ELSEVIER

Agriculture, Ecosystems and Environment 51 (1994) 99–113

Agriculture
Ecosystems &
Environment

Production and decay of structural root material of winter wheat and sugar beet in conventional and integrated cropping systems[☆]

M. van Noordwijk[a,*], G. Brouwer[a], H. Koning[a], F.W. Meijboom[a], W. Grzebisz[b]
[a]*DLO Research Institute for Agrobiology and Soil Fertility (AB-DLO), P.O. Box 129, 9750 AC Haren, the Netherlands*
[b]*Akademia Rolnicza Poznan, 60-626 Poznan, Poland*

Accepted 3 November 1993

Abstract

Production of structural root material of sugar beet and winter wheat was quantified by analysis of root growth and decay in a time series of minirhizotron images, combined with a single auger sampling. Cumulative root production of winter wheat was about 1700 kg ha^{-1} for conventional crop management and 1960 kg ha^{-1} for integrated (less pesticides and mineral fertilizer, less intensive soil tillage and more organic manure) crop management; in 1990 the difference between the two management systems was statistically significant. At harvest time 85% and 68% (in 1986 and 1990, respectively) of this structural root production remained as intact roots in the soil in both management systems. For sugar beet total fine root production was estimated at 1150 kg ha^{-1} in 1987 and 1989, with a significantly lower amount on the field on which minimum tillage was introduced in 1986; on average 47% of total root production remained as intact roots at harvest.

Winter wheat root decay was studied with litter pots after crop harvest and in the following growing season. Initially, the N concentration in remaining roots increased while dry weight decreased. No net immobilisation or mineralisation of N and P during autumn was evident. During the next growing season net mineralisation was proportional to loss of root weight in an exponential decay with a half-life of 600 degree days (daily temperature sum). This N release pattern during the next growing period thus contributes to the synchrony between N demand and supply, but no difference between the two management systems was found.

Keywords: Decomposition; Farming system, conventional; Farming system, integrated; Minirhizotron technique; Root turnover; Sugar beet; *Triticum aestivum*

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1. Introduction

Roots link plant and soil. All agricultural soil management activities are, directly or indirectly, aimed at a achieving a better plant growth. Root ecology must therefore be an integral part of a soil ecological search for possibilities to make arable farming more environmentally sound, while maintaining an adequate productivity of land, labour and financial investments. In this article some aspects of root ecological research are discussed, which were part of the Dutch Programme on Soil Ecology of Arable Farming Systems (Brussaard et al., 1988; Kooistra et al., 1989; Lebbink et al., 1994).

[☆] Communication No. 54 of the Dutch Programme on Soil Ecology of Arable Farming Systems.

[*] Corresponding author at: ICRAF, S.E. Asia, P.O. Box 161, 16001 Bogor, Indonesia.

SSDI 0167-8809(94)08013-P

A number of root ecological aspects are relevant to a study of soil ecology.

(1) The extent and distribution of active root surface area determines to a large extent the efficiency of a plant in extracting available water and nutrients from a soil (De Willigen and Van Noordwijk, 1991; Van Noordwijk and De Willigen, 1991); it thus indirectly determines the amount of nutrient required for a specified crop production and which level of available nutrients should be maintained in the soil (Van Noordwijk et al., 1990 discussed this for P).

(2) Root-derived carbon forms the basis of a separate 'energy channel' for the belowground food web (Moore et al., 1988; De Ruiter et al., 1994); it differs from other organic inputs, such as aboveground crop residues and organic manures, not only in quantity and chemical quality, but also in time and space. Root-derived carbon is, apart from the CO_2 respired by the roots, composed of mucilage, root tip slough offs and exudates around a growing root tip, exudation and gradual loss of cell contents by fully functional roots and finally by the root structural material when the roots die, during or at the end of the growing season. When live roots are consumed by soil organisms the pattern of C release may be modified. The position of roots in the soil, partly in the soil matrix, partly in larger aggregates or cracks, differs from the spatial distribution of other organic inputs, which occur in clusters and clumps, to a bigger or lesser degree depending on the soil tillage operations used.

(3) Structural root residues, especially if they have a low N concentration where plants experience some nitrogen stress at the final growth stages, may immobilise N after harvest time and thus reduce N losses by leaching,

(4) The degree of root–soil contact indicates whether roots are primarily following pre-existing macropores (less than 100% contact), or penetrate the soil matrix and thus create new macropores (100% contact) (Kooistra et al., 1992; Van Noordwijk et al., 1993c; Schoonderbeek and Schoute, 1994).

(5) The 'home range' of a root system determines the spatial scale where heterogeneity of soil properties shifts from what is, in principle, a positive aspect to a negative aspect, when considering nutrient use efficiency at crop level (Van Noordwijk and Wadman, 1992).

(6) The degree of 'synlocation' of roots and decaying organic inputs and macropores in the soil (Van Noordwijk et al., 1993b).

Here we will concentrate on the second and the third issue, structural root production and its subsequent decay. Root length data relevant to the uptake efficiency will be discussed elsewhere. The aim of our research was to quantify structural root production of winter wheat and sugar beet grown in two farming systems ('conventional' and 'integrated') and, secondly, to test the hypothesis that N immobilisation in decaying low-N residues may help to conserve N after harvest of the crop. For this hypothesis only wheat root residues were considered.

Estimates of total root production during a growing season are only possible if separate information on root growth and root decay is obtained. Frequent measurements of standing root density are not sufficient for this purpose. Little is known about the longevity of individual plant roots under field conditions. In comparison with studies on longevity and turnover of leaves the problems in observing root turnover are manifold. Based on various methods of observation, estimates of root longevity in the field for various crops and under various conditions range from a few days to several years (Dickinson, 1982; Huck and Taylor, 1982; Atkinson, 1985; Coleman, 1985). As root longevity is a crucial factor in studies of the uptake potential of roots as well as in estimating the organic matter input from roots to the soil ecosystem, a reliable method of observation is essential. We analysed minirhizotron images for root decay at the level of individual roots and estimated median root longevity as the difference in time between 50% of the season's root growth and 50% of the season's root decay. To avoid problems of tube–soil contact with rigid minirhizotrons (Van Noordwijk et al., 1985a), we developed an inflatable minirhizotron, based on motorbike tubes (Gijsman et al., 1991). Decay of root residues after harvest was measured in 'litter pots'.

2. Material and methods

Observations were made on the Lovinkhoeve Experimental Farm in the Noordoostpolder (Marknesse, the Netherlands) on a calcareous silt loam with pH-KCl 7.3–7.7. Kooistra et al. (1989) and Lebbink et al. (1994) described the soil profile and the layout of the experiment. In the experiment, which started in 1985, a 'conventional' cropping system is compared with an 'integrated' system, in which the use of pesticides and mineral fertiliser and the intensity of soil tillage are reduced and the use of organic manures is increased. Most of the observations were made on two fields: field 16A with 'integrated' management following ley farming (soil organic matter content about 2.8%) and field 12B with 'conventional' management following a low organic input management (soil organic matter content about 2.2%). The original expectation that in these two fields the soil organic matter levels would remain more or less constant proved to be correct (Van Faassen and Lebbink, 1994). For brevity the fields will be indicated here as 'integrated' (INT) and 'conventional' (CONV), although especially in the first years the field history may have been at least as important as the current management.

2.1. *Crops and fields sampled*

Winter wheat (*Triticum aestivum* cv. 'Arminda') was sampled in CONV and INT in 1986 and 1990, sugar beet in 1987. In 1986 a row spacing of 12.5 cm and 25 cm was used for winter wheat in CONV and INT respectively (160 kg and 170 kg seed ha^{-1} respectively); in 1990 the row spacing in both systems was 12.5 cm. Data are also presented for sugar beet in 1989 on field 17A (similar in history and management to 16A, also indicated as INT) and field 17C (soil organic matter content about 2.5%), which was in transition to minimum tillage (MT-new) since the autumn of 1986.

2.2. *Auger sampling*

Sampling schemes were based on Van Noordwijk et al. (1985b). Correction factors for losses of dry weight due to sample handling (storage, washing, subsequent storage) were based on experiments with solution-grown roots. Winter wheat was sampled on 23 June 1986 and 15 June and 17 August 1990; 24 auger series were taken (two positions for six plants in two fields). A correction factor of 1.2 was used (Van Noordwijk and Floris, 1979). Sugar beets were sampled on 3 September 1987 and 8 September 1989. Three positions were sampled around four plants in two fields, giving a total of 24 auger series, with 11 depth zones each. A correction factor of 1.4 was used (Grzebisz et al., 1989).

2.3. *Observing root dynamics with minirhizotrons*

Root growth and decay was quantified from black-and-white photographs made by endoscopy in minirhizotrons. Inflatable minirhizotrons (Gijsman et al., 1991) of 8 cm×8 cm diameter were inserted under a 30° angle with the soil surface; a tension of 0.118 MPa was maintained in the tubes; for observations the tubes were deflated and removed temporarily.

Winter wheat in 1986

In CONV and INT four minirhizotrons were inserted on April 22; two tubes were placed in the row and two in between rows. Data given per treatment and tube position are averages for two sides of one lexane tubes and two sides of one inflatable tube placed under an angle of 30°.

Winter wheat in 1989/1990

Eight tubes of 1.7 m (allowing observations down to 0.7 m) and 2.1 m (allowing observations down to 0.9 m) were placed under a 30° angle in the last week of November 1989 (4 weeks after sowing) in two positions: in the row and halfway between two plant rows. Photographs were taken at 3 weekly intervals until harvest at 15 August 1990 and in 4 weekly intervals after harvest to observe root decay.

Sugar beet in 1989

Twelve minirhizotrons of 1.7 m were inserted, allowing observations down to a depth of 0.7 m; two sample positions were used: in the row and halfway between two plant rows. Each position was replicated three times in each field (INT and MT-new). The tubes were inserted on 8 May, when seedlings (planted on 6 April) had just emerged and the rows were visible. Photographs were taken on 1 and 15 June, 3 and 13 July, 11 August, 8 September and 5 October (crop harvest).

Data analysis

Individual roots were compared on subsequent photographs with a counting grid as overlay in exactly the same position by checking each intersection between a root and a line. In this way the length of new roots since the previous observation and the length of roots which had disappeared could be measured (Van Noordwijk et al., 1993a). For each depth interval on each tube the cumulative new root length N_n was determined and root growth and decay in each interval between two observations was expressed relative to this total root production. Statistical analysis of effects of minirhizotron position and field were based on these relative values. For the relative root growth and decay of sugar beet in 1989 a logistic growth equation was fitted for each depth zone; the form was: $Y=(1+\exp[-b(t-m)])^{-1}$ where t is time after 1 January, the parameter m (also in days after 1 January) indicates the time when half of the annual production had occurred in this zone and b determines the shape of the S-curve. As the b parameters did not differ significantly between the different layers, a combined estimate was made for b, with only the m parameter specific for four depth layers (0–10, 10–30, 30–50 and 50–70 cm). For each zone the difference $m_{\text{growth}}-m_{\text{decay}}$ was interpreted as the median life span of roots.

2.4. Total structural root production estimates

Annual production of root material (excluding the storage roots of sugar beet) N_{rp} can be estimated (Van Noordwijk, 1987) by assuming that its ratio with the amount of live roots present at time s, is equal to the ratio $r_{ps}(i)$ of live roots on time s and total root production on the minirhizotron images in layer i.

$$r_{ps}(i)=\frac{N_r(s,i)}{N_n(h,i)} \tag{1}$$

where $N_n(h,i)$ is the cumulative root (length) production until harvest time h on minirhizotron images in zone i, $N_r(s,i)$ is actual root length on minirhizotron images in zone i at time s. By summation over n depth zones i and after applying a correction factor C_d top the root weights, we obtain:

$$N_{rp}(i)=C_d\sum_{i=1}^{n}\frac{h(i)D_{rv}(s,i)}{r_{ps}(i)} \tag{2}$$

where $h(i)$ is the depth interval of zone i, $D_{rv}(i)$ is the root weight density in zone i at time s (auger sampling), and C_d is the correction factor for dry weight losses due to washing and storage of the auger samples. The root residue at harvest, R_h, is estimated in the same way as:

$$R_h=\sum_i\frac{N_{rp}(i)N_r(h,i)}{N_n(h,i)} \tag{3}$$

The root residue of winter wheat at harvest in 1990 was also measured independently to validate this estimation procedure.

2.5. Ceramic litter pots

Decay of roots was measured with a modified litter pot method. A series of ceramic pots (250 ml) were filled with sieved topsoil and a known amount of root or stubble material. The pots were placed in the field and recovered at regular intervals to measure the remaining amount of root or stubble.

For each pot sieved soil was weighed in, to approximate field bulk density; the soil after sieving still contained small fractions of dead roots. Root and stubble material was collected from the field and washed and equal portions were made on a fresh weight basis (after 30 s in a household spin dryer): 1.2 g per pot of root or stubble. The material was placed in pots which had been three-quarters filled and were gently mixed through the soil before the remaining soil was added. The pots were covered with a screen and placed back into the soil (screen downward, ventilation hole upward), with a label and a rope to recover them at a later date. During preparation all material was stored at 4°C, covered with cloth. For each observation time five replicates were used for each treatment. At sampling the pots were brought to the laboratory and washed over a 0.3 mm sieve; fresh weight and dry weight of stubble and roots were determined. The root weight in the stubble series was used to correct for the root weight in the sieved soil. The first sample was washed from one series of pots on the day of placement in the soil. Two incubation studies were made, one in spring and one directly after harvest.

In the spring experiment roots were collected from the field on April 14, litter pots were prepared, stored at 4°C and placed back into the soil on 27 May (after sowing of sugar beet) at two depth intervals, 0–10 and 10–20 cm, either in the sugar beet row or between two rows.

In the autumn experiment roots and stubble were collected at wheat harvest and incubated in the field within 1 week. All litter pots were placed at 5–15 cm depth.

Data analysis was based on relative dry weights remaining in the pot, after correction for root debris. For dry weights five replicates per time were available; for N content only one pooled sample was analysed. Soil temperature data (daily average, at 10 cm depth) were obtained from the Royal Dutch Meteorological Institute, KNMI, meteorological station at Lovinkhoeve.

3. Results

3.1. Winter wheat structural root production

Estimates of total structural root production and root residue at harvest of winter wheat in 1986 and 1990 are presented in Tables 1 and 2. In 1986 little new root growth was recorded in the topsoil of both INT and CONV after 21 May, 4 weeks after placing the observation tubes on 22 April. In the topsoil maximum standing root intensity was observed on 23 June, but subsequent decrease was slow. The two positions of the observation tubes, in the row and between rows, gave similar results on CONV (row distance 12.5 cm), but on INT (row distance 25 cm) more new root growth was observed between 21 May and 23 June between rows than in rows. Otherwise the pattern of root growth and decay was similar between fields.

Standing root intensity was 85% and 94% of cumulative total root intensity for CONV in and between rows, respectively; for INT it was 82% and 89%, respectively. The rate of root decay was higher in topsoil than in subsoil. Standing root length intensity in the topsoil was 85% and 81% of cumulative root length intensity for CONV and INT, respectively, and about 90% in the subsoil for both systems. In 1986 the auger sampling indicated no statistically significant differences between the fields CONV and INT in total root dry weight or root distribution with depth (Table 1).

Table 1

Root dry weight per unit volume (D_{rv}) of winter wheat in 1986 as a function of depth on 23 June 1986 and estimates of annual root production (N_{rp}) and root residue at harvest (R_h), based on root dynamics along minirhizotrons (Eqs. 1 and 3). The field indicated as CONV had a lower soil organic matter percentage and received more chemical inputs than the field indicated as INT. A correction factor of 1.2 was used for dry weight losses due to sample handling

Depth (cm)	D_{rv} (mg cm^{-3})		N_{rp} (kg ha^{-1})		R_h (kg ha^{-1})	
	CONV	INT	CONV	INT	CONV	INT
0–10	0.782	0.826	889	960	756	778
10–30	0.192	0.257	437	583	371	473
30–60	0.133	0.096	466	370	424	329
60–100	0.024	0.020	109	106	100	94
0–100	0.166NS	0.170	1900NS	2018	1650	1673

Table 2
Fine root production (dry weight per unit volume, D_{rv}) of winter wheat in 1989 on two fields, INT and CONV; the D_{rv} data were obtained on 15 June 1990; r_{ps} is the actual root length at that date, relative to the annual production of root length (Eq. 2); the total annual production of structural root material (N_{rp}) and the root residue at harvest (R_h), are estimated according to Eqs. 1 and 3. A correction factor of 1.2 was used for dry weight losses due to sample handling. Average weights were based on a 1:1 ratio of row and between-row samples (row distance 12 cm). Significance of an F test of differences between fields is indicated for D_{rv} and r_{ps} (*$P<0.05$; **$P<0.01$; ***$P<0.001$)

Depth (cm)	D_{rv} (mg cm^{-3})		r_{ps}		N_{rp} (kg ha^{-1})		R_h (kg ha^{-1})	
	CONV	INT	CONV	INT	CONV	INT	CONV	INT
0–5	0.703	0.931 *	0.623	0.740 *	564	630	246	427
5–10	0.355	0.490 **	0.768	0.838 NS	232	292	144	209
10–20	0.174	0.241 *	0.849	0.888 NS	205	271	157	204
20–30	0.133	0.156 NS	0.897	0.853 NS	149	184	115	137
30–40	0.082	0.108 NS	0.866	0.830 NS	95	131	79	95
40–50	0.070	0.064 NS	0.888	0.858 NS	78	74	65	56
50–60	0.061	0.070 NS	0.916	0.913 NS	67	77	54	62
60–70	0.052	0.087 ***	0.910	0.904 NS	56	98	44	77
70–80	0.036	0.074 ***	0.885	0.912 NS	41	82	35	64
80–90	0.012	0.048 ***	0.9[a]	0.9[a] NS	13	53	11	44
90–100	0.005	0.013 ***	0.9[a]	0.9[a] NS	5	14	4	12
0–100	0.115	0.168 ***			1505	1904	953	1388

[a] Estimated value.

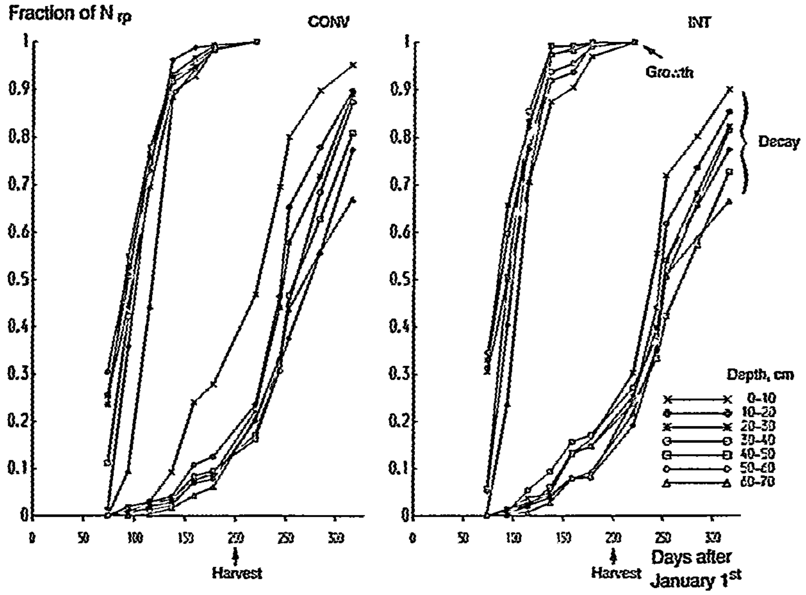

Fig. 1. Winter wheat root growth and decay along minirhizotrons expressed as fraction of cumulative root length production, N_{rp}, in each zone on CONV and INT fields in 1990.

In early spring roots contained 2.1% and 1.9% N (dry weight basis) on CONV and INT, respectively. At maximum standing root mass (auger sampling 21 June) the N concentrations had decreased to 0.79% and 0.51% and at harvest to 0.44% and 0.39%, respectively. The N content of

Table 3
Winter wheat fine root residue (kg ha^{-1}) at harvest on 17 August 1990 measured by auger sampling and estimated on the basis of auger sampling on 15 June and minirhizotron root dynamics (Eq. 3), on CONV and INT fields

Depth (cm)	CONV			INT		
	Auger 15/6	Estim. 17/8	Auger 17/8	Auger 15/6	Estim. 17/8	Auger 17/8
0–30	836	662	716	1108	977	1058
30–100	317	290	306	571	412	367
0–100	1153	953	1022	1679	1388	1426

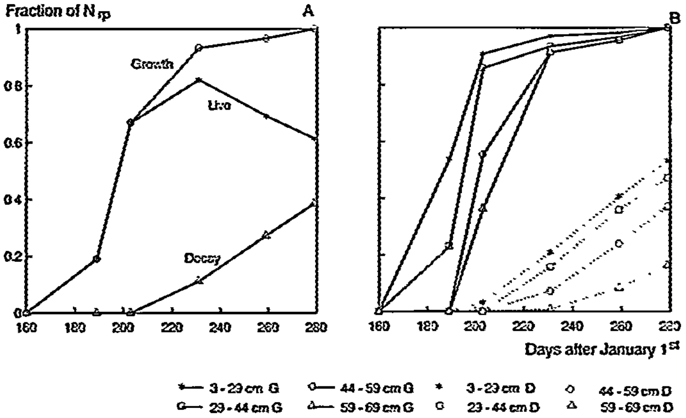

Fig. 2. Sugar beet fine root growth and decay along minirhizotrons expressed as fraction of cumulative root length production, averaged for CONV and INT fields in 1987. (A) Cumulative growth, cumulative decay and length actually present; averaged over 3–69 cm depth; (B) growth and decay for various depth intervals.

Table 4
Structural fine root production (kg ha^{-1}) of sugar beet in 1987; root dry weight (kg ha^{-1}) is given for an auger sampling on 2 September (no significant differences between fields). Annual production (N_{rp}) and fine root residue at harvest (R_h), averaged over the two fields, are estimated from root dynamics along minirhizotrons. The correction factor for dry weight losses due to sample handling C_d is 1.4

Depth (cm)	2/9/1987 CONV	2/9/1987 INT	N_{rp}	R_h
0–10	151	215	674	249
10–30	75	96	229	119
30–60	105	64	204	117
60–100	30	24	45	37
0–100	360NS	400	1152	522

the root mass was 13 kg and 8.7 kg ha^{-1} and at harvest 8.4 kg and 7.9 kg ha^{-1}, if we assume that losses due to sampling were the same for N and dry weight.

In 1990 dynamics of root growth and decay were measured on more dates and tubes were inserted in autumn to record root growth in early spring. Results are shown in Fig. 1 and Table 2. The auger sampling on 15 June showed a significantly higher root dry weight in the top 20 cm on INT than on CONV. Between 20 and 60 cm depth the difference was not significant, but deeper root development was more pronounced on INT. On CONV new root growth after the auger sampling was slightly stronger than on INT, as indicated by the lower r_{ps} values for the top layers. The total structural root production was 21% lower on CONV than on INT and the root

Table 5
Root weight density D_{rv} (mg cm^{-3}) of sugar beet on 8 September 1989 on fields INT and MT-new (reduced tillage); values in the same row followed by different letters are significantly different. A correction factor for dry weight losses due to sample handling of 1.4 was used

Depth (cm)	INT		MT-new	
	In row	Betw. row	In row	Betw. row
0–5	0.531 a	0.179 b	0.224 b	0.203 b
5–10	0.199 a	0.052 b	0.088 b	0.098 b
10–20	0.1820 a	0.055 b	0.099 ab	0.055 b
20–30	0.211 a	0.038 b	0.129 ab	0.048 b
30–40	0.119 NS	0.018	0.073	0.027
40–50	0.059 NS	0.034	0.076	0.036
50–60	0.059 NS	0.038	0.053	0.036
60–70	0.055 NS	0.042	0.039	0.038
70–80	0.027 NS	0.029	0.039	0.035
80–90	0.021 NS	0.021	0.031	0.018
90–100	0.010 NS	0.011	0.011	0.008
0–30	0.252 a	0.077 b	0.127 b	0.084 b
30–100	0.049 NS	0.028	0.046	0.028
0–100	0.111 NS	0.042	0.070	0.045

Table 6
Parameters of regression equation for sugar beet fine root growth and decay in 1989, for two positions (in row and between row) on two fields INT (17A) and MT-new (17C). The model fitted was: $Y=(1+\exp[-b(t-m)])^{-1}$ where t is time after 1 January and the parameter m (also in days after 1 January) was fitted for four depth layers (0–10, 10–30, 30–50 and 50–70 cm) with a single b parameter for each series

	INT				MT-new			
	In row		Betw. row		In row		Betw. row	
	Est.	SE	Est.	SE	Est.	SE	Est.	SE
Growth								
b	0.137	0.006	0.236	0.009	0.157	0.008	0.334	0.021
m(0–10)	176	1.1	173	0.8	170	1.1	180	0.4
m(10–30)	160	0.7	171	0.5	156	0.6	181	0.3
m(30–50)	169	0.7	178	0.4	176	0.7	188	0.3
m(50–70)	186	0.6	186	0.3	191	0.6	196	0.4
%Var.ac.	83.4		92.8		88.0		92.4	
Decay								
b	0.0289	0.00078			0.0324	0.00081		
m(0–10)	233	2.6	228	2.4	229	2.4	237	2.2
m(10–30)	240	1.8	265	2.2	230	1.6	262	1.7
m(30–50)	258	2.1	286	2.7	254	1.7	283	2.2
m(50–70)	301	3.4	312	4.1	306	3.6	308	3.6
%Var.ac.	59.0				67.4			

SE, standard error of the estimate.
%Var.ac., percentage of variance accounted for.

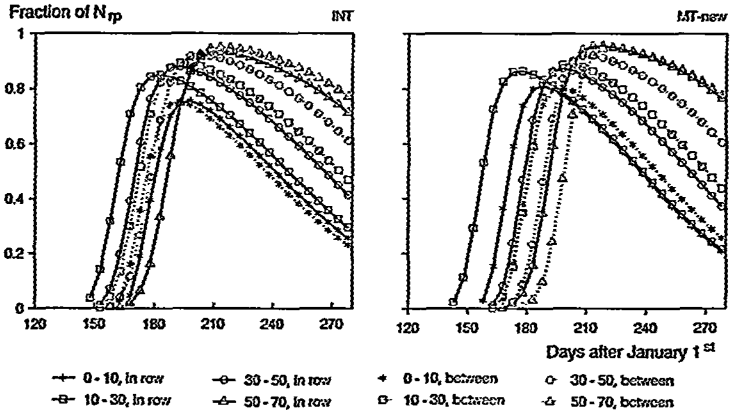

Fig. 3. Sugar beet fine roots actually present (difference between growth and decay curve) expressed as fraction of cumulative root length production, N_{rp}, in 1989 on INT and MT-new fields.

Table 7
Median life span of sugar beet roots (days) as a function of depth and sample position (in and between rows)

Depth (cm)	INT		MT-new	
	In row	Betw. row	In row	Betw. row
0–10	64	63	68	67
10–30	87	102	82	90
30–50	97	116	85	103
50–70	123	134	124	118

residue at harvest 31% less. The root residue at harvest was 63% and 73% of total root production on CONV and INT, respectively.

The reliability of the extrapolation of root weights to other dates on the basis of minirhizotron root dynamics was checked in 1990 with an independent auger sampling of root residues at harvest (Table 3). The root dry weight in the auger samples was lower at harvest than in June (11% and 15% on CONV and INT, respectively), but the minirhizotron root dynamics predicted a slightly stronger decrease (17% on both fields). Root decay along minirhizotrons may thus be slightly overestimated and the root residue may thus be underestimated.

3.2. Sugar beet structural fine root production

No significant difference between INT and CONV was found in the fine root dry weight of sugar beet in 1987 in the auger sampling. Root dynamics along minirhizotrons was also similar between the fields, so only an average pattern is presented in Fig. 2 and an average estimate of N_{rp} and R_h is presented in Table 4. R_h was on average 45% of N_{rp}. The N concentration in sugar beet roots on 3 September 1987 was 1.92% and 1.94% on CONV and INT, respectively; the N content was about 7.3 kg ha^{-1} on both fields.

In 1989 INT and MT-new were sampled (Table 5). Aboveground crop development on MT-new was slower than on INT. Table 6 gives parameters of a logistic curve-fit to relative root growth in four depth zones, in two sample positions on INT and MT-new, accounting for about 90% of the variation between replicate observation series. As the shape parameters *b* were not significantly different between depth zones a single estimate was obtained. Between the rows the *b* parameter had a higher value (indicating a 'steeper' S-shaped curve) and on MT-new it was higher than on INT. The parameters *m* indicate the time that half of the root development had occurred in each zone. The earliest relative root development was found in the 10–30 cm layer in the plant row in both fields (average half-production date for this zone was 8 June). Root development in the 50–70 cm depth layer had reached 50% of its final value on 7 July in INT and about 1 week later in MT-new. The relative actual root length along minirhizotrons (ob-

Table 8

Total fine root production (dry weight) of sugar beet in 1989 on INT and MT-new; D_{rv} were given in Table 5; r_{ps} and r_{ph} are the actual root length at date s and at harvest h, relative to the annual production. The total annual production of structural root material (N_{rp}) is estimated from D_{rv}/r_{ps} for each zone and a 1:2 ratio of row and between-row-samples. R_h is root residue at harvest.

Depth (cm)	r_{ps}		r_{ph}	N_{rp} (kg ha^{-1})	R_h (kg ha^{-1})
	In row	Betw. row			
INT					
0–10	0.449	0.417	0.325	455	148
10–30	0.498	0.676	0.497	375	186
30–50	0.626	0.789	0.604	139	84
50–70	0.855	0.889	0.784	104	82
70–100	0.9[a]	0.95[a]	0.85[a]	64	54
0–100				1137	554
MT-new					
0–10	0.410	0.478	0.298	336	100
10–30	0.420	0.672	0.428	281	120
30–50	0.611	0.802	0.564	133	75
50–70	0.896	0.902	0.795	88	70
70–100	0.95[a]	0.95[a]	0.85[a]	71	60
0–100				910	426

[a] Estimated value.

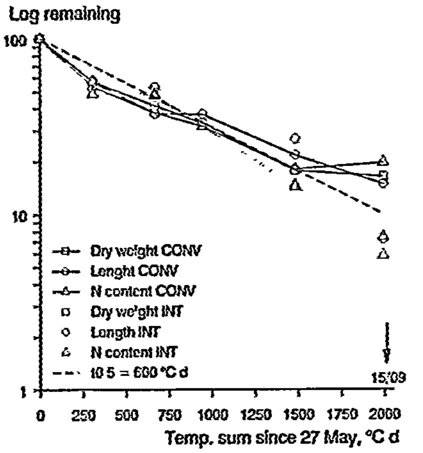

Fig. 4. Winter wheat root decay in litter pots in the following growing season (1987). Root dry weight, root length and root N content (N concentration times dry weight) are expressed as fraction of the amount at the start of the incubation. Average soil temperature during the incubation period was 17.8°C. The solid line indicates an exponential decay curve with a half-life of 600 degree days.

tained as difference between fitted relative root growth and root decay lines) is presented in Fig. 3.

Logistic curve fits to the relative root decay data accounted for a lower percentage of the total variance than for relative root growth; especially in the last month the curve fits tended to overestimate root decay. For the calculation of the root residue at harvest therefore the average observed values were used, rather than the fitted values. The difference between the half-production time m_{growth} and half-decay time m_{decay} can be interpreted as median life span of roots (Table 7). The median life span was 2 months in the top 10 cm and increased up to 4 months in the 50–70 cm depth layer.

Estimates of N_{rp} and R_h for 1989 are given in Table 8. On both fields the fine root residue at harvest was 48% of N_{rp} in 1989. Both the estimate of N_{rp} and R_h for INT were close to the values for 1987.

3.3. Winter wheat root decay in the subsequent summer

Fig. 4 shows that decay of winter wheat root length, root dry weight and root N content of the 1986 crop followed an approximately exponen-

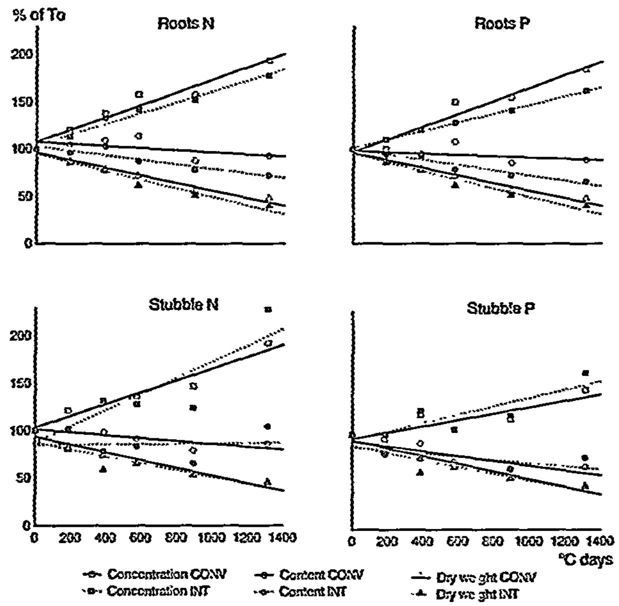

Fig. 5. Dry weight, N and P concentrations and contents of root and stubble material of winter wheat after harvest in 1990, expressed as fraction of the initial value (T_0).

Table 9
Regression analysis of data in Fig. 5; parameters for the model $Y=a+bX$ are given where X is temperature sum and Y is expressed relative to the initial value (100%)

Y	a	SE	b	SE	r^2	Sign.
Dry weight						
CONV roots	95.9	2.1	−0.0399	0.0029	0.865	**
CONV straw	94.6	2.8	−0.0450	0.0039	0.820	**
INT roots	93.5	2.7	−0.0405	0.0037	0.801	**
INT straw	87.9	3.6	−0.0368	0.0050	0.649	**
N concentration						
CONV roots	107.7	2.2	0.0663	0.0031	0.940	**
CONV straw	104.3	1.3	0.0572	0.0018	0.973	**
INT roots	103.0	2.1	0.0625	0.0029	0.942	**
INT straw	88.3	6.6	0.0847	0.0093	0.916	**
P concentration						
CONV roots	96.5	2.2	0.0686	0.0031	0.944	**
CONV straw	101.1	0.3	0.0461	0.0004	0.998	**
INT roots	95.1	2.7	0.0338	0.0038	0.728	**
INT straw	94.4	3.5	0.0442	0.0049	0.731	**
N content						
CONV roots	107.5	3.6	−0.0110	0.0050	0.119	NS
CONV straw	102.7	3.4	−0.0237	0.0047	0.457	**
INT roots	101.3	3.5	−0.0153	0.0049	0.235	*
INT straw	84.8	5.1	0.0016	0.0071	<0	NS
P content						
CONV roots	97.7	3.4	−0.0066	0.0047	0.033	NS
CONV straw	99.5	3.1	−0.0276	0.0043	0.582	**
INT roots	92.3	3.5	−0.0253	0.0049	0.466	**
INT straw	86.4	4.0	−0.0167	0.0057	0.210	*

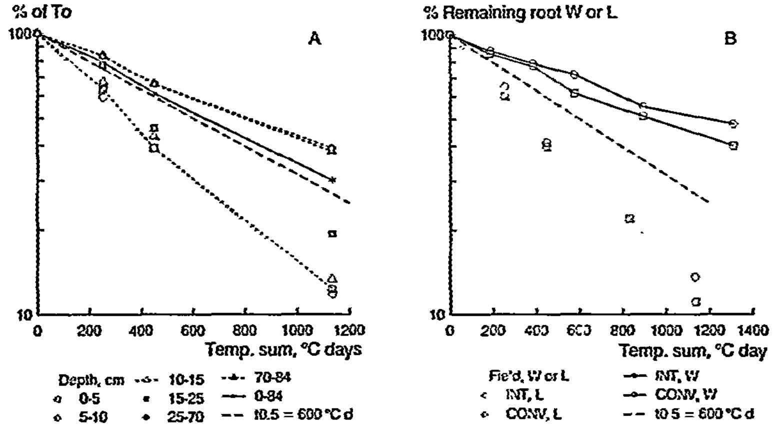

Fig. 6. (A) Decay of winter wheat roots along minirhizotrons after crop harvest in 1990, as a function of depth, expressed as fraction of the initial value (T_0). (B) Comparison of relative decay of root length along minirhizotrons and relative decay of root dry weight in litter pots of winter wheat in 1990. The solid line indicates an exponential decay curve with a half-life of 600 degree days.

tial decay during the subsequent growing season (1987). The initial N concentration (sampled on 14 April) was 2.11% and 1.99% on CONV and INT, respectively, five times higher than the N concentrations measured in August 1986 (0.44% and 0.39%). The average half-life time was about 600 degree days (or 34 days at 17.8°C); decay tended to be slightly faster on INT than on CONV in the last month. No significant effect was found of positioning the litter pots in the 5–15 or 15–25 cm depth layers.

3.4. Winter wheat root decay after harvest

The second litter pot experiment (Fig. 5), immediately after harvesting winter wheat in 1990, confirmed the gradual increase in the N concentration (per unit remaining dry weight) in decaying roots in autumn. While the dry weight was reduced by 50% between crop harvest (17 August) and the next winter (5 March), the N concentration doubled. A slight net N immobilisation phase was followed by a slow net N mineralisation, but on average no significant or a slight negative trend was found (Table 9). For P similar results were obtained. Stubble material (below- and aboveground stem remaining after the 'straw' had been removed) followed essentially the same pattern for N, but had a net P mineralisation during the period of study.

The root decay data for the minirhizotron series of Fig. 1 are plotted in Fig. 6(A) as percentage of the amount of 'live' roots at harvest time in each layer. No difference between CONV and INT was found in decay, so average results are presented here. In each zone an approximately exponential decay was found; averaged over the total profile, the half-life was about 600 degree days, but decay in the top 15 cm was twice as fast and decay in the deeper layers only half as fast as this average rate. In autumn soil temperature in deeper layers tends to be higher than in the topsoil (De Vos et al., 1994), so the slower decay in deeper layers cannot be explained by a lower temperature. Fig. 6(B) shows that decay of root weight in litter pots was about four times slower than decay of root length along minirhizotrons in the same layer in autumn.

4. Discussion

Clear differences in structural fine root production between the two crops sugar beet and winter wheat became evident in this study. Winter wheat cumulative root production was about 1900 kg ha^{-1} (with a significantly lower amount on CONV in 1990) and at harvest 85% and 68%

of this structural root production was still present in the form of intact roots in the soil (1600 or 1300 kg ha^{-1}), in 1986 and 1990 respectively. The data on root dynamics for 1990 are probably more reliable than those for 1986, as root growth in early spring (before 22 April) was not recorded in that year. Sugar beet had a total fine root production of about 1150 kg ha^{-1} (with a significantly lower amount on MT-new in 1989) and on average 47% of total root production was still present in the form of intact roots at harvest (540 kg ha^{-1}). The difference between the maximum standing root mass (in June for winter wheat and in September for sugar beet) was a factor of 3. In an earlier evaluation of fine root dynamics of sugar beet on a sandy soil, we found similar results as in the present study: N_{rp} was about 50% more than the maximum amount present at any moment, and more than double the amount present at harvest time (De Willigen and Van Noordwijk, 1987). Kücke and Löfler (1989) found a two-fold difference in fine root length between winter wheat in June and sugar beet in September on a loam soil. Literature data (Van Noordwijk and Brouwer, 1991) on maximum standing root biomass for winter wheat are around 1.5 Mg ha^{-1} (cumulative root length per unit root surface area, L_{ra}, of about 300 cm cm^{-2}, specific root length about 200 m g^{-1}); for sugar beet fewer published data are available.

Many previous estimates of total fine root production were based on methods, such as sequential destructive sampling, which are considered less reliable (Singh et al., 1984). For winter wheat data can be compared with the ^{14}C pulse labelling study by Swinnen (1994) on the same fields in the same year. Assuming a C content of 42%, his estimate of total fine root (dry weight) production (decay during growing season plus harvest residue) of 1467 kg and 1402 kg ha^{-1} on CONV and INT, respectively, is 25% lower than our data, but his estimate of the fraction of structural root production present as intact roots at harvest (57%) is 11% lower than the value reported here for the same crop. Different results could be based on different corrections for dry weight losses due to sample handling (storage and washing), to effects of the pulse labelling method on plant growth, to differences in root dynamics on a length (minirhizotron) or weight (pulse labelling) basis or to a different criterion for distinguishing 'intact' roots and 'root debris'. More difficult to explain is the fact that the auger samplings showed a significantly higher root dry weight on INT than on CONV, while the pulse labelling study suggested a difference (although not statistically significant) in the opposite direction.

In the summer incubation study, winter wheat root residue decayed at the same rate, whether expressed as root dry weight or as root length. Both parameters are based on roots which were handpicked as 'intact' roots from a washed sample. This suggests no change in 'specific root length' (length per unit dry weight) and the disappearance of entire roots from this pool (by 'comminution' or consumption). Decay of roots during the growing season was mostly based on a gradual process and between-operator differences in evaluation are likely (all our data in each year were obtained by a single operator). Only a small fraction of the roots which disappeared, disappeared completely, either through consumption by meso- or macro-organisms, or as artefact due to the inflatable minirhizotrons. The difference between the decay of root dry weight in litter pots (unfortunately no measurements of specific root length were made during the incubation) and root length along minirhizotrons (Fig. 6(B)) may be based on an overrepresentation of relatively thick roots in the root material obtained for the incubation and a possible difference in decay between fine and thicker roots.

During decay of winter wheat belowground residues after harvest, a slight immobilisation of N is followed by a slow mineralisation until the next winter. The decomposition rates observed here under field conditions (temperature and soil water content in the litter pots follow those of the surrounding soil, accessibility for soil macro-organisms is restricted, however) are slower than assumed in several models. Verberne et al. (1990) assumed a rate constant for decomposition of structural plant material (SPM) of 0.1 day^{-1} at 15°C, corresponding to a half-life of 100 degree days. Bradbury et al. (1993) found good agreement between a model of the C and N balance and results of a 4 year study with ^{15}N, when the decomposition constant for wheat harvest residues (straw, stubble and roots) was taken as 0.16 per week at 10°C, corresponding to a half-life of 300 degree days. The models assume that organic inputs are transformed to (microbial) biomass and/or stable soil organic matter. In our data part of the decaying 'intact' roots is transformed to 'root debris', so one might expect our decay rates to be higher instead of lower than the model results.

The increase in N concentration, on a remaining root dry weight basis, of decaying roots during autumn deserves some attention. The conventional view on 'immobilisation' during decomposition of material with a high C/N ratio (above 20, Handayanto et al., 1992) is based on decomposers obtaining N from mineral sources (or from food with a low C/N ratio). One would not expect an increase in the N concentration of the remaining food source in this case, unless all the biomass (and its N) formed by decomposers is included in the washed root samples obtained from the litter pots. Although at least some living bacteria and fungal hyphae can be observed inside decaying wheat roots (J. Bloem, personal communication, 1992), quantitative explanation of our present results appears to be difficult. A further study of the process of, and organisms responsible for, decompositionb of root material is needed.

Returning to the aims of this study, only comparatively small differences in structural root production of winter wheat and sugar beet grown were found between the two main cropping systems CONV and INT. The hypothesis that N immobilisation in decaying low-N residues may help conserve N after harvest of the crop was partially confirmed, but again no substantial difference between CONV and INT was found in degree of synchrony of N mineralisation from root residues and the demands for N by the subsequent crop.

Acknowledgements

Soil temperature data were supplied through the Royal Dutch Meteorological Institute, KNMI. Thanks are due to Ir. S.L.G.E. Burgers for help with fitting logistic equations and to Dr. A.P. Whitmore and Drs. H.G. van Faassen for comments on the manuscript.

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