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Vertical and horizontal development of the root system of carrots following green manure

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Abstract

Cover crops grown as green manure or for other purposes will affect nitrogen (N) distribution in the soil, and may thereby alter root growth of a succeeding crop. During two years, experiments were performed to study effects of nitrogen supply by green manure on root development of carrots (*Daucus carota* L). Total root intensity (roots cm^{-2} on minirhizotrons) was significantly affected by the green manures, and was highest in the control plots where no green manure had been grown. Spread of the root system into the interrow soil was also affected by green manure treatments, as the spread was reduced where spring topsoil N_{min} was high. Although N supply and distribution in the soil profile differed strongly among the treatments, no effect was observed on the rooting depth of the carrot crops. Across all treatments the rooting front penetrated at a rate of 0.82 and 0.68 mm day^{-1} $°C^{-1}$ beneath the crop rows and in the interrow soil, respectively. The minirhizotrons only allowed measurements down to 1 m, and the roots reached this depth before harvest. Extrapolating the linear relationship between temperature sum and rooting depth until harvest would lead to rooting depths of 1.59 and 1.18 m under the crop rows and in the interrow soil respectively. Soil analysis showed that the carrot crop was able to reduce N_{min} to very low levels even in the 0.75 to 1.0 m soil layer, which is in accordance with the root measurements. Still, where well supplied, the carrots left up 90 kg N ha^{-1} in the soil at harvest. This seemed to be related to a limited N uptake capacity of the carrots rather than to insufficient root growth in the top metre of the soil.

Introduction

In organic vegetable production, green manure is an important source of N. In crops such as carrots, which normally have a low N demand (Bishop et al., 1973; Moje and Scharpf, 1994; Sørensen, 1993) an autumn grown green manure may supply enough N for the crop (Thorup-Kristensen, 1993b).

Growing green manures will influence not only the amount of N available for subsequent crops, but also the depth distribution of the available N. Green manures will increase the N supply in the topsoil by N mineralization from the green manure crop material, but on the other hand they will often reduce subsoil N availability by their N uptake (Thorup-Kristensen and Nielsen, 1998). Without plant cover, winter rains may leach topsoil N into the subsoil.

The amount and distribution of N in the soil have been found to influence the root growth of crops. Several experiments have shown that roots of N-limited plants tend to proliferate in soil layers with much N (Bingham et al., 1997; Drew, 1975; Robinson, 1996; Van Vuuren et al., 1996), but it has also been shown that excessive N supply may reduce the spread of the root system and reduce the root/shoot ratio (Klemm, 1966).

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In a previous experiment, catch crops were found to influence the rooting depth of broccoli (Thorup-Kristensen, 1993a). Where catch crops had left the subsoil almost depleted of available N, very few broccoli roots were observed in the subsoil, but where catch crops had increased subsoil N availability they promoted deep rooting of the broccoli crop.

The effect of green manures on N availability in the subsoil can vary considerably with the choice of species and with incorporation time (Thorup-Kristensen, 1993b). As green manures may have a significant effect on root growth by their effect on subsoil N availability, the management of the green manure could be important to avoid negative effects on rooting depth, or obtain positive effects on root growth.

Knowledge of the root growth of crops is important to adjust crop management for increased N utilisation and reduce N losses in vegetable production, both in organic and in conventional farming. Estimates of root growth are essential for the utilisation of the N_{min} method (Demyttenaere et al., 1989), and in the application of simulation models for predicting N needs (Greenwood et al., 1982; Greenwood et al., 1987). For simulation models, it is also important to know the rates of depth penetration by the root system and not only final rooting depths. In organic farming where crops must rely more on the soil supply of nitrogen, it is important to know the rooting depth of the crops, to be able to design N efficient crop rotations.

The rooting depth of carrots is not well known, but has been estimated to be 60 cm (Demyttenaere et al., 1989). However, Greenwood et al. (1987), proposed an equation relating rooting depth of various crops to total dry matter production, and based on this equation the rooting depth of carrots could be at least twice as deep as that.

The objective of the present work was to test the hypothesis that green manures through their effects on subsoil N availability can affect the depth penetration and final rooting depth of a succeeding crop. We further wanted to estimate the rate of depth penetration by the carrot root system, the final rooting depth of carrots and their ability to take up N from deep soil layers.

Materials and methods

Root growth of carrot (*Daucus carota* L., 'Fancy') grown after different green manure treatments was measured in two years on organically grown crops planted around 20 May in 1995 and 1996.

The experiment was located at the Research Centre Aarslev (10°27′ E, 55°18′ N), on a Typic Agrudalf soil, which had been grown organically in the two years preceding the experiments. The upper 40 cm contains 2% organic matter, 11% clay, 14% silt, and 73% sand. The 40–100 cm layer contains 0.2% organic matter, 19% clay, 13% silt, and 67% sand. Average daily air temperature measured at 2 metres height was used for calculating temperature sums. In 1995 the precipitation deficit during growth of the carrots was 171 mm, and the carrots were irrigated seven times with a total of 187 mm. In 1996 the precipitation deficit was 147 mm, and the carrots were irrigated three times with a total of 80 mm.

Green manure treatments

In the spring in the year before the carrots a spring barley crop was sown. This crop was removed in late July, and the green manures were sown at the beginning of August. Five treatments were used, a control treatment and four green manure treatments. The experimental design was a randomised complete block, with three replicates (for the crop and soil measurements) but only two replicates were included in the root measurements.

The green manure treatments were designed to create large variations in the amount and depth distribution of available N for the carrots. The treatments were:

C: control, without green manure. This was kept free of weeds. GM_{aut}: Green manure, mixture of winter rye (*Secale cereale*) and hairy vetch (*Vicia villosa*), rotovated into the soil in the late autumn, around November 10 each year. $GM3_{aut}$: as GM_{aut}, but green manure was harvested from an adjacent area twice the size of the plot and added before rotovation, such that the total amount of aboveground green manure incorporated was three times as high as in GM_{aut}. The green manure to be transferred was cut of just below the soil surface. GM_{spr}: as GM_{aut}, but the green manure was left growing on the soil until spring and rotovated into the soil around April 1. RR: Pure stand winter rye which was left growing on the soil until around May 5 (two weeks before sowing of the carrots), after which the above ground rye material was removed from the plots before rotovation.

The carrot crop was sown with a row distance of 0.5 m and 100 seeds per meter row. Plants were

Table 1. N uptake and yield (top and root dry matter (DM) and root fresh weight (FW)) of carrots following green manures

	Top	Root	Total	Top DM	Root DM	Root FW
	kg N ha^{-1}			Mg ha^{-1}		
1995						
RR	36^c	64^c	100^a	2.6^a	9.8^a	88^a
C	43^c	74^c	117^a	2.9^a	10.5^{ab}	96^{ab}
GM_{aut}	59^b	102^b	161^b	3.5^b	11.0^b	102^b
GM_{spr}	63^{ab}	103^b	166^b	3.4^b	10.5^{ab}	100^b
$GM3_{aut}$	68^a	117^a	185^c	3.4^b	10.7^b	101^b
1996						
RR	27^a	59^a	86^a	1.6^a	8.2^a	70^a
C	53^b	111^b	164^b	2.9^b	10.9^b	97^b
GM_{aut}	52^b	115^b	166^b	2.8^b	10.8^b	95^b
GM_{spr}	52^b	118^b	170^b	2.6^b	10.5^b	89^b
$GM3_{aut}$	65^c	140^c	205^c	2.9^b	10.8^b	93^b

GM_{aut}: autumn incorporated green manure; $GM3_{aut}$: triple amount of green manure incorporated in the autumn;
GM_{spr}: spring incorporated green manure; RR: rye removed in spring before incorporation, and C: control without green manure.
Figures within a column not followed by the same letter are different, LSD ($P<0.05$).

sampled and analysed for dry matter production and N uptake at harvest, 26 September 1995 and 3 October 1996. N content in the plant material was analyzed by combustion (Hansen, 1989). Soil samples were taken in early summer approximately two weeks after sowing and again at harvest and analysed for ammonium-N and nitrate-N after extraction for one hour in a 1 *M* KCl solution. In the GM_{aut} and $GM3_{aut}$ treatment, soil samples were taken both in the rows and in the interrow soil at harvest both years. In 1996, such samples were taken in the control treatment too. The soil samples were in all cases taken in four soil layers of 0.25 m down to one metre, with 9 sub samples for each position in each plot.

Root measurements

Directly after sowing, minirhizotron glass tubes (70 mm in outer diameter and 1.5 m long) were inserted into the soil (Thorup-Kristensen and Van den Boogaard, 1998). In each plot three minirhizotrons were placed directly under the crop row and three minirhizotrons placed in the middle of the interrow space, 0.25 m from the carrot rows.

The minirhizotrons were installed at an angle of 30° from vertical, reaching a depth of approximately 1.0 m in the soil. The holes for the minirhizotrons were made by drilling twice, first with a spiral auger with a diameter of 60 mm to remove most of the soil, and subsequently with a piston auger with a diameter of 74 mm. It was necessary to use an auger with a slightly higher diameter than the minirhizotrons, as the holes drilled in the moist soil shrank. The plasticity of the soil at this time also meant that a good contact between the soil and the minirhizotrons were obtained by this procedure.

Two counting grids consisting of 4×128 fields were painted on the 'upper' surface of each minirhizotron with a field size of 100 mm^2, each representing a soil layer 8.7 mm thick (cos(30°)). Registrations were made using a mini-video camera to record the roots on the minirhizotron surface on videotapes. The videotapes were subsequently analysed by counting the number of grid fields showing roots.

Root intensities were calculated as simple averages of registrations within each soil layer (fraction of the 100 mm^2 counting fields where roots were observed) for each observation date. Root depth was estimated as the deepest root observation on each of the two counting grids on each minirhizotron.

Root observations (depth or intensity) for each of the two positions relative to the crop row are thus the average of six single registrations per plot (three minirhizotrons with two counting grids each). Data were analysed with the GLM procedure of the SAS statistical package (SAS, 1990).

Results

The green manures strongly affected the amount and depth distribution of available N in the soil (Table 4). Accordingly, large differences in N uptake by the subsequent carrot crops were found (Table 1). In spite of these differences in N supply and N uptake, the yield response of the carrots was small. Only in the RR treatment, which had very low N uptake, a small decrease in root yield was observed.

Effects of green manure on root growth

Although the green manure treatments gave large variations in N uptake by the carrots, there were no significant differences in rooting depth or in the rate of depth penetration between the treatments. Still, highly significant differences in the root intensity (Table 2) were found. The root intensity was highest in the control treatment (C) followed by the autumn incorporated rye-vetch mixture (GM_{aut}).

Root distribution also differed significantly between the treatments (Figure 1, Table 3). In the rye-removed treatment (RR), where the N supply was very low, the root intensity in the interrow soil was on average 60% of the root intensity beneath the crop rows. This was a significantly higher fraction than in any of the other treatments. Where the green manure was spring incorporated (GM_{spr}) and where triple amount of green manure was incorporated in the autumn ($GM3_{aut}$) the fraction was only 45% and 36%, respectively. These differences were closely related to N_{min} in the topsoil. Where topsoil N_{min} was high, the fraction of the roots observed in the interrow soil was low.

Root growth and distribution did not seem to be related to subsoil N_{min}. The effect of the green manure treatments on subsoil N_{min} differed between the two years. In 1995 treatment $GM3_{aut}$ and GM_{aut} had the highest subsoil N_{min}, but in 1996 the highest subsoil N_{min} was found in C. In both years, the lowest subsoil N_{min} was found in RR. The differences between treatments and years were not reflected in any of the root measurements.

Table 3. Interrow rooting, root intensity in the interrow soil expressed as precentage of the root intensity in the row soil. Average over all measurement dates and depths

	1995	1996
	Interrow rooting*	
RR	52^a	70^a
C	40^b	61^a
GM_{aut}	40^b	60^a
GM_{spr}	30^c	65^a
$GM3_{aut}$	26^c	39^b
$LSD_{0.05}$	8	17

Legends as in Table 1. Figures within a column not followed by the same letter are different, LSD ($p < 0.05$).

Table 2. Root intensity (0–100 cm). Average over all measurement dates and depths

	1995	1996
	Root intensity (%)	
RR	29^c	31^{bc}
C	36^a	40^a
GM_{aut}	35^{ab}	34^b
GM_{spr}	31^{bc}	28^c
$GM3_{aut}$	31^{bc}	30^{bc}
$LSD_{0.05}$	5	4

Legends as in Table 1. Figures within a column not followed by the same letter are different, LSD ($p < 0.05$).

Depth penetration rate of carrot roots

Although the depth penetration rate of the root system was different among the two years (Figure 2), a rooting depth beneath the crop rows of 100 cm was reached at least two months before harvest every year. In the interrow soil, only in 1995 the roots reached the bottom of the minirhizotrons before harvest, whereas in 1996 average rooting depths only reached between 80 and 90 cm at the end of the experiment. Due to the length of the minirhizotrons, the maximum depth we could observe was 100 cm. Therefore, only observations made until the roots had reached an average depth of 90 cm were included in the calculations of depth penetration rates.

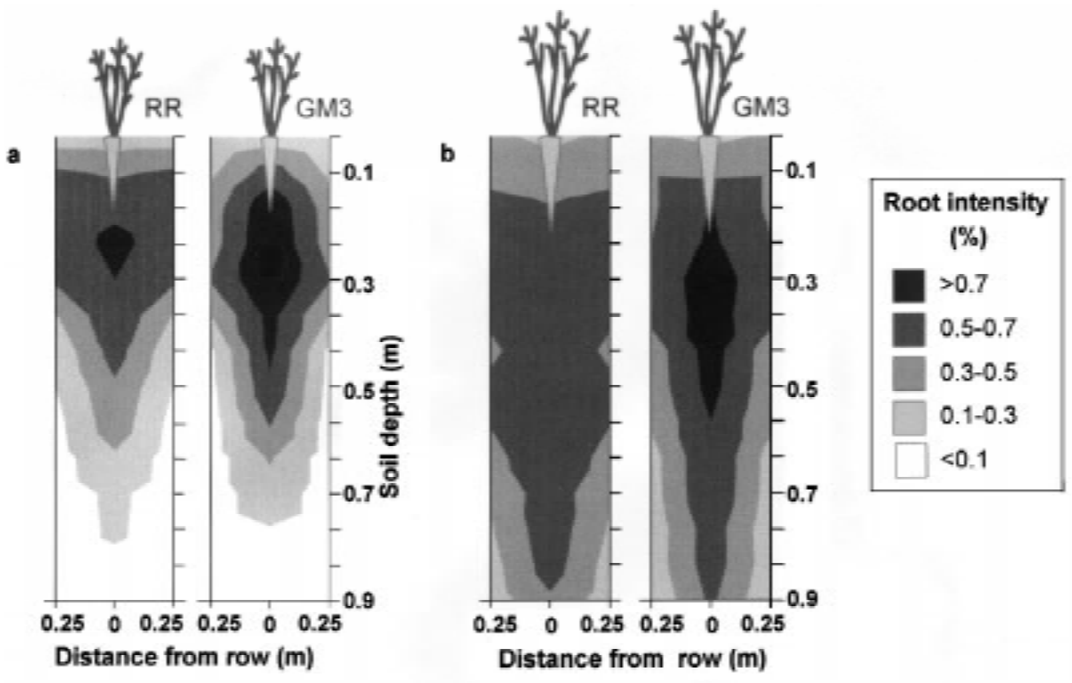

Figure 1. Root intensity distribution beneath carrots approximately (a) 10 weeks after sowing and (b) at harvest, approximately 20 weeks after sowing. The figure shows the more even distribution of roots between row- and interrow soil in the low N RR treatment than in the high N GM3$_{aut}$ treatment (Table 3). Data are average across the two years of measurement.

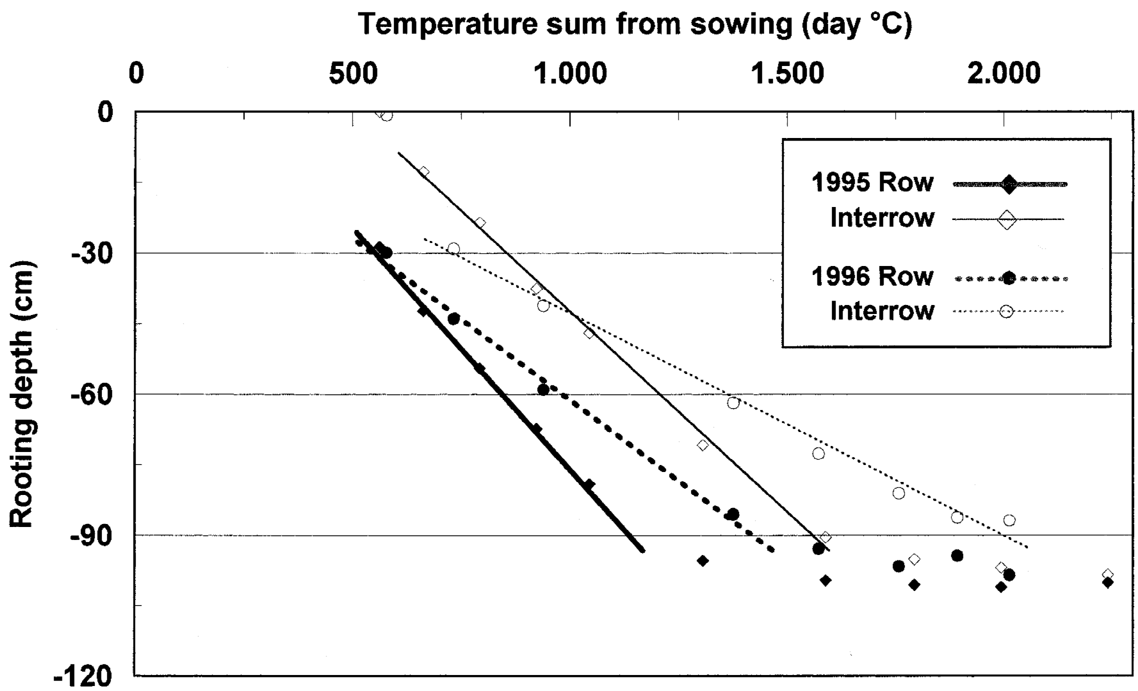

Figure 2. Rooting depth of carrot roots in row and interrow soil. The rooting depth was linearly related to temperature sum, until the length of the minirhizotrons prevented measurement of further dept penetration. Data are averaged across the five treatments. Measurements in the rooting depth range of 10 to 90 cm were used for the regression lines.

The best fit between temperature sum (calculated from daily average air temperature at 2 m) and rooting depth was obtained using a base temperature of 4 °C (r^2=0.934), but similar fits were obtained using any base temperature from 0 to 8 °C (r^2 between 0.932 and 0.934). Using chronological time instead of thermal time reduced the fit slightly (r^2=0.920). Various estimates for base temperatures for carrot development have been proposed. Tamet et al., (1996), Visser et al. (1995), and Wheeler et al. (1994) estimated base temperatures of 3.5, 0, and −1 °C, respectively. Two plantings, as used for our root measurements, is not enough to estimate a base temperature. Therefore, a base temperature of 0 °C was chosen for further rate calculations.

Across the two years of measurements in all treatments, the root depth of carrots was found to increase linearly with temperature sum (Figure 2). The overall rate was 0.75 mm day^{-1} °C^{-1}. This rate of depth penetration varied between years (0.96 mm day^{-1} °C^{-1} in 1995 vs. 0.54 mm day^{-1} °C^{-1} in 1996, $p<0.001$). The depth penetration rate was significantly higher beneath the crop rows than in the interrow soil 250 mm from the crop rows (0.82 vs. 0.68 mm day^{-1} °C^{-1}, $p<0.001$). The regression equations for the two positions across the two years were:

$$Row : y = -135 + 0.82x \quad (1)$$

$$Interrow : y = -247 + 0.68x \quad (2)$$

where y is rooting depth (mm) and x is temperature sum (day °C). By extrapolation of the linear relationships between rooting depth and temperature sum until harvest (2100 day °C from sowing to harvest), rooting depths of 1.59 m under the rows and 1.18 m between the rows can be estimated. According to the two equations a rooting depth of 250 mm will be reached beneath the crop row after 469 day °C and in the interrow soil afte 731 day °C. As the distance between the two positions is 250 mm, this gives a horizontal root penetration rate of 0.95 mm day^{-1} °C^{-1}.

Between early summer and harvest, N_{min} fell strongly in all treatments (Table 4). In all treatments except $GM3_{aut}$, N_{min} was reduced to between 12 and 32 kg N ha^{-1}. In $GM3_{aut}$ it was reduced only to 65 and 90 kg N ha^{-1} in 1995 and 1996, respectively.

The carrots were able to deplete N_{min} to very low levels down to a depth of 100 cm. In both years subsoil N_{min} (50 to 100 cm soil layer) was reduced to less than 10 kg N ha^{-1} in most of the treatments, and in several cases to less than 5 kg N ha^{-1}. In the GM_{aut}, GM_{spr} and C treatments subsoil N_{min} was reduced by approximately 50% from early summer until harvest each year. In the RR treatment the carrots were not able to reduce subsoil N_{min} to below the very low level already observed at sowing. In the $GM3_{aut}$ treatment subsoil N_{min} was almost unchanged during the growing period, even though the carrots had the same root intensity as the GM_{spr} and C treatments.

Measuring N_{min} separately in row and interrow soil showed differences in the amount of N_{min} left at the two positions (Table 5). Surprisingly these differences were most pronounced in the upper soil layers where the root intensity in the interrow soil was quite high.

Table 4. Soil nitrogen (N_{min}) measured early summer and at harvest under carrots following green manures. Figures in brackets are SE, n=3

	RR	C	GM_{aut}	GM_{spr}	$GM3_{spr}$
	N_{min} kg N $^{ha-1}$				
12 Jun 1995					
0–25 cm	$35^{(6)}$	$46^{(3)}$	$55^{(3)}$	$75^{(4)}$	$69^{(1.4)}$
25–50 cm	$9^{(4)}$	$21^{(3)}$	$23^{(3)}$	$24^{(4)}$	$35^{(2)}$
50–75 cm	$2^{(0.9)}$	$7^{(1.0)}$	$9^{(0.1)}$	$8^{(1.7)}$	$19^{(3)}$
75–100 cm	$1^{(0.6)}$	$6^{(0.4)}$	$10^{(0.9)}$	$7^{(1.3)}$	$28^{(4)}$
Total	$47^{(11)}$	$80^{(4)}$	$98^{(0.4)}$	$114^{(1.7)}$	$151^{(5)}$
26 Sep. 1995					
0–25 cm	$13^{(0.6)}$	$11^{(1.5)}$	$12^{(6)}$	$16^{(0.9)}$	$20^{(4)}$
25–50 cm	$2^{(0.1)}$	$3^{(0.9)}$	$5^{(1.5)}$	$7^{(2)}$	$8^{(1.0)}$
50–75 cm	$1^{(0.1)}$	$2^{(0.2)}$	$4^{(0.5)}$	$4^{(1.2)}$	$11^{(3)}$
75–100 cm	$2^{(0.3)}$	$3^{(0.3)}$	$5^{(1.4)}$	$4^{(1.2)}$	$26^{(7)}$
Total	$18^{(0.8)}$	$18^{(1.6)}$	$26^{(3)}$	$32^{(6)}$	$65^{(13)}$
29 May 1996					
0–25 cm	$17^{(1.1)}$	$56^{(0.9)}$	$67^{(5)}$	$68^{(6)}$	$111^{(17)}$
25–50 cm	$2^{(0.3)}$	$40^{(4)}$	$22^{(2)}$	$9^{(0.3)}$	$33^{(5)}$
50–75 cm	$1^{(0.5)}$	$16^{(2)}$	$6^{(0.9)}$	$4^{(0.7)}$	$7^{(0.6)}$
75–100 cm	$1^{(0.1)}$	$9^{(1.1)}$	$6^{(0.4)}$	$4^{(0.1)}$	$6^{(0.7)}$
Total	$22^{(1.3)}$	$121^{(6)}$	$110^{(7)}$	$85^{(6)}$	$157^{(21)}$
3 Oct. 1996					
0–25 cm	$8^{(0.2)}$	$11^{(1.3)}$	$13^{(2)}$	$11^{(1.1)}$	$37^{(8)}$
25–50 cm	$2^{(0.2)}$	$8^{(0.4)}$	$6^{(0.5)}$	$4^{(0.6)}$	$39^{(11)}$
50–75 cm	$1^{(0.2)}$	$6^{(0.2)}$	$4^{(0.2)}$	$2^{(0.4)}$	$8^{(1.3)}$
75–100 cm	$1^{(0.2)}$	$6^{(0.6)}$	$4^{(0.6)}$	$2^{(0.1)}$	$7^{(0.9)}$
Total	$11^{(0.5)}$	$30^{(2)}$	$28^{(3)}$	$19^{(0.3)}$	$90^{(21)}$

Legends as in Table 1.

Table 5. Soil nitrogen (N_{min}) in row and interrow soil at harvest under carrots following green manures. Figures in brackets are SE, *n*=3

	C		GM_{aut}		$GM3_{aut}$	
	Row	Interrow	Row	Interrow	Row	Interrow
	N_{min} kg N ha^{-1}					
26 Sep. 1995						
0–25 cm			$12^{(1.2)}$	$11^{(1.2)}$	$18^{(3)}$	$22^{(4)}$
25–50 cm			$3^{(0.0)}$	$7^{(2)}$	$5^{(0.2)}$	$12^{(1.9)}$
50–75 cm			$3^{(0.7)}$	$5^{(1.2)}$	$9^{(3)}$	$12^{(3)}$
75–100 cm			$4^{(1.1)}$	$6^{(1.8)}$	$24^{(6)}$	$27^{(8)}$
Total			$22^{(0.5)}$	$29^{(5)}$	$55^{(10)}$	$74^{(15)}$
3 Oct. 1996						
0–25 cm	$9^{(8)}$	$12^{(0.4)}$	$9^{(0.8)}$	$17^{(4)}$	$19^{(1.1)}$	$54^{(15)}$
25–50 cm	$4^{(3)}$	$12^{(0.7)}$	$4^{(0.6)}$	$9^{(0.4)}$	$37^{(11)}$	$40^{(11)}$
50–75 cm	$3^{(1.9)}$	$10^{(0.4)}$	$3^{(0.7)}$	$5^{(0.4)}$	$7^{(0.7)}$	$9^{(1.9)}$
75–100 cm	$5^{(1.1)}$	$7^{(0.3)}$	$4^{(0.9)}$	$5^{(0.5)}$	$5^{(0.2)}$	$8^{(1.8)}$
Total	$21^{(0.7)}$	$40^{(5)}$	$20^{(3)}$	$36^{(4)}$	$69^{(12)}$	$111^{(30)}$

Legends as in Table 1.

Discussion

As a result of the green manure treatments, large differences in total N supply and in subsoil N_{min} were obtained. Accordingly, significant effects of green manure crops on some root parameters were found, but rooting depth was not affected. The root intensity in the subsoil was as high after the RR treatment, where subsoil N_{min} was very low, as after other green manure treatments where subsoil N_{min} was much higher. This is in contrast to many other results showing that roots tend to proliferate in soil enriched in nutrients (Bingham et al., 1997; Robinson, 1996; Van Vuuren et al., 1996). Under field conditions, Schröder et al. (1996) found that placing fertilizer between the rows of maize strongly increased interrow root growth. Our finding, that root intensity in the subsoil was high even after green manures which left very little N_{min} in the subsoil (GM_{spr} and RR), is in contrast to previous results with broccoli (Thorup-Kristensen, 1993a), which did not develop roots in N depleted subsoil layers.

Root intensity within the whole soil profile was significantly affected by the green manure treatments (Table 2), but the observed effects did not appear to be related to the N supply of the carrots. In both years, the highest root intensity was found where no green manure was grown (C) followed by GM_{aut}. This result could indicate a negative effect of the rye material on the subsequent root growth of carrots, rather than an N effect. Rye has previously been shown to have allelopathic effects (Creamer et al., 1996), and such effects could be the reason for the present results, though negative effects were not observed on crop growth and yield.

Root proliferation in nutrient rich subsoil may be the normal response of many plant species (Drew, 1975; Robinson, 1996), but it may not necessarily occur in all plant species or in plants which is already well supplied with nutrients. In natural conditions, wild carrots thrive in closed grass swards, where significant amounts of available N in the subsoil are unlikely. If carrots reacted to low subsoil N availability by restricting their rooting depth, it would normally become shallow rooted in its natural habitat, and thus not be able to utilize water and other resources from deeper soil layers. Hence, carrots may well be adapted to grow deep roots even where very little available N is present in the deeper soil layers.

The carrots obtained a higher root intensity beneath the crop rows, than in the interrow soil. Such a root distribution has been observed for other row crops such as lettuce (Steingrobe and Schenk, 1994) or celeriac (Hösslin, 1954). In contrast, in cotton (Prior et al., 1994) or cauliflower (Thorup-Kristensen and Van den Boogaard, 1998) such differences were small or absent. The root distribution between row and interrow soil was affected by the green manure treatments, and this response seemed to be related to N availability in the topsoil. In both years the root system became more evenly distributed between row and interrow soil where spring topsoil N_{min} was low. A similar effect was observed for maize (Schröder et al., 1996), where the root distribution was more even in the unfertilized control treatment than in the broadcast fertilizer treatment.

Rooting depth of carrot

Our results on rooting depth are in accordance with the equation for the relationship between rooting depth and crop dry matter production proposed by Greenwood et al. (1987):

$$Rooting\ depth = -180 + DW^{*}85.9 \quad (3)$$

where rooting depth is in mm and DW is dry matter production in Mg ha^{-1}. Using this equation, a rooting depth at harvest of 1.12 m for the RR treatment and 1.38 m for GM_{aut} can be estimated, without much difference between the two years. These estimates are in accordance with the final rooting depths as estimated by extrapolation of our measurements. Thus, both our results and Equation (3) suggest much deeper rooting of carrots than the 60 cm proposed by Demyttenaere et al. (1989). However, our results do not confirm the relationship between dry matter production and rooting depth indicated by Equation (3), as we found no indication of reduced rooting depth in the N starved RR treatment which produced less dry matter than any of the other treatments.

The estimated rates of rooting depth penetration by the carrots are comparable to other vegetable crops as leek (0.8 mm day^{-1} °C^{-1}, Smit et al., 1996), pea (0.9 mm day^{-1} °C^{-1}, Thorup-Kristensen, 1998), cauliflower (1.0 mm day^{-1} °C^{-1}, Thorup-Kristensen and Van den Boogaard, 1998), or Brussels sprouts (1.3 mm day^{-1} °C^{-1}, Smit et al., 1996).

The root measurements show that carrots should be able to utilize available N and other soil ressources down to at least one metres depth. The N_{min} measurements suggest that this actually occurred, but only in the treatments with limited N supply. Carrots grown at high N supply did not reduce the amount of available N in the subsoil, though their root system was also well developed in this soil layer. This is is also in accordance with previous results showing that carrots can deplete subsoil N_{min} efficiently down to 100 cm, but that adding more N to the topsoil results in more unused N in the subsoil (Thorup-Kristensen, 1993b). Robinson et al. (1994) found that plants well supplied with N were much slower to deplete a localised supply of ^{15}N than N deficient plants. Even though the N deficient plants had a lower root length density in the N enriched soil volume, they captured 73% of the labelled N within a week while the plants well supplied with N took up only 13%. Even when depletion of the subsoil does occur, the uptake from the deeper soil layers will occur later and be slower than the uptake from the upper soil layers (Strebel and Duynisveld, 1989).

Such effects could also be the explanation for the less efficient depletion of the interrow soil. The difference in the amount of N residues found in row and interrow soil was much larger than what has been found with cruciferous crops (Everaarts et al., 1996; Thorup-Kristensen and Van den Boogaard, 1998). This difference may be related to the high N uptake capacity of cruciferous crops, which makes it less likely that supply will exceed uptake capacity.

It has previously been shown that uptake capacity can often be the factor limiting plant N uptake (Laine et al., 1994; Robinson et al., 1994). In accordance with this idea, the present results indicate that crop N uptake capacity rather than insufficient root growth was the factor which limited soil N depletion in the top 1.0 m of the soil by the carrots.

Conclusion

Growing green manures did affect root growth of the subsequent carrot crop, but not in the expected way. Though large differences in subsoil N_{min} were obtained due to the green manure treatments, rooting depth and root intensity in the subsoil was not affected. Instead, green manures generally reduced the root intensity of the carrots, and affected the spread of the root system into the interrow soil. After green manures that left little available N in the topsoil, the root system was more evenly distributed among row and interrow soil than after green manures that left high amounts of available N in the topsoil.

At harvest carrots had a well-developed root system in all of the top 1.0 m of the soil. Still, appreciable amounts of available N were often left in the soil, apparently due to limited N uptake capacity by the carrot crop. Thus, in spite of the deep root system of carrots, it is necessary to avoid any excess fertilization of this crop to allow it to deplete the soil N efficiently at harvest.

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