b	5.0	b	2.0		52	b	74	a
Turnip, then spring wheat	3.4	b	6.7	ab	1.8		61	ab	83	a
Hairy vetch, then spring wheat	3.6	b	7.1	ab	1.8		67	ab	93	a
Oats, then spring wheat	3.4	b	6.8	ab	1.9		64	ab	94	a
Pr>F	0.0027		0.0017		NS		0.0556		0.0993	
3rd YEAR										
Early sown, winter wheat	6.9	a	12.4	a	1.3	b	90	ab	107	a
Winter wheat	6.8	a	12.2	a	1.3	b	86	ab	104	a
Bare soil, then spring wheat	3.9	b	6.6	b	1.4	b	57	b	66	b
Fodder radish, then spring wheat	5.6	ab	9.5	ab	1.8	a	99	a	118	a
Pr>F	0.003		0.0009		0.001		0.0254		<0.0001	
AVERAGE										
Winter wheat	5.6		9.8		1.6		88		109	
Bare soil, then spring wheat	3.3		6.1		1.8		59		71	
Brassica CC, then spring wheat	4.6		8.6		1.8		80		97	

wheat sown in September in the third year showed a deeper development in the spring measurement compared to the other years, which was related to the higher temperatures during the autumn of 2004. Our estimated root penetration rate can be used for predicting wheat root depths. For instance, it can be estimated that wheat roots will penetrate to 1 m depth after around 800 ^{o}C day. Therefore, for average temperatures (Danish weather data from 1960 to 1990), winter wheat sown during early September will not penetrate to 1 m depth until early March, whereas winter wheat sown in August allows accumulation of 800 ^{o}C day before the onset of winter.

Soil N depletion

Because of its deep rooting winter wheat proved almost as efficient as the combination of catch crops and spring wheat for reducing subsoil N content. Deep soil N depletion by catch crops during autumn and winter has previously been reported (Thorup-Kristensen 2006), but not much information about N content below 1 m is available for winter wheat. Often shallow soil samplings have been used in winter wheat studies (Baeckstöm et al. 2006; Karlen et al. 1996; Smith et al. 1998; Watson et al. 1993) assuming little activity of wheat roots below 1 m depth, and therefore, N below this depth is often considered lost. Our results show that this may lead to misleading conclusions.

In November, winter wheat had not depleted much N compared to bare soil. Large amounts of N subsequently moved to below 1 m under winter wheat as well as in bare soil plots, the extent of movement depending on surplus precipitation for each year. Addiscott and Darby (1991) also observed a movement of N down the soil profile, depending on the drainage up to that date. Similar soil N profiles to ours were found by Kuhlman et al. (1989) and Watson et al (1993) in winter wheat, with most N moved below 1 m. However, at harvest, deep roots of winter wheat had depleted most of this N, whereas large amounts of N were left after spring wheat. Other studies indicate similar results after spring wheat (Campbell 2006a, b), but when spring wheat crop was replaced by a autumn seeded rye crop, there was hardly any N leached (Campbell 2006b), supporting our findings with winter wheat.

When growing spring wheat after catch crops, great reductions in the subsoil N content were observed compared to spring wheat alone at all measurement dates, showing reduced N leaching risks during the whole growing season. Studies on catch crops preceding spring barley have also shown significant reductions of nitrate leaching (Thomsen et al. 1993). Furthermore, when spring wheat was grown after catch crops in the present study, more N was available to the crop in the topsoil in the early spring, due to N mineralization from the catch crop biomass incorporated into the uppermost soil layers.

The significant activity of winter wheat roots we found in the subsoil agrees with other findings that report significant water absorption at 1.5 m and below by winter wheat (Sauer et al. 2002). Also Kuhlman et al. (1989) observed that 39% of the total amount of N taken up by winter wheat from tillering to maturity came from the 0.9–1.5 m layer. However, no N uptake was found in the 1.5 to 2 m layer by Kuhlman et al. (1989), probably because the crop reached this soil depth too late in the season. Anderson et al (1998b) observed that large quantities of nitrate remained below 1.2 m depth at winter wheat harvest. The inability of wheat to extract this N resource could be related to the high initial N content and to the poor grain yields obtained in their experiment (1.6 to 2.4 Mg ha^{-1}) (Anderson et al. 1998a).

The low root intensities we found below 1 m in the 1st year and by early sown winter wheat in the 3rd year proved high enough to deplete N form the subsoil. Also Kuhlman et al. (1989) observed significant amounts of N depleted from the subsoil, though low root intensities were found in the 1.2 to 1.5 layer. Other studies have shown that the capacity of crops to take up N at depth is based primarily on the inherent rooting depth of species rather than on different root density in the profile (Kristensen and Thorup-Kristensen 2004; Thorup-Kristensen 2001). Also Robinson (1996) found that low root densities can still be sufficient for depleting soil N content to low levels and that the proliferation of roots often seen in N rich soil layers does not seem necessary for depleting locally available nitrate.

The comparison between winter wheat and spring wheat preceded by catch crops will depend on soil and weather conditions. The extent of N leaching during autumn and winter depends on soil water holding capacity and precipitation. In the present study leaching moved N to deep soil layers, but much of it was still available to the deep roots of winter wheat during its main growing season. However, on more sandy soils, or with higher precipitation N will leach to larger depths in the soil, and much of it can leach to below the root depth of winter wheat. Under such circumstances, growing spring wheat after catch crops should be the better environmental solution.

In fertilized conventional systems, different results should be expected as well, as wheat plants would have higher N availability in the top soil, and this might affect root activity and the final depth distribution of residual soil N. Robinson et al (1994) found that plants did not respond to localized N supplies in spite of high root densities when excess N status was present in the plant. Anderson et al (1998b) found in field studies that winter wheat with high initial N content was unable to take up much N from below 1.2 m, despite root growth to 1.7 m depth. Also Kuhlmann et al (1989) showed greater subsoil N depletion in unfertilized wheat from the 1.2 to 1.5 m layer than in fertilized winter wheat. Lower nitrogen use efficiencies (14% lower) have been documented in both spring and winter wheat conventional systems when compared to organic systems (Baeckström et al. 2006). But little is known about subsoil N distribution under conventionally fertilized winter wheat. Studies of N dynamics in deep soil layers in conventional systems could be relevant for improved understanding of how to utilize N available deep in the soil, in order to increase N use efficiency in conventional wheat production.

Wheat grain yield

Winter wheat grain yields were on average 2.2 Mg ha^{-1} higher than those of spring wheat, but spring wheat yields were in most cases increased when grown after catch crops. These positive effects of catch crops have also been found by others with leguminous catch crops (Breland 1996) and ryegrass catch crops (Hansen et al. 2000). Other experiments with ryegrass found reduced barley yields (Andersen and Olsen 1993; Thomsen and Christensen 1999). In our experiment positive or negative effects of catch crops on spring wheat yield and N uptake were related to effects of catch crops on N supply (N_{eff}) to between 1 and 1.5 m soil depth (Table 5), depths corresponding well to the estimated rooting depth of the spring wheat crop. Turnip, fodder radish, oats and the vetch catch crops ploughed under in early spring had increased N content in this layer due to N mineralization by the April measurement. However, the rye catch crop led to a negative N_{eff} whether measured to 1 or 1.5 m soil depth, and correspondingly reduced spring wheat yield and N uptake. The results point to the importance of considering the rooting depth of the succeeding crop when calculating catch crop N effects, as has previously been pointed out (Thorup-Kristensen et al. 2003).

The yield relationships between the winter wheat, spring wheat and spring wheat after catch crops varied among years. Winter wheat generally gave the highest yields, and catch crops generally increased spring wheat yields, except for winter rye in the 1st year. The year to year differences were not consistent with variations in winter season precipitation and indicate that other factors such as water availability may have been important as well. In general, spring wheat yields following catch crops can be expected to be closer to those of winter wheat when winter season precipitation is very high.

Importance of subsoil N dynamics

Deep soil measurements in this experiment were crucial for comparing the different treatments, as the large differences in subsoil N among the treatments would have not been observed when measuring up to 1 m. The need of deep soil measurements when studying catch crops effects has previously been reported (Kristensen and Thorup-Kristensen (2004). Different and wrong conclusions would have been obtained if we had only studied soil N dynamics to 1 m depth as is often done. Important differences among catch crops in the autumn and among spring wheat and winter wheat at harvest would have been overlooked. At the time of wheat harvest no significant differences where observed among any of the treatments in the 0 to 1 m soil layer, but highly significant differences were observed in the 1 to 2.5 m layer, differences which are important for understanding the N dynamics of these wheat cropping systems.

Other studies including deep soil samplings in spring wheat support our findings, with differences between treatments highlighted in the 1.2–1.3 to 2.4–2.5 m soil layer (Campbell et al. 2006a, b), whereas studies up to 0.9 m with winter wheat and spring wheat did not show differences between the two crops (Baeckstöm et al. 2006). Also deeper soil measurements before sowing in studies of N recommendations in wheat often relate better to winter grain yields than shallower ones (Addiscott and Darby 1991; Bundy and Andraski 2004; Olson et al. 1976). Understanding the availability of N from deep soil layers will be especially important in organic farming systems or other production systems with limited N

Table 5 Catch crop N effect (N_{eff}) on soil accumulated N content up to different depths in spring and on aboveground plant N content at harvest (kg N ha^{-1}), calculated as the difference between the catch crop treatments and the spring wheat only

	Catch crop effect (kg N ha^{-1})					
FIRST YEAR	**0–0.5 m**	**0–1 m**	**0–1.5 m**	**0–2 m**	**0–2.5 m**	**Plant N content**
Fodder radish	56	21	-44	-95	-123	16
Common vetch	55	32	-19	-50	-56	26
Rye	41	-4	-66	-110	-133	-31
SECOND YEAR						
Turnip	30	14	-48	-113	-148	9
Hairy vetch	55	53	17	-26	-47	19
Oats	22	24	-16	-59	-80	20
THIRD YEAR						
Fodder radish	59	70	54	32	3	66
AVERAGE	45	30	-17	-60	-83	18

input, as possible utilization of N from below 1 m will be more important for successful crop growth than in highly fertilized systems.

Significant N absorption from the subsoil by winter wheat can be the reason why changes in soil N often do not consistently match increases in crop N when considering soil samplings of 1 m or above (Baggs et al. 2000). Different mineral N content in the top 1 m soil layer at harvest (38 kg and 42 kg N /ha for winter wheat and spring wheat, respectively), could not explain the different average N uptake by the wheat crops in our experiment (109 and 71 kg N/ha for winter wheat and spring wheat, respectively). Also Sauer et al (2002) concluded in a winter wheat study that it was not possible to predict potential groundwater pollution on the basis of the mineral N content in the first meter of the soil profile. Differences in plant N content at harvest did not consistently match differences in the N content in the 0 to 2.5 m layer in our experiment; generally the differences in soil N were larger than differences in crop N content. This was maybe due to the effects of wheat on N contained in the soil organic pools, through root N, root exudates and litter loss. However, it was the large differences in N content observed in the deep soil layers that made it possible to compare the N leaching potential between the different treatments.

Conclusions

Our results show that winter wheat has much deeper rooting than spring wheat, allowing it during spring and summer to take up N that was leached to below 1 m during the autumn and winter period. Therefore, winter wheat proved to be more efficient in using soil N than normally assumed due to its limited growth and N uptake during autumn. The use of catch crops when growing spring wheat proved a successful way to reduce N leaching, while also increasing N availability for the spring wheat. The comparison between winter wheat and spring wheat with or without catch crops depends on the extent of N leaching. Under conditions with more extensive N leaching growing spring wheat after catch crops is expected to be a better system for minimizing nitrate leaching than winter wheat. Under such conditions more N will leach too deep into the soil even for winter wheat roots, and the ability of catch crops to take up much soil N already in the autumn and retain it during winter will become more important.

Grain yields of winter wheat were higher than yields of spring wheat grown without winter catch crops, but catch crops grown before spring wheat were able to increase spring wheat grain yields almost to the yield level of winter wheat due to higher N availability in spring.

The large differences observed in the subsoil N content in this experiment showed that it is crucial that root and soil N measurements are extended to well below 1 m to understand N dynamics in the wheat cropping systems studied.

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