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The Wageningen Rhizolab – a facility to study soil-root-shoot-atmosphere interactions in crops

II. Methods of root observations

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Abstract

Roots in the Wageningen Rhizolab are observed using two methods: (i) non-destructively, using horizontal, glass minirhizotrons at intervals of 14 days between observations; (ii) with destructive sampling using augers on three dates in the season. This paper reports changes with depth and time in root numbers per unit interface area of the minirhizotron tube (number of intersections) of four crop species (wheat, Brussels sprouts, leek and potato). The number of root intersections of Brussels sprouts, wheat and potato declined with depth at any time, whereas leek showed a different pattern because maximum root growth was observed at a depth of 10–20 cm. Root density generally decreased in the following order: Brussels sprouts, wheat, potato and leek. Plots of root length densities, L_{rv}(cm. cm^{-3}), obtained by auger sampling, versus the number of intersections showed considerable variation in slope with species, time in the season and year, implying that a single, universal equation to convert minirhizotron observations into volumetric root densities does not exist. Causes of variation in the slopes are discussed. It is concluded that limited auger sampling combined with minirhizotron observations yield adequate quantitative estimates of relevant root properties.

Introduction

The Wageningen Rhizolab was built to study processes in the soil and in the plant canopy simultaneously (Van de Geijn et al., 1994). Current agriculture is challenged to use such resources as nutrients and water as efficiently as possible to produce in an environmentally acceptable way. Knowledge of transport, uptake and utilisation processes is important to design strategies for optimum use. Roots play a key role in the uptake of water and nutrients. Therefore, reliable quantitative measurements of root growth and distribution in the soil profile are essential.

Root studies in the Rhizolab are also important for applications other than in agriculture. Measurements of root dynamics can throw light on the mechanism of competition between species in natural vegetations and on adaptation of species to their habitat. In the light of maintaining ecodiversity, such knowledge becomes more and more important for the management of natural surroundings.

In this paper the methodology of the root observations in the Wageningen Rhizolab is described. Root growth is quantified with two methods (i) non-destructively using horizontal, glass minirhizotrons and intervals of 14 days between observations; (ii) with destructive sampling using augers limited to three dates in the season.

Several attributes of roots such as dry weight, surface area and length can be quantified. Concepts and

models dealing with uptake of nutrients and water commonly use the volumetric root length density as the most relevant variable explaining the behaviour of the system (e.g. Barraclough, 1986; De Willigen and Van Noordwijk, 1987). Assessment of the volumetric root density (L_{rv} in cm root length per cm^3 soil), however, is only possible with auger sampling. Therefore, the nature and the stability of the relationship between minirhizotron observations and L_{rv}, was analysed for various crops in the experiments ran in the Wageningen Rhizolab in 1990–1992.

Material and methods

Crops

In the Wageningen Rhizolab plants are grown in a crop situation by surrounding the compartments with border rows (Van de Geijn et al.; 1994). Root observations of four crops in the period 1990–1992 were analysed for this paper (Table 1). Leek, Brussels sprouts and wheat were cultivated by applying common crop husbandry. To diminish plant variation in potatoes, 15 cm tall sprout cuttings were planted without ridging. Four compartments per year were available for each crop, except in 1991 when Brussels sprouts and leek were grown in only two compartments.

Except for wheat in 1990, different treatments were allotted to compartments within each crop species. The treatments consisted of various CO_2-levels (wheat), nitrogen rates (Brussels sprouts and leek), water supply and presence of potato cyst nematodes (potatoes). This paper focuses on root observations and the effects of treatments on crop performance are not discussed.

Rows of wheat and leek were perpendicular to the direction of the minirhizotrons.

Soil profile in the compartments

The soil profile in the compartments of 1.25 m × 1.25 m × 2.00 m (width × length × depth) consisted of a top layer of 1 m of humic sand (4.1–4.8% organic matter, pH-KCl 4.9–5.5) and a 1-m subsoil layer of coarse sand without organic matter into which the roots did not penetrate, very probably caused by the fact that the moisture content in the upper layer of the coarse sand (at −115 cm) usually was very low (± 5%). The compartments were filled manually by adding successive layers of approximately 5 cm. Upon adding a new layer, the soil was compressed manually

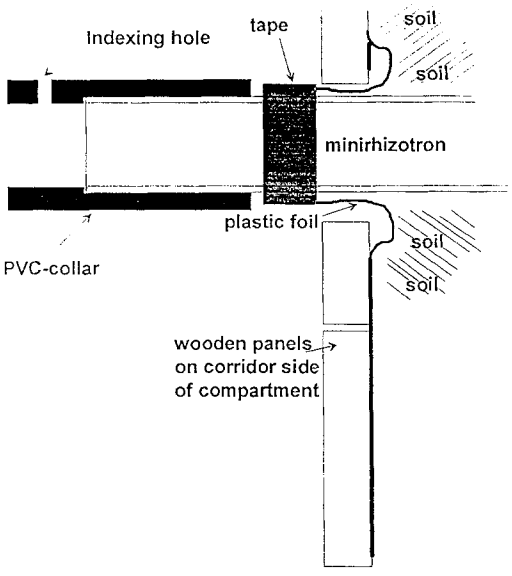

Fig. 1. Minirhizotron end protruding into the corridor with PVC-cap and indexing hole.

to a bulk density of 1.51 g cm^{-3} (subsoil) or 1.32–1.47 (top soil); these soil densities were measured by taking samples. Capacitance moisture sensors (for measuring the volumetric moisture content as well as temperature and electrical conductivity), thermocouples, samplers for soil solution and soil air, and minirhizotrons were placed in fixed positions during the process of filling the compartments. (Van de Geijn et al., 1994).

Installation of minirhizotrons

Glass minirhizotrons were chosen, because the properties of glass (silicon) approximate those of the natural soil particles, which avoids electrostatic interferences with root growth (Voorhees, 1976). Twelve minirhizotrons (length 130 cm, outer diameter 6.00 cm and inner diameter 5.36 cm (tolerance 0.1–0.2 cm)) were installed horizontally during the filling of the compartments with the top side of the minirhizotron at 5 cm, 10 cm, 15 cm, 20 cm, 30 cm, 45 cm, 60 cm, 80 cm, 100 cm, 125 cm, 150 and 175 cm below the soil surface. The open end of the minirhizotrons protruded approximately 20 cm into the corridor. To allow downward movement of the tubes, resulting from further compaction of the soil during the course of the season, the holes in the wooden panels of the corridor side were ellipse-shaped with a largest diameter of 10 cm in the vertical direction.

Table 1. Experimental details of the crops grown in the Wageningen Rhizolab. In the last column the first mentioned distance is parallel to the minirhizotrons

Crop	Number of compartments	Planting date	Harvest date	Auger sampling			Row distance/ plant distance(cm)
				Early	Middle	Late	
Wheat 1990	4	29/5	27/9	12/7	8/8	25/9	12 × 4
Wheat 1991	4	4/4	26/8	5/6	2/7	29/8	10 × 4
Potato 1990	4	31/5	3/10	12/7	8/8	2/10	20 × 25
Potato 1991	4	17/5	29/10	9/7	7/8	30/10	20 × 25
Br. sprouts 1990	4	7/6	13/11	25/7	4/9	15/11	45 × 45
Br. sprouts 1991	2	30/5	28/11	12/7	21/8	27/11	63 × 42
Leek 1991	2	17/6	28/11	24/7	21/8	27/11	42 × 14
Leek 1992	4	12/6	13/11	22/7	19/8	9/11	42 × 14

To ensure a water and gas tight system, the wooden panels were lined on the inside with a plastic sheet. At the locations of the glass tube, the linen was provided with a cuff which also protruded into the corridor side, there it was taped to the minirhizotron tubes (Fig. 1). The minirhizotrons were stuffed with cylindrical insulating foam to prevent temperature gradients between the outer surface of the tubes and the adjacent soil. Thermocouples placed on the glass surface and in the bulk soil indicated that temperature differences between the minirhizotron and the soil never exceeded 0.1°C. Possible adverse effects of light on root growth (Voorhees, 1976) were also avoided by the insulating material in the tube and by a metal can which was placed over the open end when the camera was not in use.

Installation of the tubes during compartment filling assured a good contact between soil and tubes; voids which could interfere with root growth were totally absent. Downward movement of the minirhizotrons during the season was negligible, indicating that a stable soil structure was achieved during the filling process. The positions of the 12 minirhizotrons in each compartment are shown in Fig. 2. The tubes were placed in four vertical lines (at 25 cm, 50 cm, 75 cm and 100 cm from the left side), enabling auger sampling in the vertical zones between the tubes. The vertical distance between the tubes was less near the surface than at greater depths because higher rates and faster changes with depth of processes in the top layers than in the bottom layers were expected.

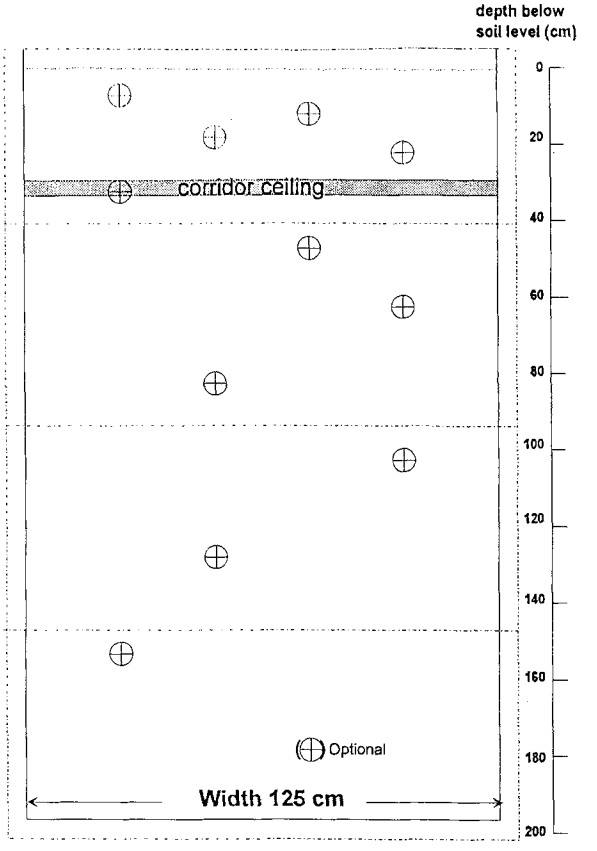

Fig. 2. View of the compartment from the corridor with the positions of the minirhizotrons.

Root observations with the camera system

Root observations were done with a minirhizotron-video-camera (Bartz Technology Company, BTC, San-

ta Barbara, CA, USA). The camera system was specifically designed for root observations because lighting and the video sensor can be placed directly inside the minirhizotron access tube.

On the open end of the mini-rhizotrons a PVC (polyvinylchloride) collar (Fig. 1) was glued to attach the camera system. A 0.5-cm hole on the upper side of the collar was used to position the camera-head on prefixed locations along the minirhizotron tube. This made it possible to compare recordings between observation dates throughout the season.

The camera system consisted of the following modules:

(i) camera head (4.9 cm diameter and 34.2 cm long) and cable. The colour CCD (Charged Coupled Device) video camera used a 12.7 mm video sensor to provide 570 horizontal and 485 vertical pixels for 360 horizontal and vertical TV-lines. The field of view on the exterior of the minirhizotron tubes was 1.3 cm × 1.8 cm.

The light system consisted of four 5-mm 1.2-Watt incandescent bulbs. An ultra violet light option was also available: two quartz Ultra Violet pencil lamps 9 mm in diameter by 50 mm long producing 1000 μW/cm2 at 365 nm wavelength at a distance of 1.91 cm from the bulbs. The camera system incorporated an electrically controlled remote focus system and an adjustable white lighting system.

(ii) a square (2.5 cm) aluminium 120 cm (slide)handle allowed movement of the camera along the tube while keyed to the index hole at the top of the PVC-cap (described above). The design was modified from an original design described by Ferguson and Smucker (1989). The camera can be returned exact to locations at 1.25 cm mutual distances; the first position (number 1) is 14.5 cm from the inside of the corridor side and the the last one (number 70) is 102 cm from the corridor side.

A position of a root observation is defined here as a 1.3 cm × 1.8 cm = 2.34 cm^2 area along the upperside of the horizontal minirhizotrons; the 1.3 cm dimension is parallel to the direction of the tube. This means that adjacent positions on the minirhizotrons were recorded with an overlap of 0.05 cm.

(iii) a Camera Control Unit which enabled adjustable lighting and remote focus;

(iv) a high resolution 35 cm colour monitor (Sony PVM142 QM, super fine pitch, 0.25 mm dot pitch) for viewing and focusing;

(v) a S-VHS video recorder (JVC-BR600).

Root observations usually started 14 days after sowing or planting of the crop and were repeated every 14 days during the growing season. At low root densities (roots visible at less than half of the positions) each position was recorded for at least one to two seconds; at higher root densities every second position was recorded. Compartment number, minirhizotron depth and position number were recorded on the audio track of the video tape by voice.

Processing of root recordings

The video tapes were processed by manually counting the number of roots visible in each image. Following Upchurch (1986), side and lateral branches were counted as separate intersections. Decaying roots (substantial shrinking combined with a black or grey appearance) were not counted. The number of intersections was calculated per cm^2 minirhizotron surface. Usually the average number was calculated for each minirhizotron tube (depth), but see the next paragraph.

Assessment of root distribution in the vertical and horizontal plane

For crops with relatively small distances between plants and rows, the average number of roots of all positions along a tube (usually 30) was used as an estimate of the root density for the corresponding depth. If plants of a crop are widely spaced (e.g. Brussels sprouts were grown with a plant density of only 4 plants per m^2, Table 1), it can be assumed that large differences in rooting density occur in the horizontal plane, especially early in the season and in the upper soil layers. To evaluate whether the limited number of minirhizotron tubes also provides insight in the horizontal distribution of Brussels sprouts roots, the positions along the minirhizotrons were broken down into categories of similar horizontal distance to a plant. The number of root intersections were averaged for those positions which had a distance of approximately 6 cm, 13 cm, 19 cm, 23 cm and 29 cm from a plant. Because of the pattern of placement of the minirhizotrons (Fig. 2) in relation to the plant positions of Brussels sprouts (Table 1), certain combinations of depth and horizontal distance did not occur. For this crop at depths of −10 cm, −15 cm, −45 cm and −80 cm, no positions were present with a horizontal distance of 6 cm to a plant.

Auger samples

Auger samples were taken at 10 cm increments in a zone of 50 cm parallel to but most remote from the corridor (the 'rear end'). The diameter of the auger was 4.77 cm; auger samples therefore had a volume of 178.8 cm^3. In each compartment, four replicate samples were taken three times during the growing season.Two replicate samples were taken exactly between rows or plants and two samples were taken within the row or in the proximity of a plant. Sampling took place early in the season (as soon as roots were seen in the greater part of the profile), in the middle and at the end (at harvest) of the growing season for each crop (Table 1).

The soil samples were stored at −18°C until processed; after thawing samples were washed with a hydropneumatic elutriation system (Gillison's Variety Fabrication, Inc, Benzonia, Michigan, USA) based on principles described by Smucker et al. (1982). Root length of each sample was estimated by the modified Newman Line-Intersect method (Tennant, 1975) with a grid of 1 or 2 cm depending on the total length of the root sample.

Correlation between the number of root intersections and root length density

Volumetric root length densities as measured in auger samples were available for the 10-cm depth intervals from 0-100 cm. The number of root intersections, however, were observed at discrete depths (−5 cm, −10 cm, −15 cm, −20 cm, − 30 cm, −45 cm, −60 cm, and −80 cm). To enable comparison of the number of root intersections with volumetric root length densities, the latter were calculated for soil layers with an average depth corresponding to the depth of observations with the minirhizotrons (Table 2). For instance, minirhizotron observations at −20 cm were matched with the average of the (8) auger samples from the 10-cm −20-cm and the 20-cm −30-cm layers.

Also another method was used. After regression of root length densities on depth, interpolations were made at the depths of the minirhizotrons. For potatoes this led to the same conclusions, for other crops the latter method was not used.

The root length density (L_{rv}) was regressed on the number of root intersections with the statistical program Genstat (Payne et al., 1987) forcing the regression line through the origin. Separate regressions were carried out for each combination of crop and year.

Table 2. Depth of the minirhizotron observations and the corresponding soil layer. Where applicable root length densities (L_{rv}), assessed in individual 10-cm soil layers, were pooled to calculate the average root length density in the corresponding soil layer

Depth of minirhizotron (cm)	Corresponding soil layer
5	0–10
10	0–20
15	10–20
20	10–30
30	20–40
45	40–50
60	50–70
80	70–90
100	90–100

Auger sampling date was treated as an additional factor, because it accounted for most of the variance within a year.

Results

Root growth in depth and time

Figure 3a-c show the average number of root intersections versus depth and time for wheat, Brussels sprouts and leek. The rooting characteristics were clearly different between crop species. In wheat the number of intersections increased at any depth during the first half of the season of 1990 and decreased during the second half of the growing season. Especially early in the season, rooting decreased exponentially with increasing depth; maximum values encountered at a depth of −5 cm were 2.7 cm^{-2}; below −60 cm the number of intersections never exceeded 1.0 cm^{-2} at any time.

For Brussels sprouts (Fig. 3b) the number of intersections at any depth and time was at least as high as on the previous date, except for the last date of observation when slightly lower rooting densities were found in the top layers. In 1991 the maximum values at -5 cm were close to 5 cm^{-2}; from 9 August onwards most values were higher than 1 cm^{-2} at any depth and time. The cumulation of roots that was found in the 80–100-

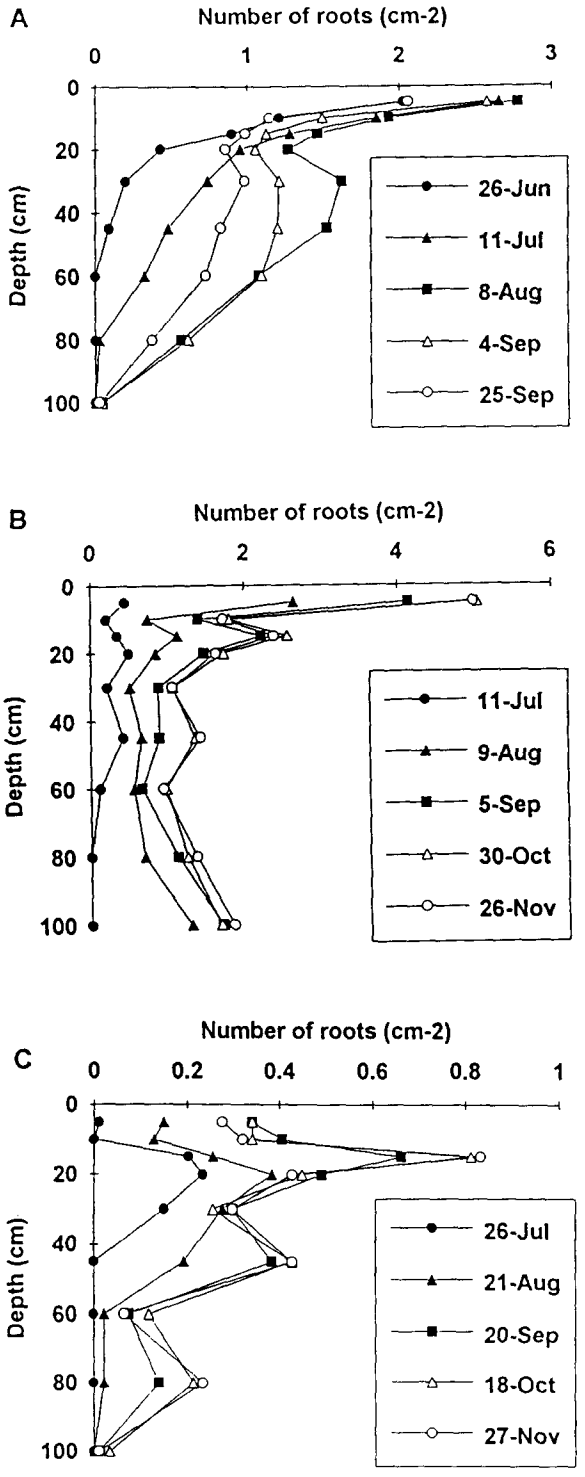

Fig. 3. Number of root intersections per cm^2 minirhizotron surface of wheat (**A**, average of four compartments in 1990), Brussels sprouts (**B**, one compartment in 1991) and leek (**C**, one compartment in 1991) with depth and time.

cm layer was possibly caused by the border effect of the two soil horizons.

Leek (Fig. 3c) showed a characteristic rooting pattern which differed from those of wheat and Brussels sprouts. A continuous increase in the number of roots was observed throughout the season. The maximum number of root intersections at any depth and any time of observation was smaller than 1 cm^{-2}; this maximum was not found at −5 cm but at −15 cm. At lower depths the number of intersections was smaller than 0.4 cm^{-2}. Rooting of significance was almost completely confined to the layer −10 cm to −45 cm. Also at −5 cm almost no root growth was observed.

Root growth observations in the horizontal direction

Figure 4 shows for Brussels sprouts the variation in root growth in the horizontal and vertical plane on 9 August (Fig. 4a) and on 3 October 1991 (Fig. 4b). As early as on August 9 this crop showed uniform rooting throughout the profile with the exception of the observations at −5 cm depth. In this top layer the number of roots was slightly over 6 cm^{-2} near the plants, whereas values of about 2 cm^{-2} and less were found elsewhere in the profile. Root distribution on October 3 (Fig. 4b) was similar with that on August 9, except that the number of roots near the plant had risen to 12 cm^{-2}.

The relationship between root length density and root intersections

The relationship between n (the number of root intersections) and L_{rv} (the root length density determined by auger sampling) appeared to vary with year, date within a year and crop species (Fig. 5a-g).

For reference the line $L_{rv} = 2n$ is drawn in each graph; this line represents the theoretical relation between these variables as derived by Melhuish and Lang (1968) and Lang and Melhuish (1970) provided that there is no preferential direction of root growth.

For wheat, a reasonable correlation existed between the results of both methods in 1990 and 1991. In 1990, however, an increasing slope (L_{rv}/n) in the course of the season was observed whereas in 1991 the opposite occurred.

Compared to wheat, the relationship between n and L_{rv} showed much more variation for potatoes. Both in 1990 and 1991, a strong decrease of L_{rv}/n was observed in the course of the season (Fig. 5 c,d). Also for Brussels sprouts L_{rv}/n changed during the season with gen-

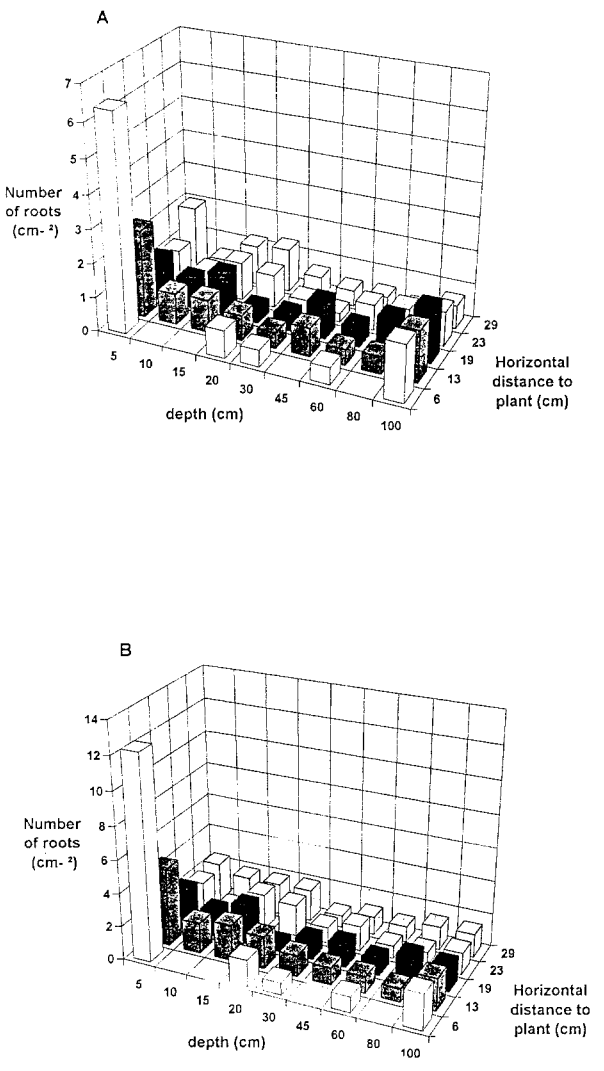

Fig. 4. Rooting in the horizontal and vertical plane of Brussels sprouts on 9 August 1991 (**A**) and on 3 October 1991 (**B**). Observations with a distance of 6 cm to a plant and at depths of −10 cm, −15 cm, −45 cm and −80 cm are missing

erally steeper slopes in 1991 than in 1990 (Fig. 5 e,f). For leek the relation was relatively constant with time (Fig. 5g, h), although more variation existed in 1992 than in 1991.

Table 3 summarizes the influence of crop, year and time within the year on the value of L_{rv}/n. In this table also the standard error of this parameter and the percentage of variance of L_{rv} accounted for by n and the sampling date are indicated for each crop/year combination. Except for 'wheat - late', L_{rv}/n was much lower in 1990 than in 1991 for all crops.

Discussion

The current minirhizotron method revealed differences between crops in inherent rooting depth and root distribution in the profile. For relatively widely spaced crops such as Brussels sprouts and leek (data not shown), a three dimensional pattern of the root distribution in the profile could be discerned. Leek differed from the other crops because maximum root growth occurred at −10 cm to −20 cm instead of an exponential decay with depth as observed in the other crops. This can be explained by reference to the rooting morphology of this crop (rooting confined to the base of the plant), the depth of planting and the fact that apparently fewer roots grew upward. The ultimate parameter that is needed to explain root functioning, however, is not the number of root intersections per unit surface area of a minirhizotron tube, but the volumetric root density. Several procedures were adopted to estimate the root length density from minirhizotron observations. Huck and Taylor (1982) and Cheng et al. (1991) assumed that they could observe roots behind the glass soil interface over a certain depth. This depth of view was used to calculate the root length density. Another, less arbitrary, method is to calibrate the minirhizotron observations to auger sampling, a method which is also followed in this study (cf. Vos and Groenwold, 1983, 1987).

Data presented here were based entirely on the number of intersections, but the question arises whether the length of the roots on the minirhizotrons would not relate better to the volumetric root densities obtained with auger sampling. However, in the course of a growing season the Wageningen Rhizolab generates tens of thousands of root observations. From a practical point of view the vast number of images by itself already requires a simple and reliable method for estimating the root density in the compartments. Making counts of root numbers is simpler than determining root length on each image. Automated processing of videotapes with image processing could solve that problem, but we do not plan to implement image processing at present because the current image analysis programs are not able to differentiate transparent roots from the background or to distinguish correctly between a dying root and a living root. In addition, it is also questionable whether the length of the roots on the image would give a better correlation with the root length density in the bulk soil. Following Upchurch (1986), it is assumed that the density of roots in the surrounding soil determines the number of arrivals of roots at the interface, but not necessarily

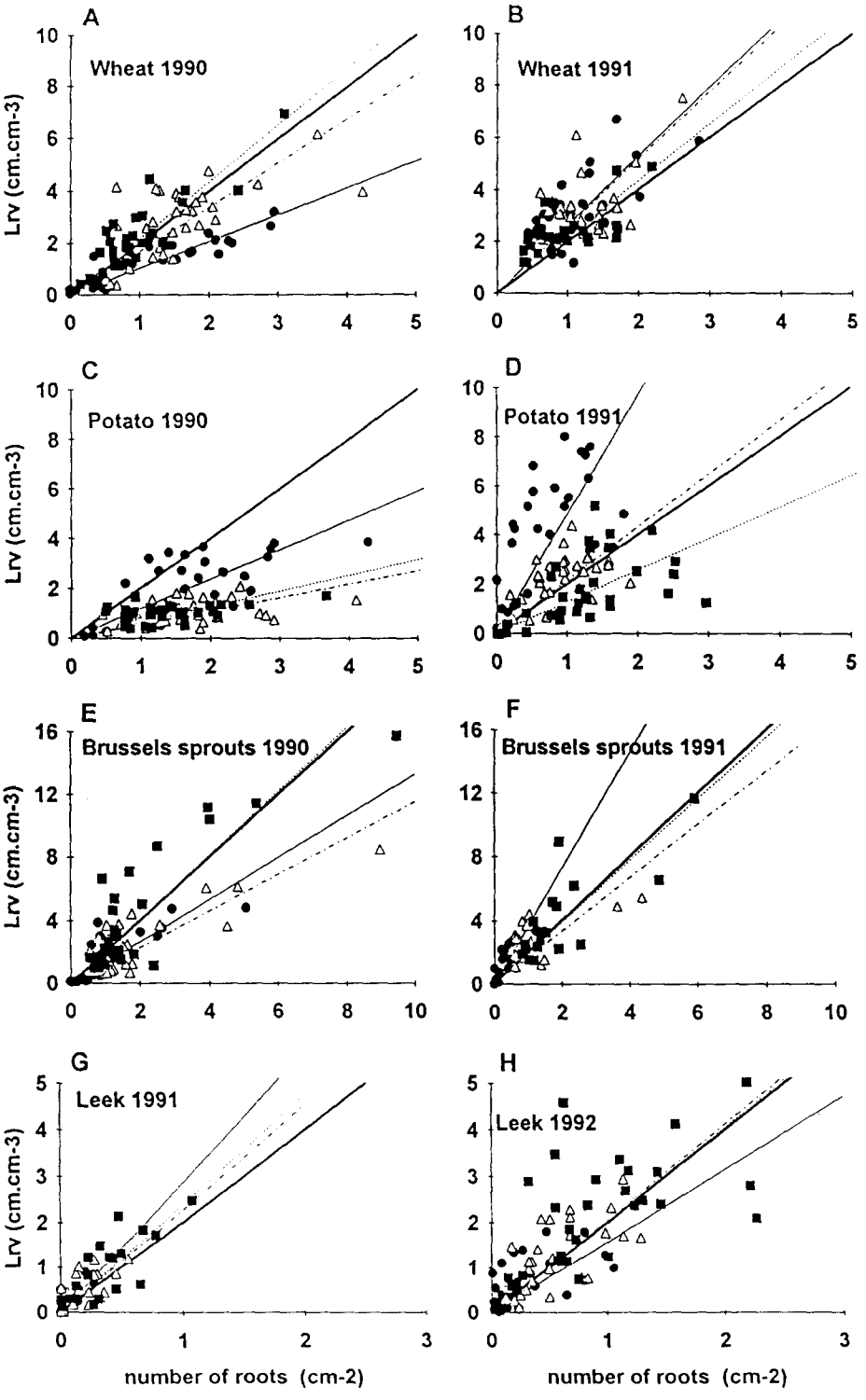

Fig. 5. The relationship (data points and regression line) between N (number of root intersections per cm^2) and the volumetric root length density (L_{rv}) early (•, ——), in the middle (Δ,–.–.–.–) and late (■, ...) in the growing season (dates in Table 1) for, respectively, wheat (**A**, 1990; **B**, 1991), potato (**C**, 1990; **D**, 1991), Brussels sprouts (**E**, 1990; **F**, 1991) and leek (**G**, 1991; H, 1992). The reference line y = 2x is drawn as a bold line in each graph (——)

Table 3. Values of root length density/root intersection density (L_{rv}/n) observed for wheat, potato, Brussels sprouts (1990, 1991) and leek (1991, 1992) at three dates (see Table 1) in the growing season. s.e. = standard error of the regression coefficient (L_{rv}/n); r^2 is the fraction of the variance accounted for. In 1991 the data set for wheat was restricted to the soil layer 0–60 cm because of a heavy infestation by root knot nematodes (*Meloidogyne naasi*) in the deeper layers of the compartments

Crop and year	Date of auger sampling						r^2
	Early		Middle		Late		
	L_{rv}/n	s.e.	L_{rv}/n	s.e.	L_{rv}/n	s.e.	
Wheat 1990	1.032	0.107	1.692	0.084	2.179	0.127	0.647
Wheat 1991	2.648	0.167	2.588	0.161	2.175	0.190	0.251
Potato 1990	1.182	0.064	0.540	0.060	0.629	0.075	0.488
Potato 1991	4.836	0.315	2.162	0.244	1.286	0.169	0.472
Br. sprouts 1990	1.330	0.167	1.152	0.103	2.036	0.098	0.734
Br. sprouts 1991	3.632	0.810	1.672	0.209	1.937	0.144	0.551
Leek 1991	2.855	0.780	2.270	0.331	2.383	0.176	0.625
Leek 1992	1.572	0.376	2.068	0.250	2.037	0.141	0.431

the length of the roots at the interface. The length of roots at the interface is a function of both the arrival of the root and growth of the root after the intersection. Especially with minirhizotrons installed in the field, voids between the minirhizotron and the surrounding soil interfere with root growth after arrival of the root at the glass surface. Although in our situation no air spaces could be detected, we nevertheless assume that the number of intersecting roots is at least an equally reliable parameter. In studies to estimate root turnover, however, length would be an essential and necessary assessment (Cheng et al., 1991). Melhuish and Lang (1968) and Lang and Melhuish (1970) showed that according to geometric probability theory for randomly oriented lines the following relation is valid, provided that there is no preferential direction of root growth:

$$L_{rv} = 2.n$$

This equation is based on n, being the average point density on three mutually perpendicular planes. In our situation only observations from one plane are available, the horizontal plane. Slopes of the regression lines between L_{rv}, and n (= L_{rv}/n) greater than the reference line in the graphs of Figure 5 suggest that root growth is oriented more horizontally than random, because in this situation, at a given volumetric root density, fewer roots would intersect the horizontal minirhizotrons. Likewise, smaller slopes suggest a preponderance of vertically oriented roots. For most crops, the current data (Fig. 5) do not reveal systematic effects on the value of L_{rv}/n with respect to time in the season (developmental stage) or with respect to differences between crop species. The effect of the year seemed systematic with steeper initial slopes in 1991 (suggesting more horizontal root growth) than in 1990 (see also Table 3). For potatoes and wheat this might be related to the time of planting (Table 1). Planting was late for these crops in 1990 because the Rhizolab first became operational after the normal planting time of these crops had passed.

For potatoes the strong decreasing value of L_{rv}/n in the course of the season also seemed systematic. This would imply a shift in the direction of root growth from random to more vertical (1990) or from more horizontal to more vertical (1991). This effect needs further analysis, especially whether or not a relation with the depth is involved. For potatoes the formation of shallow horizontal roots ("runner roots") early in the season has been described by Goedewaagen (1942). It could be a partial explanation of the shift of L_{rv}/n in time but experimental confirmation is needed.

A shift of L_{rv}/n in the course of the season from more horizontal to more vertical as experienced with minirhizotrons has not been reported earlier. For oats Bragg et al. (1983) show a change in the same direction comparing data from July 8 and August 12 (their Fig. 1) but they did not analyse this effect.

In addition to the poor soil contact with field installed minirhizotrons, the direction of root growth could attribute also to the poor correlations as often found between minirhizotron data and auger sampling, (Parker et al., 1992; Vos and Groenwold 1983; 1987) for potatoes (especially in the upper soil layers) and in maize between minirhizotron data and monolith sampling (Majdi et al., 1992).

The results indicate that at least for potatoes additional observations on the lateral side of the minirhizotron should be done and perhaps also on the bottom side of the minirhizotrons, if upward root growth is assumed. If no upward and no preferential lateral direction of root growth occurs, only one lateral plane will suffice.

Beside direction of root growth, another partial explanation for a decline in the slopes with time would be that decaying roots remain visible in the minirhizotrons but are lost during the washing process of the soil samples. A third explanation is that very fine roots were not recovered in the washing process and that in time the fraction of fine roots is increasing.

The variation in the slope in Figure 5 implies that one universally applicable equation to convert minirhizotron observations into calculated root length densities apparently does not exist. With the current method of observation, a calibration of minirhizotron data with destructive sampling remains, therefore, necessary for each crop and each treatment periodically during the season. Bland (1989) arrived at a similar conclusion after correlating the root numbers assessed with the core-break technique (in a way comparable with minirhizotron observations) with the volumetric root length density.

The combination of both methods (minirhizotrons and auger sampling), however, provides the possibility to draw a relatively complete picture of important properties of a root system and its changes during the season. Quantitative estimates can be obtained for length and weight distributions, penetration into deeper layers, and its rate can be followed, and properties such as diameters and residence times of root members in the interface can be quantified.

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