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The spatial and temporal rooting pattern of Brussels sprouts and leeks

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Abstract

The vegetables Brussels sprouts (*Brassica oleracea* L. var *gemmifera)* and leeks (*Allium porrum* L.) differ widely in the degree of nitrogen utilisation under field conditions. Brussels sprouts usually take up nitrogen in a relative short period after planting and leaves a profile depleted of nitrogen. Leeks, however, utilise in general only half of the available nitrogen. This implies that for this crop large amounts of nitrogen can be subject to losses to the environment during or after the growing period. In order to investigate the role of the root system in nitrogen utilisation, rooting intensity and distribution of the two crops were assessed in field experiments and in the Wageningen Rhizolab, a rhizotron facility built in 1990. In field experiments rooting was quantified in the various layers of the profile as the volumetric Root Length Density (RLD, cm cm^{-3}) and in the Rhizolab with horizontal glass minirhizotrons as the Number of Roots per cm^2 (NR). A regression procedure of RLD and NR on thermal time (accumulated average daily temperature above ground) after planting revealed that the rooting depth of Brussels sprouts increased faster with thermal time than rooting depth of leeks, e.g. in one of the experiments in the Rhizolab 0.13 cm (°C $day)^{-1}$ and 0.08 cm (°C $day)^{-1}$ respectively. Furthermore, leeks showed an unusual distribution of roots in the profile with maximal rooting intensity at depths of 10–20 cm. In all experiments the proliferation of roots (calculated as the increase in NR or RLD with thermal time) was slower in leeks than in Brussels sprouts, especially in the deeper layers of the soil profile. Therefore leeks can be considered as a shallow rooting crop. Compared to the Rhizolab, the field experiments showed in general the same difference between the crops: for Brussels sprouts a higher root density, a deeper rooting and a faster proliferation of roots. For both crops, however, the proliferation of roots at the deeper layers was in the field much slower, probably due to unfavourable conditions in the subsoil caused by higher bulk densities or temporary high water tables. The consequences of different rooting patterns for nitrogen utilisation are discussed.

Keywords: Brussels sprouts, leeks, minirhizotron, nitrogen utilisation, rhizotron, rooting intensity and distribution, thermal time

Introduction

One of the goals in modern agriculture is an efficient use of nitrogen (N) to prevent losses to the environment. However, especially in vegetable growing recovery in the crop is low (Greenwood *et al.*, 1989; Smit & Van der Werf, 1992) implying losses of nitrogen to the groundwater during or after the growing period.

Improvements in nitrogen utilisation are expected if the crop's specific pattern of N-demand is synchronised with the availability of nitrogen. The amount of nitrogen available during the growing season is governed by N-mineralisation, (which on its turn is influenced by soil temperature and other soil characteristics), the N fertiliser N rate and the method of fertilisation (e.g. time of application, split application). To achieve a high degree of utilisation, N availability and N demand should correspond in time as well as in space. Smit & Van der Werf (1992) have indicated that the crop's growth rate at harvest and related to that the pattern of N-uptake is an important factor influencing N-utilisation. Roots and nitrogen should be also (more or less) at the same location in the soil profile, showing the need to study rooting characteristics of a crop. Various crop rooting characteristics have been related to nitrogen utilisation: root distribution and rooting intensity in the soil profile (Jackson & Bloom, 1990; Wiesler, 1991; Schenk *et al.*, 1991; Jackson and Stivers, 1993), the uptake capacity of the root system (Heins & Schenk, 1987; Steingrobe & Schenk, 1991) and root morphology (Feil *et al.*, 1990). In general root length per unit soil volume is not considered to be limiting for nitrate uptake (De Willigen and Van Noordwijk, 1987), but this may not be the case in the period immediately after planting and at lower depths. The rate at which a crop can explore the profile (rooting depth in time) might, however, be an important rooting characteristic crucial for the amount of nitrogen leached during or after the growing season. According to Van der Werf *et al.* (1996) the rate of soil exploration will strongly depend on the growth rate of a crop. Thorup-Kristensen (1993) investigated root development in nitrogen catch crops and found large differences in root growth patterns. Catch crops with a fast establishment of deep rooting most strongly reduced the mineral nitrogen content in the subsoil.

Therefore, the aim of this article is to quantify the spatial and temporal pattern of rooting of two vegetable crops differing widely in their ability to utilise nitrogen. Leeks (*Allium porrum* L.), usually show a low nitrogen recovery (50%) even when fertilised at recommended rates (Smit & Van der Werf, 1992), whereas a crop of Brussels sprouts (*Brassica oleracea* L. var *gemmifera*) utilises all the nitrogen made available during the growing season, leaving the profile at the end of the growing season depleted of nitrogen (Smit *et al.*, 1995; Booij *et al.*, 1993).

For both crops the relationship between rooting intensity/depth and (thermal) time was assessed in field and rhizotron experiments. The data on root growth presented in this paper can be incorporated in models simulating crop growth and nitrogen uptake. Modelling increases the potential to develop crop specific fertilisation strategies to minimise leaching, or fertilisation strategies to optimise yields with a concurrent reduction of nitrogen fertilisation. In addition to the development of new fertilisation strategies, quantitative information on the temporal and spatial pattern of rooting can also has potential to estimate crop water use and irrigation requirements (Jaafar *et al.*, 1993).

Materials and methods

Field experiments

Field experiments for each of the two crops were carried out in 1991 and 1992 on a sandy soil in Wageningen (AB-DLO Experimental Farm 'Droevendaal'). The experiments are described in more detail by Booij *et al.*, 1996. Table 1 shows the experimental set up and the dates of planting, soil sampling and harvest of the field trials, which were all laid out in a randomised complete block design in 4 replicates.

In the field experiments Brussels sprouts were grown at a row distance of 75 cm and 40 cm within the row. Leeks were grown at a row distance of 40 cm and a distance within the row of 14.5 cm.

Rooting intensity in the soil profile was assessed at 10 cm increments by core sampling (diameter 4.77 cm, length 10 cm yielding 180 cm^3 per sample) until a depth of approximately 60 to 70 cm was reached. Below this depth occasionally high water tables occurred and no roots were found. Samples were taken on areas representative with respect to plant and row distance. For Brussels sprouts in each experimental plot at least 3 soil cores were taken in the cropped surface area per plant, described by Van Noordwijk *et al.* (1985) as the representative quarter of the 'unit soil area' for a regular plant spacing, which is the case for Brussels sprouts. For leeks, being a row crop, three samples per field plot were taken, one close to the row, one touching the centre line between two rows and one in between. Thusdoing in both field experiments for each depth (10 cm interval) and each treatment 12 samples (4 replicates and 3 samples per plot) were taken. The individual soil samples were washed with the elutriaton chamber described by Smucker *et al.* (1982) , the length of the obtained root samples was assessed with the modified Newman line intersect method (Newman, 1966; Tennant, 1976), averaged per treatment and expressed as Volumetric Root Length Density (RLD) in cm root length per cm^3 soil volume.

Rhizolab experiments

The Wageningen Rhizolab consists of two rows of eight experimental units spaced at intervals along a central underground corridor. The compartments are 125 cm × 125 cm and 200 cm deep. Further details can be found in Van de Geijn *et al.* (1994).

In 1990 a Rhizotron experiment was carried out with Brussels sprouts (cultivar *Kundry*) in 4 compartments; in 1991 two compartments were grown with Brussels sprouts (cultivar *Kundry*) and 2 compartments with leeks (cultivar *Arcona*), in 1992 4 compartments were grown with leeks (cultivar *Arcona*). Experimental treatments and dates of planting, root observation and harvest are indicated in Table 1. Module raised transplants of Brussels sprouts were transplanted in 1990 at 45 × 45 cm (9 plants per compartment), in 1991 at 42 × 63 cm (6 plants per compartment). Bare-

Table 1.Treatments and planting time for the two crops. Dates for root sampling and harvests are indicated in days after planting (DAP).

Crop	Site	Year	(Fertiliser) Treatment	Planting date	Root Sampling/ Root Observation dates (DAP)	Harvest date (DAP)
Brussels sprouts	Rhizolab	1990	0 kg N/ha 130 kg N/ha 65+65 kg N/ha 65+65 kg N/ha +drought	7 June	20, 35, 49, 65, 78, 90, 106, 121, 133, 147, 161	161
Brussels sprouts	Rhizolab	1991	100 kg N/ha 200 kg N/ha	30 May	8, 15, 23, 29, 44, 56, 72, 84, 93, 99, 113, 127, 141, 155, 169, 182	183
Brussels sprouts	Field	1991	200 kg N/ha	28 May	44, 78, 105, 133	189
Brussels sprouts	Field	1992	0 kg N/ha 200 kg N/ha	19 May	25, 85, 175	175
Leeks	Rhizolab	1991	125 kg N/ha 250 kg N/ha	17 June	11, 26, 38, 54, 66, 75, 81, 95, 109, 123, 137, 151	165
Leeks	Rhizolab	1992	100 kg N/ha 200 kg N/ha 100 kg N/ha + drought 200 kg N/ha + drought	12 June	14, 28, 42, 56, 70, 83, 99, 112, 126, 139, 151	155
Leeks	Field	1991	250 kg N/ha	18 June	43, 91, 126	155
Leeks	Field	1992	0 kg N/ha 250 kg N/ha	11 June	26, 56, 96, 131, 159	159

rooted transplants of leeks were planted at a depth of 16 cm at a planting pattern of 13.9 × 42 cm (27 plants per compartment) in both 1991 and 1992.

The soil profile in the experiments consisted of a top layer of 1 m (1990, 1991) or 0.7 m (1992) of humic sand (4.1–4.4% organic matter). The subsoil layer was of coarse sand containing no organic matter. Usually no roots were observed in this layer. Before each experiment the compartments were filled and compressed manually layer by layer of 5 cm to an average bulk density of 1.37 g cm^{-3} (1990), 1.33 g cm^{-3} (1991) and 1.32 g cm^{-3} (1992).

Root growth and distribution were observed usually every fourteen days after planting with a mini colour video camera (BartzTechnology Company, Santa Barbara CA, USA) sliding into horizontally installed root observation tubes at 5, 10, 20, 30, 45, 60, 80 and 100 cm below soil level. The glass tubes (minirhizotrons) were 130 cm long and had an outer diameter of 6 cm.

Root growth was observed at approximately 30 positions of 13 mm × 18 mm each along the upper surface of each minirhizotron. Root growth was quantified by counting the number of root intersections per position. An average for each depth was calculated and expressed in number of root (intersections) per cm^2 minirhizotron surface (NR). Further details were given by Smit *et al.* (1994).

Statistical procedures

Within the scope of this paper (focusing on rooting depth and the increase of rooting in the period after planting) the data of the different treatments in the Rhizolab (Table 1) were pooled because in this period nitrogen had a relatively minor influence and drought (in 1991, 1992) was introduced later in the season. Data from the field experiments were also pooled for the different nitrogen fertilisation treatments. For Brussels sprouts no significant influence of nitrogen fertilisation on root length density was observed. For leeks in the experiment of 1992 the treatment without nitrogen fertilisation resulted in a somewhat higher rooting intensity, but also the two treatments in this experiment were pooled because significance was low ($P<0.06$). So, nitrogen fertilisation possibly had a minor influence, probably because at planting mineral nitrogen content in the profile (0–60 cm) in the non-fertilised fields was already relatively high (in 1991 67 kg and 73 kg N per ha; in 1992 65 kg and 116 kg N per ha for Brussels sprouts and leeks respectively).

Rooting depth and the rate of increase in rooting intensity were quantified by regressing RLD and NR for each depth/layer on thermal time (accumulated daily average temperature above ground at 1.5 m, base temperature 0 °C). Thermal time was chosen instead of days after planting (DAP) to allow a better comparison between years and between experimental sites and also because the relationship between rooting intensity and thermal time was more linear.

For a specific soil layer (field) or depth (Rhizolab) a lag period (in °C day) after planting is assumed in which no rooting occurs, for most crops this period will be longer with increase in depth. After this lag period, rooting (numbers per cm^2 in Rhizolab experiments and length per cm^3 in the field experiments) increases linearly with thermal time with a rate depending on depth.

The corresponding regression model is:

$RLD_{i,t}$ or $NR_{i,t} = 0$ for $t < K_i$ (1)

$RLD_{i,t}$ or $NR_{i,t} = A_i * t$ for $t > K_i$ (2)

where :

t = thermal time in °C days after planting

i = soil layer (1 = 0–10 cm, 2 = 10–20 cm......, 7 = 60–70 cm, 8 = 70–80 cm) or depth (1= 5 cm, 2 = 10 cm , 3 = 20 cm ...., 8 = 80 cm, 9 = 100 cm)

$RLD_{i,t}$ = the root length density ($cm\ cm^{-3}$) for soil layer i (field experiments) at time t

$NR_{i,t}$ = the number of root intersections (cm^{-2}) at depth i (Rhizolab experiments) at time t

K_i = lag time for rooting for depth or layer i in °C days

A_i = the rate of increase in root number in cm^{-2} (°C day)$^{-1}$ or the increase in root length in $cm^{-3}\ cm^{-3}$ (°C day)$^{-1}$ for layer or depth i after the lag period (K_i).

The present paper deals with rooting in the months following planting and especially with the rate at which both crops can explore the soil profile. The regression was carried out with data restricted to the period approximately 90–120 days after planting (dependent of the experiment). For each depth and for each experiment K_i and A_i were estimated using the non-linear regression option of the statistical program Genstat5 (Payne *et al.*, 1994).

Results

Rooting intensity and root distribution in the soil profile

Brussels sprouts

In the Rhizolab experiments of 1990 and 1991 large numbers of roots, up to 5–6 roots per cm^2, were observed for Brussels sprouts at a depth of 5 cm (Figure 1 AB). Lang & Melhuish (1970) derived theoretically that, provided the direction of root growth is random, the number of root intersections can be multiplied by 2 to arrive at an estimate of the volumetric root length density (RLD = 2 * NR). After calibrating the (Rhizolab) minirhizotron observations with auger sampling Smit *et al.* (1994) found indeed that Brussels sprouts and leeks follow about this theoretical relationship, so 5–6 roots per cm^2 are equivalent to a volumetric RLD of 10–12 $cm\ cm^{-3}$.

In the Rhizolab experiments Brussels sprouts rooted the deeper layers to 100 cm in both years relatively homogeneously with values between 1 and 2 roots per cm^2, which corresponds with a volumetric root length density of 2–4 $cm\ cm^{-3}$. At a depth of 100 cm, root numbers increased faster than at other depths, probably caused by the border effect of the two horizons in the compartments.

The rooting intensity found in the Rhizolab corresponded with those found in the field experiments of 1991 and 1992 (Figure 1CD), also here very high RLD were found in the 0–10 cm layer (>10 $cm\ cm^{-3}$) similar to the values for NR after conversion.

Compared to the Rhizolab experiments, rooting of deeper layers in the field was

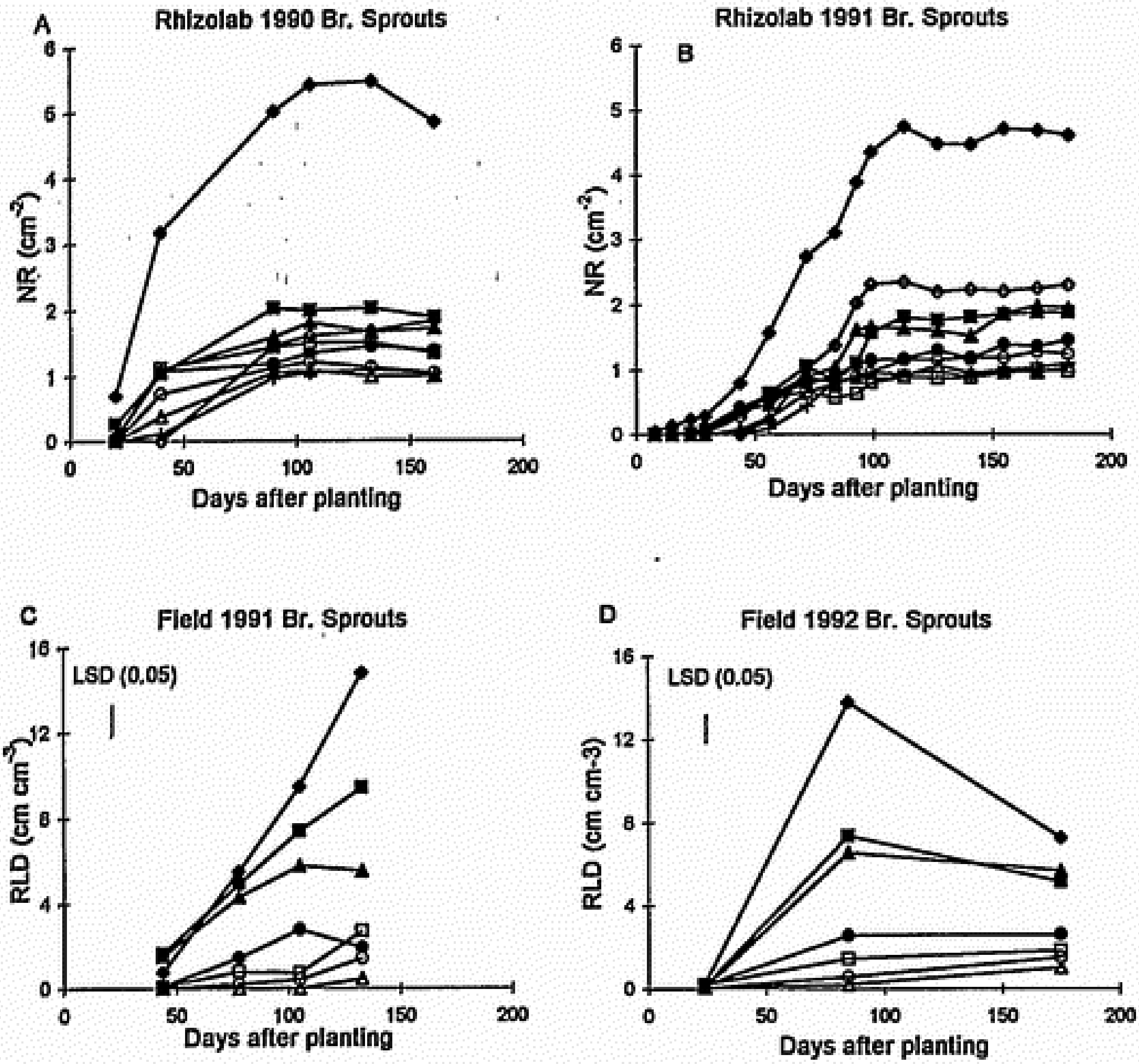

Figure 1. Number of root intersections per cm² minirhizotron surface (NR) of Brussels sprouts in 1990 (A) and 1991 (B) in the Wageningen Rhizolab with depth (◆ = 5 cm, ■ = 10 cm, ▲ = 15 cm, ● = 20 cm, □ = 30 cm, ○ = 45 cm, △ = 60 cm, + = 80 cm, ◇ = 100 cm) and time. Root length density (RLD in cm cm^{-3}) of the same crop with depth (◆ = 0–10 cm, ■ = 10–20 cm, ▲ = 20–30 cm, ● = 30–40 cm, □ = 40–50 cm, ○ = 50–60 cm, ◇ = 60–70 cm) and time as observed in field experiments in 1991 (C) and 1992 (D).

less homogeneous. In both years rooting decreased more gradually with depth, with still high root length densities in the layers between 10 cm and 30 cm. Below 30 cm root length density was usually below 2 cm cm^{-3}, but at the end of the season it generally exceeded a value of 1 cm cm^{-3}, even in the layer 50–60 cm. Especially in the field experiment of 1992 a decrease in RLD was observed, indicating that roots had died. Probably this was also the case in 1991 but then the last sampling was earlier in the season.

Leeks

Maximum root numbers in the Rhizolab experiments for leeks (Figure 2AB) were 1.1 (1991) and 1.7 cm^{-2} (1992), which is substantially lower than maximum root numbers observed in Brussels sprouts. The figures correspond to a RLD of 2.2 and 3.4 cm cm^{-3}. Maximum RLD in the field was somewhat lower than this, slightly above 2 cm cm^{-3} (Figure 2CD).

An interesting phenomenon with leeks is the distribution of roots in the profile. Maximum rooting intensity was not found as usual for most crops in the upper soil layers but between 15 and 25 cm depth. In the Rhizolab experiment of 1991 throughout the season few roots were observed at a depth of 5 cm, whereas in 1992 rooting in this layer only increased during the second half of the growing season. The same

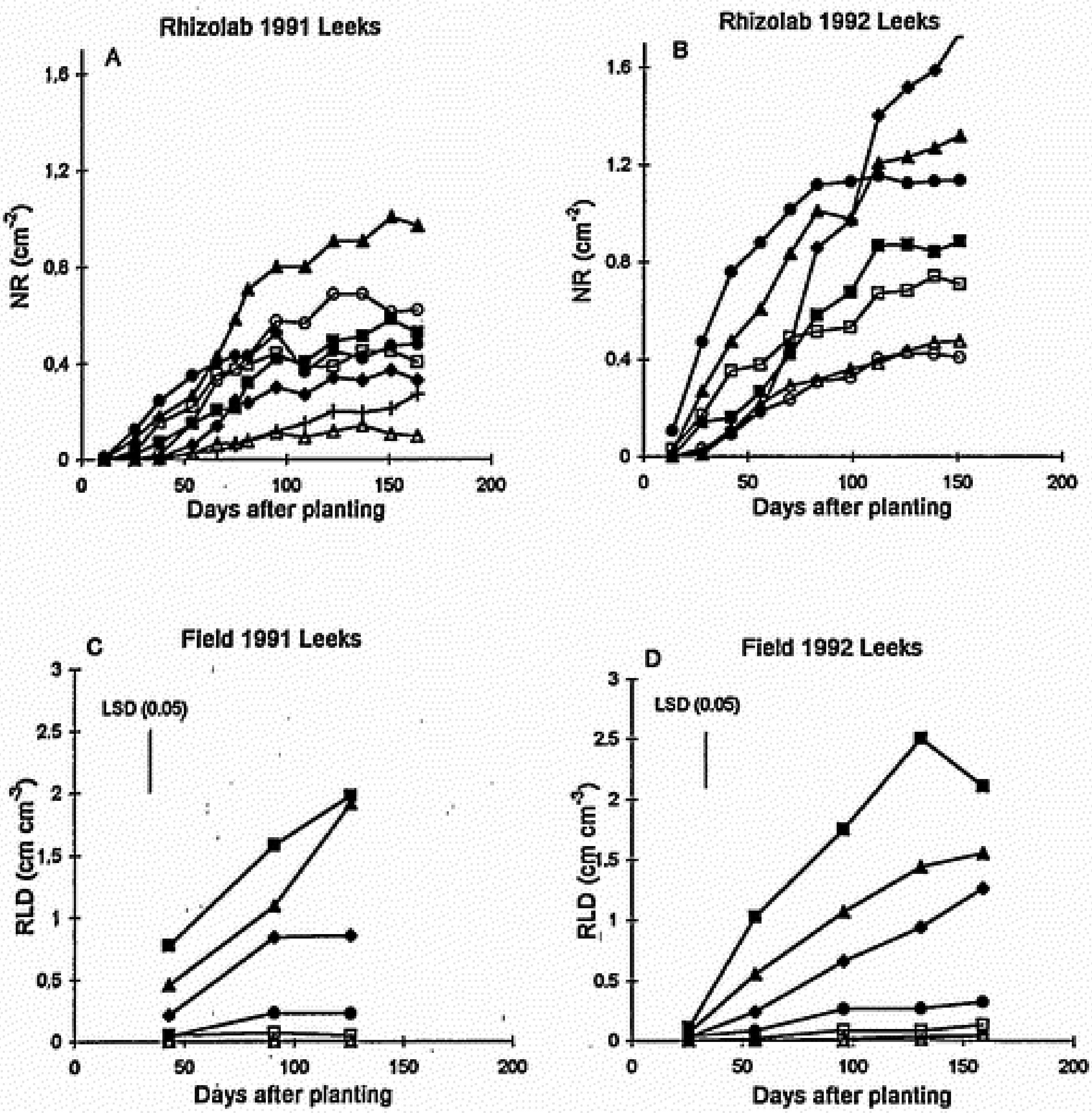

Figure 2. Number of root intersections per cm^2 minirhizotron surface (NR) of leeks in 1991 (A) and 1992 (B) in the Wageningen Rhizolab with depth (◆ = 5 cm, ■ = 10 cm, ▲ = 15 cm, ● = 20 cm, □ = 30 cm, ○ = 45 cm, △ = 60 cm, + = 80 cm, ◇ = 100 cm) and time. Root length density (RLD in cm cm^{-3}) of the same crop with depth (◆ = 0–10 cm, ■ = 10–20 cm, ▲ = 20–30 cm, ● = 30–40 cm, □ = 40–50 cm, ○ = 50–60 cm, △ = 60–70 cm) and time as observed in field experiments in 1991 (C) and 1992 (D).

distribution of roots was found in the two field experiments: most of the roots were between a depth of 10 and 30 cm and leeks showed a very low RLD below 30 cm.

Rooting depth and the rate of increase in rooting intensity after planting

The regression of NR and RLD on thermal time with the described regression model explained variance for more than 70% in most of the experiments (bottom line, Table 2). Two field experiments, Brussels sprouts (1992) and leeks (1991) could not be analysed because of the limited number of sampling dates which prevented a proper estimate of the parameters. In the remaining experiments for each depth or layer estimates were obtained of the parameters K_i (the thermal time needed after planting for the 'root front' to reach depth i) and A_i (the increase per °C day in NR (Rhizolab experiments) or RLD (field experiments)).

Subsequently, with the estimated parameters for each depth in the Rhizolab the thermal time was calculated for NR to exceed 0, 0.25 and 0.5 cm^{-2}. For the field experiments the same procedure was followed but now the predictions were made for a RLD of 0, 0.5 and 1 cm cm^{-3} in order to compare the rooting intensity of Rhizolab and field experiments at (theoretically) corresponding levels. The levels of rooting intensity were chosen rather low to give information in a range (between 0 and 1 cm cm^{-3}) where uptake of nutrients and water is thought to be limited by root length *per se*, although under dry conditions also higher root length densities might be limiting (De Willigen & Van Noordwijk, 1987).

Brussels sprouts

In Figure 3A for Brussels sprouts the line for NR = 0 shows for each depth the thermal time after planting when the first roots appeared (= K_i). The graph shows that the first roots in 1990 appeared at a depth of 100 cm after 750 °C days (about 50 days). The slope of this line gives an indication of the rate of vertical root growth, about 0.13 cm (°C day)$^{-1}$, which in this experiment corresponds with about 2.0 cm day^{-1}. At each depth the vertical distance between the lines in the graph indicate the thermal time elapsed between the indicated levels of NR. The graph then shows that the rooting pattern of Brussels sprouts enables a very fast exploring of the soil profile, roots appeared not only within 750 °C days after planting at all depths of the soil profile, also the root number increased rapidly: from 0 to 0.5 roots per cm^{-2} took not more than 600 °C days (about 30 days) and for most of the depths even less.

A similar pattern showed the Rhizolab experiment of 1991 for Brussels sprouts (Figure 3B). In this graph (and also in some of the following graphs) the line for NR = 0 does not cross at any depth the abscissa which indicates that at least at one depth the thermal time at which NR exceeds 0 is overestimated, probably because of a non-linear relation between NR and thermal time in the first weeks after transplanting.

Figure 3C shows the thermal time needed to achieve a RLD of 0, 0.5 and 1 cm^{-3} cm for the field experiment of 1991. The graph shows a very fast increase in RLD in the soil layers from 0 cm to 40 cm. An increase in RLD from 0 cm cm^{-3} to 1 cm cm^{-3} would take only 200–300 °C days (corresponding in this experiment to about 8 to 18 days). Contrary to the Rhizolab observation, the increase in RLD in time was much slower below 40 cm.

Table 2. Regression of number of roots (NR, Rhizolab) and root length density (RLD, Field) on thermal time after planting for Brussels sprouts and leeks. For each depth or layer i, estimates for K (lag time) and A (rate of increase) of RLD and NR are indicated. Depths and layers in cm are described in the Materials and Methods section. s.e = standard error.

	Brussels sprouts						Leeks					
	Rhizolab 1990		Rhizolab 1991		Field 1991		Rhizolab 1991		Rhizolab 1992		Field 1992	
Parameter	estimate	s.e.	estimate	s.e.	estimate	s.e.	estimate	s.e.	estimate	s.e.	estimate	s.e.
K_1	−15	65	334	35	540	54	732	173	713	85	631	233
K_2	68	235	238	107	327	102	501	150	301	210	348	72
K_3	41	298	455	109	238	148	377	66	153	118	359	121
K_4	−53	270	203	121	745	467	26	125	−149	163	323	628
K_5	11	314	126	165	456	685	254	137	−17	284	585	2419
K_6	110	376	251	120	844	2420	616	78	375	315		
K_7	324	522	562	130	623	483	679	589	410	259		
K_8	650	275	777	114			788	432				
K_9	740	404	769	57								
A_1	0.003513	0.000263	0.003224	0.000152	0.00816	0.00065	0.000365	0.000109	0.001023	0.000181	0.000662	0.00015
A_2	0.001457	0.000361	0.000907	0.000126	0.00542	0.00065	0.000348	0.000071	0.000461	0.000126	0.001443	9.28E-05
A_3	0.001175	0.000361	0.001367	0.000210	0.00406	0.00065	0.000638	0.000054	0.000767	0.000105	0.00085	9.28E-05
A_4	0.000877	0.000263	0.000835	0.000126	0.00293	0.00182	0.000342	0.000041	0.000736	0.000105	0.000168	9.28E-05
A_5	0.001061	0.00034	0.000538	0.000110	0.00071	0.00065	0.000351	0.000054	0.000375	0.000105	0.000063	0.00144
A_6	0.000876	0.000361	0.000801	0.000126	0.00049	0.00181	0.000575	0.000072	0.000281	0.000126		
A_7	0.000908	0.000549	0.000997	0.000210			0.000115	0.000108	0.000327	0.000126		
A_8	0.001182	0.000553	0.001305	0.000301			0.000133	0.000109				
A_9	0.00198	0.00115	0.002650	0.000301								
% explained variance	75.7		92.0		70.2		86.1		70.0		59.3	

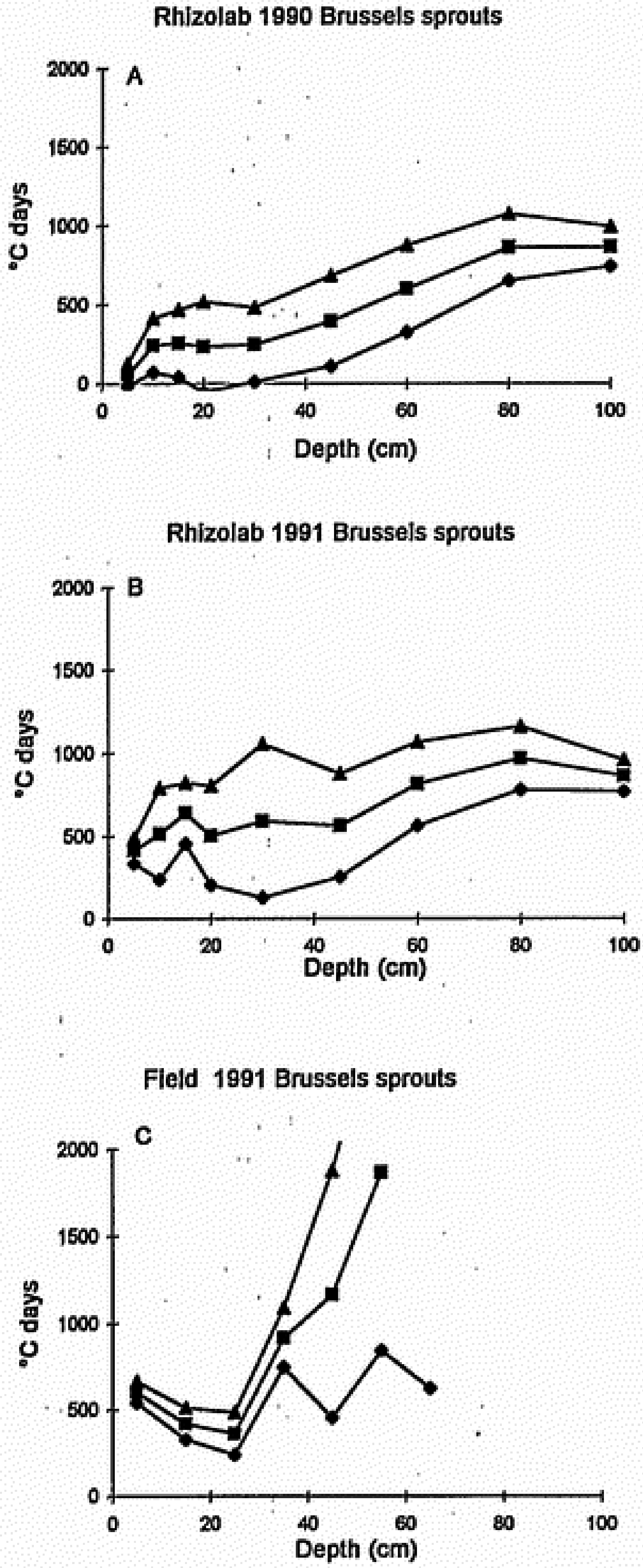

Figure 3. Thermal time after planting of Brussels sprouts which elapses before a certain level of NR (◆ = 0 cm^{-2}, ■ = 0.25 cm^{-2}, ▲ = 0.5 cm^{-2}) is attained in 1990 (A) and 1991 (B). The same for RLD (◆ = 0 cm cm^{-3}, ■ = 0.5 cm cm^{-3}, ▲ = 1 cm cm^{-3}) in the field in 1991 (C). The calculations were made on the basis of a regression procedure of NR and RLD on thermal time.

Leeks

For leeks grown in the Rhizolab in 1991 the thermal time needed to reach the three levels of NR (0, 0.25 and 0.5 cm^{-2}) is shown for each depth in Figure 4A. The line for NR = 0 cm^{-2} shows that rooting proceeds from a depth of 20 cm, about the depth at which the leeks were planted. The regression procedures predict the root front to appear at a depth of 80 cm after 750 °C day (about 40 days after planting). This would correspond to a vertical root growth rate, from a depth of 20 cm to 80 cm, of 0.08 cm (°C day)$^{-1}$, about 1.5 cm day^{-1}. At a depth of 5 cm the first roots also appeared after 700 °C days (40 days) after planting, these roots apparently grew upwards from a depth of 16 cm where the base of the plants was located (the planting depth).

An increase in root number from 0 cm^{-2} to 0.5 cm^{-2} takes, depending on depth, 800–1500 °C day in this crop (40–80 days). At depths lower than 45 cm, however, even a root number 0.25 cm^{-2} is not reached within 120 days after planting.

Figure 4B shows the same spatial pattern of leek roots in the soil profile for the Rhizolab experiment of 1992, the increase in root numbers was somewhat faster than in 1991 especially in the shallower layers of the profile. In the field experiment of 1992 (Fig. 4C) the rate of increase in root length density below 30 cm and above 10 cm was lower than in the Rhizolab experiments.

Discussion

Differences in rooting dynamics of Brussels sprouts and leeks

The results presented in this paper show that the rooting pattern of leeks in many aspects differed from the rooting pattern of Brussels spouts. Both in Rhizolab and field leek roots were concentrated in a relatively small part of the profile, between 20 and 30 cm below soil level, whereas Brussels sprouts intensely rooted the profile.

Based on the present study leeks can be characterised as a crop with a low root length density, because during the growing period RLD did not exceed 1 cm cm^{-3} in the greater part of the profile. The crop can also be characterised as a shallow rooting crop. Especially in the field experiments few roots were observed below 30 cm in both years. In the Rhizolab the crop tended to root deeper but also here proliferation of the roots was slow. Under the favourable circumstances of the Rhizolab the vertical growth rate of leeks was still lower than of Brussels sprouts (0.08 cm (°C day)$^{-1}$ vs. 0.13 cm (°C day)$^{-1}$). The value of Brussels sprouts was similar to the rate of root extension found by Masse *et al.* (1991) of winter wheat (0.12 cm (°C day)$^{-1}$). The vertical growth rate in cm day^{-1} for leeks and Brussels sprouts was calculated to be about 1.5 and 2.0 cm day^{-1} respectively. Bland (1993) found in a Rhizolab-like facility an increase in rooting depth between 1.7 and 0.7 cm day^{-1} for cotton and between 2.6 and 0.9 cm day^{-1} for soybean dependent on the soil temperature in his experiments. Bland (1993) also suggested the hypothesis that root system growth can be predicted from the local soil temperature of the deepest roots. If correct, root growth is better estimated from accumulated soil temperature (at the deepest roots) than by thermal time above ground used in this study.

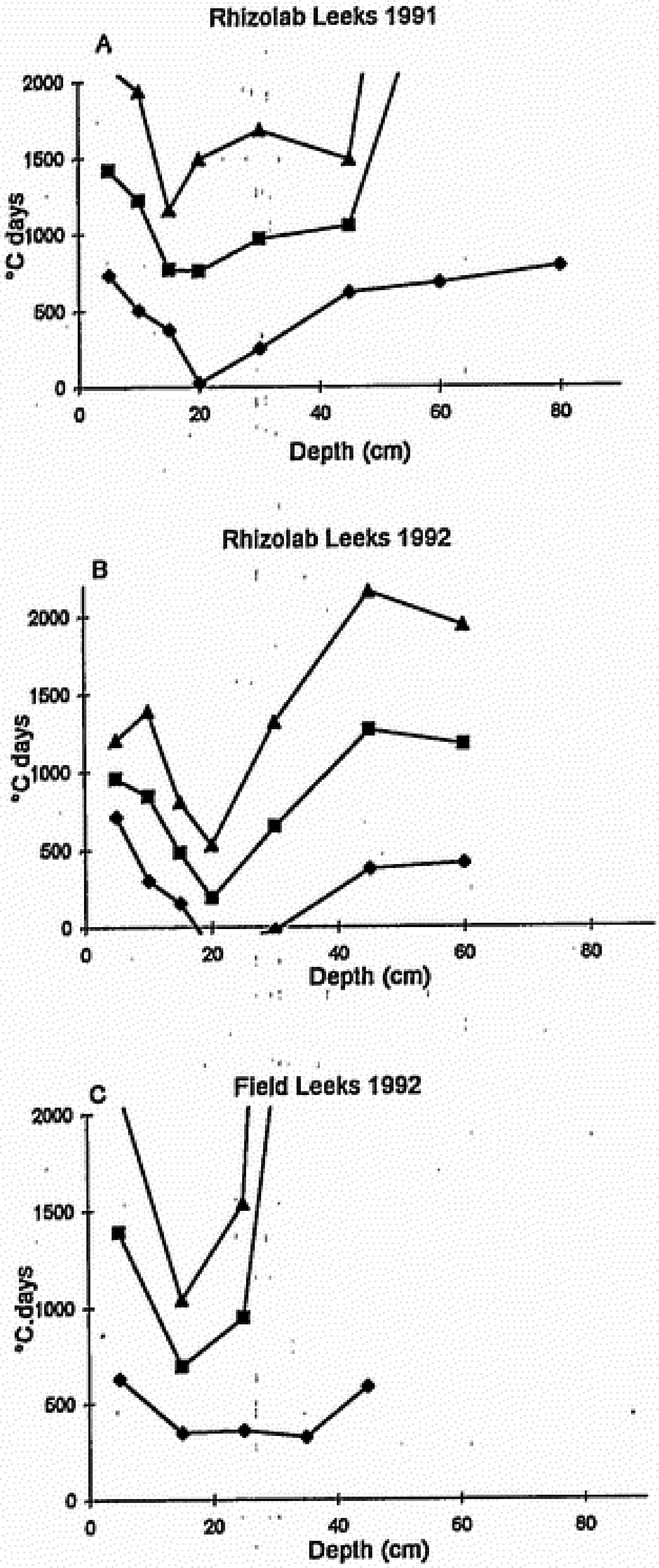

Figure 4. Thermal time after planting of leeks which elapses before a certain level of NR is attained in 1991 (A) and 1992 (B). The same for RLD in the field in 1992 (C). The meaning of the symbols is as in Figure 3. The calculations were made on the basis of a regression procedure of NR and RLD on thermal time.

Apart from rooting depth the two crops differ mainly in the rate of root proliferation, which is at all depths lower for leeks than for Brussels sprouts. Figures 3AB and 4AB show that the thermal time which elapses between appearance of the first roots and NR = 0.5 cm^{-2} is longer for leeks than for Brussels sprouts. At depths between 0 and 45 cm it takes leeks 800–1500 (40 to 80 days) and Brussels sprouts about 600°C day (about 35 days) at the most to attain a root number of NR = 0.5 cm^{-2}. Below 45 cm leeks root numbers higher than 0.25 cm^{-2} were reached slowly. This slow proliferation might be connected with the inherent low-branching character of leek roots.

In the field, at depths below 40 cm, for both crops the rate of increase of RLD with thermal time seems lower than in the Rhizolab experiments (Figures 3C and 4C), probably because root growth in the field is mechanically impaired by a higher bulk density of the subsoil in the deeper layers (Unger & Kaspar, 1994). In the Rhizolab compartments, compared to the field, conditions are more homogeneous with depth. Moreover, as has been mentioned earlier, high water tables (to a depth of 60 cm) occurred occasionally in the field. This might also have negatively influenced rooting via water saturation and subsequent O_2-deficiency. The results suggest that for a reliable prediction of rooting intensity in the field the influence of site specific physical factors should be taken into account. Data obtained in the Rhizolab can give for a particular crop an indication of the potential rooting depth and intensity.

Consequences for nitrogen utilisation

How decisive is the temporal and spatial rooting pattern of Brussels sprouts or leeks for nitrogen utilisation? Root length density of leeks in the upper part of the soil profile is much lower than of Brussels sprouts (Figures 1,2). According to De Willigen & Van Noordwijk (1987), however, even a root length density of 1 cm cm^{-3} would be sufficient to allow an uptake of 3 kg ha^{-1} day^{-1} N. The daily uptake rate of leeks in general is not higher (Booij *et al.*, 1993), but a partial root-soil contact, root clustering and drought conditions can raise the critical root length density. It nevertheless is not likely that the low nitrogen recoveries of leeks can be explained with a low root length density in the rooting zone.

Probably, the combination of shallow rooting and the time course of N-demand of leeks is the main explanation for the low nitrogen utilisation. Smit *et al.* (1995) have shown that a Brussels sprouts crop takes up virtually all nitrogen in a relative short period after planting. The relatively short period of uptake in combination with the deep and intense rooting of this crop seem to ascertainalmost that no nitrogen leaches. Leeks, however, with its slow initial growth, takes up nitrogen more evenly over the growing period, with still considerable uptake after 1 September. To keep nitrogen in the narrow and shallow rooted zone for a long period is therefore more difficult for this crop, especially under heavy rainfall or irrigation. The temporal and spatial pattern of rooting and the course of N demand urge the growers of leeks to pay more attention to split applications of nitrogen, more conclusive than is done now in practice. A late application coincides more with the demand of the crop and is less likely subject to leaching. Although rooting of leeks is more confined to depths of

10 to 30 cm, the rooting intensity of the top layer (about 1 cm cm^{-3} at 0–10 cm) at the end of the season would allow an immediate uptake. Root data presented in this paper can be used in simulation models to develop more sophisticated site-specific fertilisation scheme's for leeks.

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