Soil nitrogen depletion by vegetable crops with variable root growth

Thorup-Kristensen, Kristian; Sørensen, Jørn Nygaard

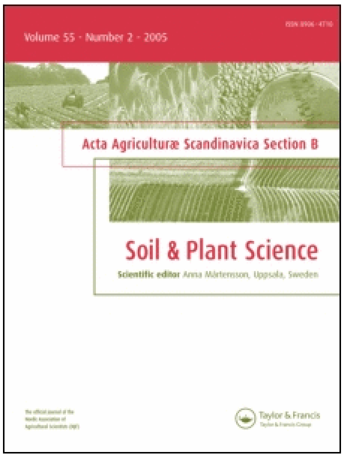
Published in:
Acta Agriculturae Scandinavica - Section B

DOI:
10.1080/09064719950135597

Publication date:
1999

Document version
Early version, also known as pre-print

Citation for published version (APA):
Thorup-Kristensen, K., & Sørensen, J. N. (1999). Soil nitrogen depletion by vegetable crops with variable root growth. *Acta Agriculturae Scandinavica - Section B*, *49*(2), 92-97. https://doi.org/10.1080/09064719950135597



Acta Agriculturae Scandinavica, Section B - Plant Soil Science
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713394126

Soil Nitrogen Depletion by Vegetable Crops with Variable Root Growth

Kristian Thorup-Kristensen; Jørn Nygaard Sørensen

Online Publication Date: 26 November 1999

To cite this Article Thorup-Kristensen, Kristian and Sørensen, Jørn Nygaard(1999)'Soil Nitrogen Depletion by Vegetable Crops with Variable Root Growth',Acta Agriculturae Scandinavica, Section B - Plant Soil Science,49:2,92 — 97

To link to this Article: DOI: 10.1080/09064719950135597

URL: http://dx.doi.org/10.1080/09064719950135597

Acta Agric. Scand., Sect. B, Soil and Plant Sci. 1999: 49, 92–97

ACTA AGRICULTURÆ
SCANDINAVICA
ISSN 0906–4710

Soil Nitrogen Depletion by Vegetable Crops with Variable Root Growth

Thorup-Kristensen, K. and Sørensen, J. N. (Danish Institute of Agricultural Science, Department of Fruit, Vegetable and Food Science, P.O. Box 102, DK-5792 Aarslev, Denmark). Soil nitrogen depletion by vegetable crops with variable root growth. Accepted June 11, 1999 Acta Agric. Scand., Sect. B, Soil and Plant Sci. 49: 92–97, 1999. © 1999 Scandinavian University Press.

The ability of carrot, leek and white cabbage to deplete the soil inorganic nitrogen (N) pool was studied. All three crops are late-harvested crops with a long growing season, but they have been found to have very different root growth. At their optimal N supply, carrot left 27 kg nitrate-N ha^{-1} in the top 100 cm of the soil, leek left 87 kg N ha^{-1} and white cabbage left only 11 kg N ha^{-1}, in accordance with previously published differences in rooting depth among the three crops. Compared at a supply of 160 kg N ha^{-1}, 52, 65 and 4 kg nitrate-N ha^{-1} was left in the soil by carrot, leek and white cabbage respectively. Apart from an extensive root system, white cabbage also had a much higher N-uptake capacity than the two other crops. The significance of differences in root growth, N-uptake capacity and other factors in determining the ability of the three crops to deplete the soil inorganic N pool is discussed.

Kristian Thorup-Kristensen and Jørn Nygaard Sørensen
Department of Fruit, Vegetable and Food Science, Danish Institute of Agricultural Science, P.O. Box 102, DK-5792 Aarslev, Denmark

Key words: carrot, leek, nitrate leaching, nitrogen uptake, rooting depth, white cabbage.

Introduction

The nitrate which is lost by leaching after vegetable cropping originates from unused nitrogen (N) left in the soil by the crop and from N mineralized from soil organic matter and from crop residues after harvest (Macdonald et al., 1989). To achieve a high N use efficiency and low losses to the environment, it is important to add only as much N as is needed for optimal crop yield.

Minimizing the N supply to the crop will reduce the amount of N left in the soil at harvest. One of the methods used for this purpose is the N_{min} method (Wehrmann et al., 1988; Sørensen, 1993). With this method, soil is sampled before establishment of the vegetable crop or early during its growth, and analysed for its content of inorganic N (ammonium-N and nitrate-N). By correcting the amount of N added as fertilizer for the amount of inorganic N in the soil, an attempt is made to add only what is needed by the crop.

Even when crops are supplied only with the amount of N needed for optimal yield, they will leave some inorganic N in the soil at harvest (Macdonald et al., 1989). In experiments with N catch crops, differences in the ability of various plant species to deplete the inorganic N pool of the soil have been found to be closely related to differences in root growth (Thorup-Kristensen, 1993a; Grindlay, 1995). In addition, among vegetable crops, large differences in rooting depth are found (Burns, 1980; Greenwood et al., 1982; Smit et al., 1996).

As carrot, leek and white cabbage all have a long growing season, they should all have the potential to produce a high biomass, take up much N and deplete the soil efficiently, but they are reported to have very different root growth. Brassica crops rapidly produce an extensive and deep rooting system (Burns, 1980; Greenwood et al., 1982; Smit et al., 1996; Thorup-Kristensen & Van den Boogaard, 1998). Leek and other allium crops have shallow root systems (Burns, 1980; Greenwood et al., 1982; Smit et al., 1996). Carrot seems to have an intermediate rooting depth compared with the two other crops (Thorup-Kristensen & Van den Boogaard, 1999).

Using data from an experiment with N supply for vegetable crops, the aim of this study was to analyse the ability of leek, carrot and white cabbage to deplete the soil inorganic N pool at harvest, at well-defined levels of N supply. The significance of differences in root growth and other characters of the crops is discussed. Other results from the experiment have been published by Sørensen (1993).

Materials and methods

During 3 years, 1988–1990, carrots (*Daucus carota* L.), leeks (*Allium porrum* L.) and, in 1988–1989, white cabbages [*Brassica oleracea* L. convar. *capitata* (L.) Alef. var. alba DC.] were sown at the end of April. Each year the vegetable crops followed either barley (*Hordeum vulgare* L.) or white cabbage as previous crops.

The plant density of leeks, cabbages and carrots was 50, 4 and 110 plants m^{-2}, respectively. The row distance was 50 cm. The plants were irrigated and sprayed against pests when necessary.

Each vegetable crop was grown at four rates of N supply. Fertilizer N was applied twice. The first N application, just after emergence, was based on the content of soil inorganic N before sowing, measured in four layers of 25 cm each. Nitrate-N and ammonium-N were determined colorimetrically according to slightly modified methods of Best (1976) and Crooke & Simpson (1971), respectively.

The fertilization of leek and carrots was based on soil inorganic N content in the 0–25 cm layer, whereas for white cabbage the 0–50 cm soil layer was used. At the first fertilization, N was applied to bring the soil content up to half the final supply (Table 1). The second application was made after approximately 8 weeks, at the four-leaf stage for leeks and the five-leaf stage for carrots using the 0–50 cm soil layer inorganic N content for both crops. For white cabbage it was made at the 12-leaf stage using the 0–100 cm soil layer inorganic N content. Fertilizer N was added according to the total supply as specified in Table 1. At harvest, soil was sampled and analysed for its content of inorganic N in four layers of 25 cm each.

Table 1. Rates of total nitrogen supply during growth of vegetable crops

	Total nitrogen supply (kg N ha^{-1})			
	N1	N2	N3	N4
Leek	100	160	220	280
Cabbage	160	240	320	400
Carrot	60	100	140	180

The total N supply includes both soil inorganic and applied fertilizer nitrogen.

Leeks and carrots were harvested at the beginning of October and the plant production from 6 m^2 was determined. White cabbage was harvested at the end of October from an area of 8 m^2. The total dry matter (DM) production was recorded and analysed for total N (AOAC, 1984).

The N treatments were arranged in randomized complete block designs with four replicates. The experiment was conducted on a sandy loam soil. Statistical analysis was carried out on data averaged after each previous crop within each year, thus $n = 6$ for leek and carrot (3 years and two previous crops) and $n = 4$ for white cabbage (2 years and two previous crops). Data were analysed using the SAS statistical package (SAS, 1990).

Results

The N supply that was found to give the optimal saleable yield was estimated as 60, 220 and 320 kg N ha^{-1} for carrot, leek and white cabbage, respectively (Sørensen, 1993). At the optimal N supply, white cabbage took up 350 kg N ha^{-1}, approximately twice as much as each of the two other crops at their optimal N supply. This difference in N uptake among the three crops was due to a combination of high DM production and high N concentration in the DM of white cabbage (Table 2). Carrot had a similar DM production, but a much lower N content, whereas leek had a high N concentration combined with a low DM production. The low total N concentration in carrot DM was due to the fact that a high proportion of the carrot DM, more than 80%, was found in the roots which had a very low N content (Table 3). Very little DM was found in the top, which had N concentrations comparable to those of the two other crops.

When the crops were compared at a fixed supply of 160 kg N ha^{-1}, the differences in N uptake were much smaller. At this supply, carrot took up almost as much N as white cabbage, but leek still took up less than the two other crops.

Both carrots and leeks showed a lower response in N uptake than did white cabbage. Further, they showed a sharp increase in the amount of nitrate-N left in the soil when the N supply was increased from the third to the fourth level of N supply (Fig. 1), at a level of N supply where white cabbage left very little residual N in the soil.

The amount of nitrate-N left in the top 100 cm of the soil was very different among the three vegetable crops, but after all three the amount left increased with increasing N supply (Fig. 1). White cabbage left

Table 2. Dry matter production (above-ground plant parts plus carrot storage root) and N concentration in the crop dry matter at harvest

	Leek		Cabbage		Carrot	
	DM (t ha^{-1})	% N in DM	DM (t ha^{-1})	% N in DM	DM (t ha^{-1})	% N in DM
N1	6.2	1.5	13.3	1.7	15.1	1.06
N2	7.2	1.9	14.7	2.0	14.8	1.13
N3	7.5	2.2	16.0	2.2	15.4	1.24
N4	7.5	2.4	16.0	2.4	15.3	1.34
$LSD_{0.05}$	0.7**	0.3***	0.7**	0.3*	1.6^{ns}	0.16*

*** $P<0.001$; ** $P<0.01$; * $P<0.05$; ^{ns} Not significant.

very little nitrate-N in the soil, from 4 kg N ha^{-1} at the lowest N supply of 160 kg N ha^{-1} rising to only 11 kg N ha^{-1} at an optimal supply of 320 kg N ha^{-1}. Carrot had an optimal supply of only 60 kg N ha^{-1}, but still it left 27 kg nitrate-N ha^{-1} at this very low supply, rising to 67 kg N ha^{-1} at the maximum supply of 180 kg N ha^{-1}. Leek left most nitrate-N in the soil, leaving 50 kg N ha^{-1} even when the supply was only 100 kg N ha^{-1}, well below the optimal supply. At the estimated optimal supply of 220 kg N ha^{-1} it left 87 kg N ha^{-1}, rising to 122 kg nitrate-N ha^{-1}, at the maximum supply of 280 kg N ha^{-1}.

Compared at the estimated optimal N supply, it is clear that the amount of N left in the soil after the three crops was not related to the estimated optimal N supply (Fig. 1a). White cabbage, with the highest N supply (320 kg N ha^{-1}), left the lowest amount of nitrate-N in the soil with only 11 kg nitrate-N ha^{-1}. Carrot, with an estimated optimal N supply of only 60 kg N ha^{-1}, left approximately 25 kg N ha^{-1} even at this very low supply, and leek, which had an intermediate optimal N supply, left 87 kg N ha^{-1}.

Comparing the ability of the crops to take up N and deplete the soil at their optimal N supply is of practical relevance. Still, optimal N supply, defined as the N supply leading to the highest production of what is considered saleable products, is not a biologically meaningful term. Comparing the N residues left by the three crops at a similar N supply of 160 kg N ha^{-1} shows how efficient they are at depleting the soil of a fixed amount of N. Compared in this way, the high efficiency of white cabbage is even more striking, as white cabbage, carrot and leek left 4, 52 and 65 kg nitrate-N ha^{-1} respectively (Fig. 1b). The figures for carrot were calculated as the average between crops receiving an N supply of 140 and 180 kg N ha^{-1}.

The depth distribution of the N left in the soil also varied strongly among the three crops (Fig. 2). Under white cabbage the subsoil was very efficiently depleted, and most of the small amounts found were found in the upper soil layers. After leek, the lowest amounts of nitrate-N were found in the top 25 cm of the soil, with high contents in the three deeper soil layers measured. Carrots left some nitrate-N in all soil layers. Compared at the optimal N supply or at a fixed N supply of 160 kg N ha^{-1} (Fig. 3), the ability of carrot and leek to deplete the top 25 cm soil layer was not very different, but carrot depleted the soil layers below 25 cm more efficiently than leek.

Discussion

There were very significant differences in the ability of the three crops to take up N and deplete the soil inorganic N pool. White cabbage was best at depleting soil nitrate-N, followed by carrot and leek as the least efficient crop. The differences were even clearer when the ability of the crops to deplete subsoil layers was compared. This result is in accordance with the rooting depth of the three crops (Burns, 1980; Greenwood et al., 1982; Smit et al., 1996; Thorup-Kristensen & Van den Boogaard, 1998, 1999). The results thus support the hypothesis that the existing differences in rooting depth are significant for the ability of different crop species to utilize soil-available N reserves from deeper soil layers.

However, other factors than root distribution in the soil profile seem to be of importance. The observed difference in depletion efficiency between white

Table 3. Root and top dry matter production, N content and N concentration of carrots at harvest

	Root	Top	Root	Top	Root	Top
	(t DM ha^{-1})		(kg N ha^{-1})		(% N in DM)	
N1	13.2	1.8	131	29	0.99	1.57
N2	12.9	1.9	134	33	1.04	1.69
N3	13.3	2.1	153	37	1.16	1.74
N4	13.1	2.1	165	39	1.26	1.82
$LSD_{0.05}$	1.3^{ns}	0.5^{ns}	18*	8*	0.17*	0.09*

*** $P<0.001$; ** $P<0.01$; * $P<0.05$; ^{ns} Not significant.

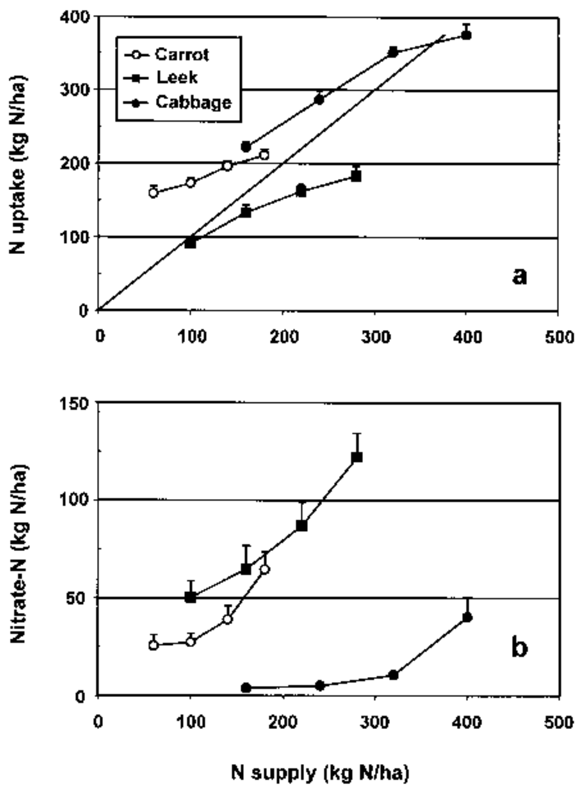


Fig. 1. Effect of N supply on (a) N uptake by the three crops and (b) the amount of nitrate-N left in the soil at harvest. Bars show SE ($n = 6$ for carrot and leek, $n = 4$ for white cabbage).

cabbage and carrot is surprisingly large. Although the rate of depth penetration of the carrot root system is slower, and carrot is less efficient than brassica crops in spreading its roots into the interrow soil (Thorup-Kristensen & Van den Boogaard, 1999), carrots develop a deep root system during their long growing season. This should make them able to deplete the top metre of the soil profile almost as efficiently as white cabbage. Previous results have shown that carrots can deplete soil inorganic N reserves to very low levels, but also that this occurs only at a quite low total N supply (Thorup-Kristensen, 1993b; Thorup-Kristensen & Van den Boogaard, 1999).

To deplete the soil inorganic N pool, a crop needs to have a sufficiently high N-uptake capacity, as well as a root system that is well distributed in the soil and brings the crop into contact with as much soil N as possible. When the amount of available N is close to the uptake capacity of the plants, it has been found that plants respond by reducing the N-uptake rates of the root system (Robinson et al., 1994). Thus, at high N supply they will leave N in the soil even if they have enough roots to deplete the soil. This is supported by the results of Engels et al. (1992), who found that the adverse effect of low root-zone temperatures on nutrient uptake was strongly dependent on shoot demand. If shoot demand was kept high, the effect of low root-zone temperature on nutrient uptake was of a very short duration; apparently, the roots adapted to the low temperature conditions to be able to meet the shoot demand of nutrients.

Thus, the N-uptake efficiency of the root system can be strongly dependent on the shoot demand for N, and it cannot be concluded from a high amount of inorganic N left in the soil that its root system was insufficient for depleting the soil. The difference in N-uptake capacity between the two crops may ex-

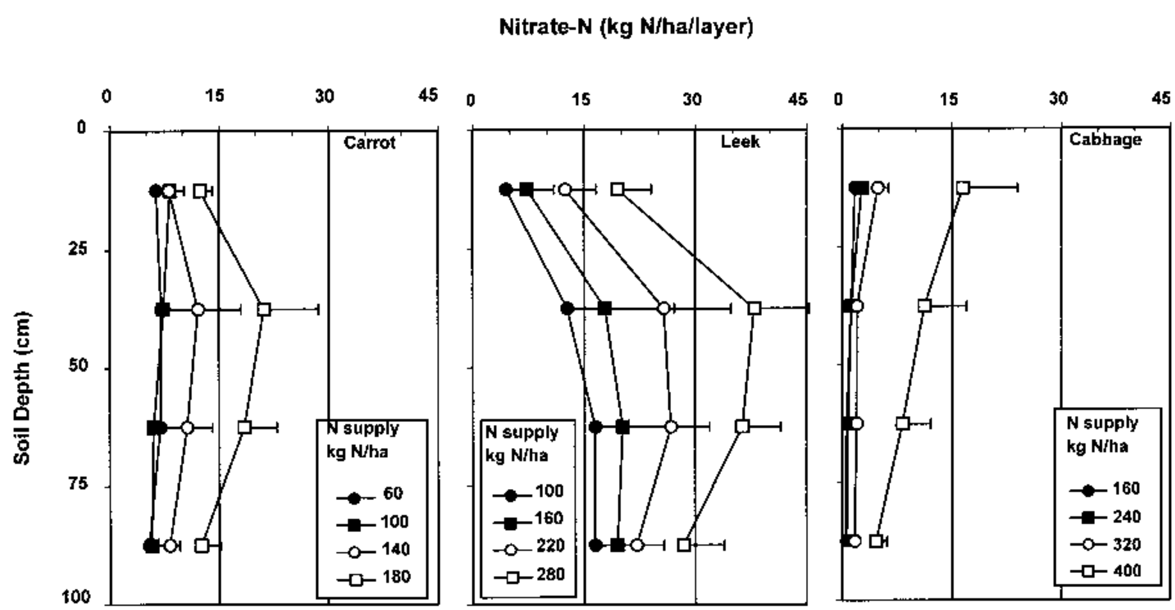


Fig. 2. Depth distribution of nitrate-N left in the soil at harvest of vegetables at variable N supply. Bars show SE ($n = 6$ for carrot and leek, $n = 4$ for white cabbage).

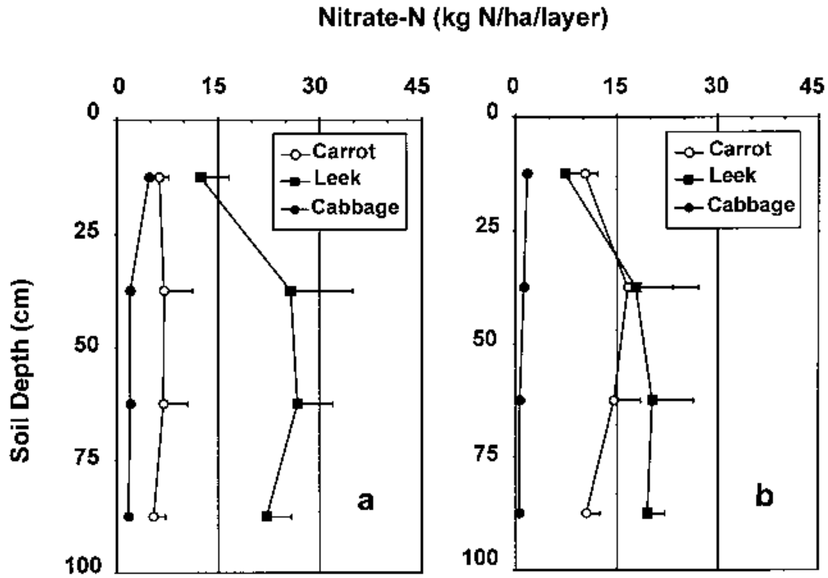


Fig. 3. Depth distribution of nitrate-N left in the soil at harvest of vegetables, compared at (a) an optimal N supply for each crop, or (b) a fixed N supply of 160 kg N ha^{-1}. For carrot the values at 160 kg N ha^{-1} were obtained as the average of the values at 140 and 180 kg N ha^{-1}, respectively. Bars show SE ($n = 6$ for carrot and leek, $n = 4$ for white cabbage).

plain why white cabbage was so much more efficient than carrot in depleting the soil. This difference in uptake capacity, where carrot takes up much less N at the same biomass production than white cabbage, can also be seen from other experiments. Carrots normally have a maximum N uptake of around 200 kg N ha^{-1} (Greenwood et al., 1980; Thorup-Kristensen, 1993b; Thorup-Kristensen & Van den Boogaard, 1999), much lower than the values to 400 kg N ha^{-1} found here with white cabbage.

The reason for the large difference in uptake capacity between carrot and white cabbage could be that carrot stores most of its biomass in the storage root, while white cabbage stores most of its biomass in the leaves (Table 3). Root material normally has lower N concentrations than leaves and above-ground plant material (Greenwood et al., 1980; Jensen, 1991), as also found in the present carrot crops (Table 3). Accordingly, it can be calculated from the data of Greenwood et al. (1980) that crops where the root material is harvested (sugar beet, red beet, radish, swede, turnip, carrot and parsnip) had much lower optimum N fertilizer rates (average 103 kg N ha^{-1}) than species grown for leaf production (leek, spinach, lettuce, Brussels sprouts, summer cabbage and winter cabbage), with average optimum N rates of 223 kg N ha^{-1}.

Leek has lower relative growth rates than, for example, brassica species (Van der Werf et al., 1996), and in this experiment (Sørensen, 1993) leek produced much less biomass than white cabbage and carrot. With a low biomass production, but with most of its biomass in N rich leaf material, the N-uptake capacity of leek was as high as that of carrot.

Root distribution and uptake capacity are important, but it is also important that the root system is efficient. Root efficiency may be reduced by, for example, pests and diseases (e.g. Haverkort et al., 1994), ageing of the plant and its root system (Cheng et al., 1990) or low temperatures (Engels et al., 1992; Hood & Mills, 1994). All of these factors could be important in the late autumn, when the measurements were made. In the late autumn, carrots will normally be losing leaf material and preparing for winter dormancy. As with leaf function, the functioning of the root system may be declining in the late autumn. Brassica species grown as catch crops in the autumn have been found to be able to maintain soil N at very low levels compared with other plant species in the late autumn at low temperatures (Thorup-Kristensen, 1994). Laine et al. (1994) found that N uptake of *Brassica napus* was less sensitive to low temperatures than N uptake of *Secale cereale*.

The soil N depletion by carrot and leek can be compared more directly, as the two crops had approximately the same level of N-uptake capacity. Thus, differences in soil depletion can be related more directly to differences in root distribution and efficiency. The data show that although leek and carrot can take up approximately the same amount of N, leek was less efficient in utilizing the N in the soil. This difference corresponds to the differences in rooting depth between the two crops (Smit et al., 1996; Thorup-Kristensen & Van den Boogaard, 1999). Even at a N supply well below its optimum, leek left much N, especially in the subsoil layers, indicating that its root system was not in contact with N in the deeper soil layers.

Differences between leek and carrot in the amount of N left in the soil were mainly found at low N supplies, where carrot left less than leek, but at the highest N supply the difference in N residues was small. At low levels of N supply carrots had the advantage of their better distributed root system, which brought the crop into contact with more of the inorganic N in the soil. At higher N supply the differences between the two crops became smaller, suggesting that uptake capacity rather than root distribution became limiting.

The results show that efficient reductions in nitrate leaching from vegetable production cannot be obtained only by optimizing fertilizer N recommendations. Strategies involving N catch crops and optimization of the crop rotation are also needed. Catch crops can be grown either after vegetable crops to prevent N leaching losses, or before the vegetable crops to ensure that the available N is concentrated in the upper soil layers, where it can also be reached by shallow-rooted crops such as leek (Thorup-Kristensen, 1993b; Thorup-Kristensen & Nielsen, 1998).

In conclusion, significant differences exist among crops in their ability to deplete soil inorganic N reserves, differences which cannot be overcome only by improving N fertilizer recommendations. The differences found among the three crops tested in the present experiment were closely related to differences in root growth, but differences in N-uptake potential also seem to be important.

References

AOAC. 1984. Official Methods of Analysis. Association of Official Analytical Chemists, USA, 16 pp.

Best, E. K. 1976. An automated method for determining nitrate-nitrogen in soil extracts. Qld J. Agric. Anim. Sci. 33, 161–166.

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.

Cheng, W., Coleman, D. C. & Box, J. E. 1990. Root dynamics, production and distribution in agroecosystems on the Georgia Piedmont using minirhizotrons. J. Appl. Ecol. 27, 259–604.

Crooke, W. M. & Simpson, W. E. 1971. Determination of ammonium in Kjeldahl digests of crops by an automated procedure. J. Sci. Food Agric. 22, 9–10.

Engels, C., Münkle, L. & Marschner, H. 1992. Effect of root zone temperature and shoot demand on uptake and xylem transport of macronutrients in maize (Zea mays L.). J. Exp. Bot. 43, 537–547.

Greenwood, D. J., Cleaver, T. J., Turner, M. K., Hunt, J., Niendorf, K. B. & Loquens, S. M. H. 1980. Comparison of the effects of nitrogen fertilizer on yield, nitrogen content and quality of 21 different vegetable and agricultural crops. J. Agric. Sci. 95, 471–485.

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

Grindlay, D. J. C. 1995. Principles governing the ability of cover crop species to trap nitrate. PhD Thesis, University of Nottingham.

Haverkort, A. J., Groenwold, J. & Van de Waart, M. 1994. The influence of cyst nematodes and drought on potato growth. 5. Effects on root distribution and nitrogen depletion in the soil profile. Eur. J. Plant Path. 100, 381–394.

Hood, T. M. & Mills, H. A. 1994. Root-zone temperature affects nutrient uptake and growth of snapdragon. J. Plant Nutr. 17, 279–291.

Jensen, E. S. 1991. Nitrogen accumulation and residual effects of nitrogen catch crops. Acta Agric. Scand. 41, 333–344.

Laine, P., Bigot, J., Ourry, A. & Boucaud, J. 1994. Effects of low temperature on nitrate uptake, and xylem and phloem flows of nitrogen, in Secale cereale L. and Brassica napus L. New Phytol. 127, 675–683.

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

Robinson, D., Linehan, D. J. & Gordon, D. C. 1994. Capture of nitrate from soil by wheat in relation to root length, nitrogen inflow and availability. New Phytol. 128, 297–305.

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

Smit, A. L., Booij, R. & Van der Werf, A. 1996. The spatial and temporal rooting pattern of Brussels sprouts and leeks. Neth. J. Agric. Sci. 44, 57–72.

Sørensen., J. N. 1993. Use of the Nmin-method for optimization of vegetable nitrogen nutrition. Acta Hort. 339, 179–192.

Thorup-Kristensen, K. 1993a. Root growth 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. 1993b. Effect of nitrogen catch crops on the nitrogen nutrition of a succeeding crop, I: Effects through mineralization and pre-emptive competition. Acta Agric. Scand., Sect. B, Soil Plant Sci. 43, 74–81.

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

Thorup-Kristensen, K. & Van den Boogaard, R. 1998. Temporal and spatial root development of cauliflower (Brassica oleracea L. var. botrytis L.). Plant Soil 201, 37–47.

Thorup-Kristensen, K. & Van den Boogaard, R. 1999. Vertical and horizontal development of the root system of carrots following green manure. Plant Soil (In press).

Van der Werf, A., Enserink, C. T., Smit, A. L. & Booij, R. 1996. Components of relative growth rate and nitrogen productivity of Brussels sprouts and leeks grown at two widely differing light intensities. Neth. J. Agric. Sci. 44, 21–29.

Wehrmann, J., Scharpf, H.-C. & Kuhlmann, H. 1988. The N_{min} method – an aid to improve nitrogen efficiency in plant production. In: Jenkinson, D. S. & Smith, K. A. (eds) Nitrogen Efficiency in Agricultural Soils. Elsevier, London, pp. 38–45.