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Soil mineral nitrogen availability to young maize plants as related to root length density distribution and fertilizer application method

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Abstract

Minirhizotron observations from 4 experiments with maize in the Wageningen Rhizolab showed strong vertical and lateral root density gradients during the first 9 weeks after emergence.

Root length density (Lrv), as determined in core samples 9 weeks after emergence, was positively related (P<0,01) to the number of roots counted concurrently on minirhizotron walls (n). Lrv/n ratios were 1.13, 1.76, 0.99 and 1.21 cm cm^{-1} in the successive experiments. Subsequently, root numbers counted on previous dates in each experiment, were converted into root length density values and related to thermal time. According to this relation, the average vertical root extension rates were 0.7 and 1.1 cm d^{-1} at temperatures of 13 and 16°C, respectively. Corresponding values for the lateral extension rate were 1.0 and 1.6 cm d^{-1}.

Calculations indicated that the nitrogen (N) content of a 9 weeks old maize crop could generally not be explained by mass flow only. Transport distances between roots and mineral N in the soil, may thus have restricted the availability of N as suggested by preferential uptake of mineral N from soil compartments with a high root length density. The recovery of N was only slightly improved by fertilizer N positioning close to the plant as compared to broadcast N or placement of N halfway between the rows. Recoveries based on the difference method and the isotopic dilution method, yielded similar values. Dry matter yields were not significantly affected by the application method of N. Apparently, the root extension rate and the initial availability of N in the soil prior to the application of fertilizer-N, were sufficient to cover shoot demand under the prevailing circumstances.

Keywords: fertilizer placement, minirhizotron, nitrogen recovery, root length density, *Zea mays* L.

Introduction

Lack of synlocalisation of nutrients and roots may limit the uptake of nutrients and crop production (De Willigen & Van Noordwijk, 1987). Under these conditions, high nutrient concentrations in the bulk soil are required to maintain a gradient-driven transport to the root surface. Young maize (*Zea mays* L.) crops generally respond positively to high rates of nitrogen (N) application. We hypothesize that this may be attributed to an insufficient synlocalisation due to the current row width (70–80 cm) and a slow lateral and vertical extension of the root system. Circumstantial evidence is provided by the positive response of the dry matter (DM) yield of maize to a row application of N (Touchton, 1988; Maidl, 1990; Maddux *et al.*, 1991; Sawyer *et al.*, 1991).

Lack of synlocalisation may be more likely at low temperatures as they restrict specific root length (i.e. length of roots per unit DM invested), root growth rate, root activity and rooting depth (Ketcheson, 1968; Clarkson & Gerloff, 1979; Engels & Marschner, 1990; Barber & Kovar, 1991; Tardieu & Pellerin, 1991; Richner, 1992), as well as the mineralisation rate (Addiscott, 1983). Hence, low temperatures may have a negative effect on the actual uptake of N. Shoot demand for N, however, is also reduced by low temperatures via effects on both the subterranean shoot meristem and aerial plant parts (Miedema, 1982). Yet, root systems may be less able to satisfy shoot demand in a cold spring, especially as the soil temperature lags behind the air temperature at that stage.

To test this hypothesis root observations in the juvenile stage are required. Reported root data generally refer to times around anthesis and focus on root length density gradients with depth rather than with lateral distance. To fill this gap in knowledge four rhizolab experiments were carried out in 1992 and 1993. These experiments were set up to describe the spatial root development as a function of thermal time and to study the interactions between N-placement, distributions of mineral N in the soil and roots, N-recovery and maize DM-production. Concomitantly, we used the experiments for a comparison of two calculation methods of the N recovery.

Materials and methods

Rhizolab

Four experiments (Experiments 1 and 2 in 1992, Experiments 3 and 4 in 1993) were carried out in four 1.70 m deep, 1.25 × 1.25 m units of the Wageningen Rhizolab. Detailed information on this facility is given in Van de Geijn *et al.* (1994), Smit *et al.* (1994) and Schröder *et al.* (1994). Rhizolab units were filled with a sandy soil with organic matter contents of 3.5 and <0.1 % for the upper 70 and 70–170 cm layers, respectively, while 7 cylindrical minirhizotrons (diameter 6 cm) were horizontally installed, perpendicularly to the plant rows at depths of 5, 10, 15, 20, 30, 45 and 60 cm (Figure 1). Concurrently, capacitance moisture sensors and nutrient sampling devices were allocated to positions exactly below the plant rows and halfway between them, at depths of 5, 15, 25, 40, 60, 85, 115 and 150 cm. The soil was recompacted layerwise to a constant bulk density of 1.4 and 1.6 kg dm^{-3} throughout the upper 70 and 70–170 cm, respectively. Soil material for the upper 20 cm was mixed with fertilizers equivalent to rates of 45 kg P and 250 kg K ha^{-1} in each experiment.

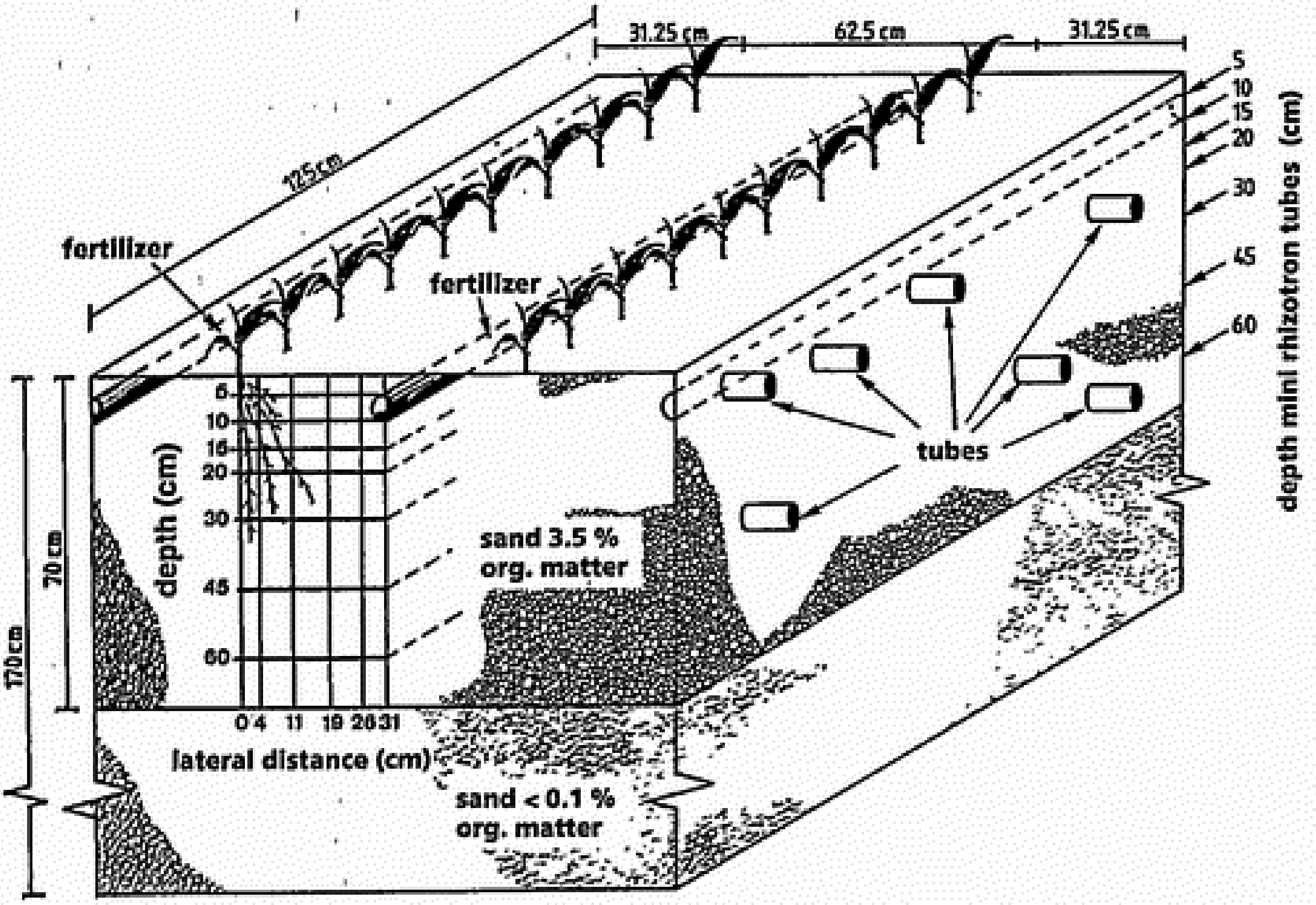


Figure 1. Positioning of maize plants, minirhizotron tubes, fertilizer bands (IR-treatment only) and imaginary compartments in the Wageningen Rhizolab.

At the end of the each experiment, the soil was removed from the units and the filling procedure was repeated for the next experiment. The excavated soil from Experiments 1 and 2 was thoroughly sieved, mixed, stored and re-used for Experiments 3 and 4.

Crop husbandry

Two rows of maize (*Zea mays* L. cv. LG 2080 for the first two, cv. Mandigo for the subsequent two experiments) were planted at a depth of 4 cm and a distance of 62.5 cm on 15th April 1992, 3th July 1992, 15th April 1993 and 1st July 1993 in each rhizolab unit. Stands were thinned to 12.8 plants m^{-2} soon after emergence. Crops were kept weed-free manually, sprayed against pests when necessary and harvested at about 9 weeks after emergence.

Weather

Average daily air temperature measurements were recorded at a weather station 1 km away from the Rhizolab and amounted to 14.1, 17.9, 14.6 and 15.5 °C for the period between emergence and harvest for Experiments 1, 2, 3 and 4, respectively. Soil temperatures were collected with thermocouples installed at depths of 5, 15, 25, 40 and 60 cm.

Precipitation was excluded by a transparent shelter covering all rhizolab units during rainfall events. Units were irrigated manually during the first 18–48 days and automatically for the remaining period with a 10×20 cm grid drip irrigation system to maintain a moisture content of 0.15–0.19 $cm^3\ cm^{-3}$ in the upper 70 cm. Averaged over experiments, measured evapotranspiration amounted to 1–2, 1.5–2.5 and 2–3 mm d^{-1} for the periods 1–3, 4–6 and 7–9 weeks after emergence, respectively. Transpiration was deduced from this by assuming that soil evaporation contributed half to evapotranspiration with a maximum of 0.5 mm d^{-1}.

Root observations

Root observations were made fortnightly and refer to the number of roots per unit area at 2.5 cm intervals along the interface of the bulk soil and the upper side of glass walls of the minirhizotrons. Root length densities were assessed at the end of each experiment in core samples taken in triplicate to a depth of 70 cm with 10 cm increments and 3 lateral positions (viz. in the row, halfway between the rows and half way between these two positions). Soil and roots were carefully separated by soaking. Subsequently, total root length was determined with the line intersect method (Tennant, 1975). Root length density values (Lrv's) were related to the corresponding number of roots on the minirhizotron walls (n) at the end of each experiment according to a linear response without intercept. The association of minirhizotron tubes and soil layers from which the core samples were taken, was adopted from Smit *et al.* (1994). Lrv/n ratios were used to convert minirhizotron observations collected in the course of the experiment into root length densities. Five lateral distance classes (0.00–3.75, 3.75–11.25, 11.25–18.75, 18.75–26.25, 26.25–31.25 cm) and seven depth positions were defined resulting in 35 compartments (Figure 1). Observations from the four experiments were pooled per compartment and plotted against thermal time (TT) which was defined as the accumulated average daily temperature (depth 15 cm, threshold (Jones & Kiniry, 1986) 8 °C) after emergence. Thermal time ranged from.0 to 700 degree-days. Data were fitted with a linear response model, allowing for a thermal time lag (LAG) needed to arrive in a certain compartment at lateral distance i and depth j (Equation 1).

$$\mathrm{Lrv}_{i,j} = 0 \text{ if } \mathrm{TT} < \mathrm{LAG}_{i,j}, \text{ else}$$
$$\mathrm{Lrv}_{i,j} = c_{i,j} \times (\mathrm{TT} - \mathrm{LAG}_{i,j}) \text{ with} \qquad 1$$

$c_{i,j}$: constant relating the root length density (Lrv) to TT in compartment i,j

Treatments

Treatments consisted of a control without N fertilizer (C) and three methods of application of 50 kg N ha^{-1}: banded at a depth of 7 cm halfway between the rows (IR), broadcast and mixed through the upper 10 cm layer (BC) or banded at a depth of 7 cm, 4 cm from each row (R). Treatments were randomly allocated to units in each experiment. ^{15}N depleted (999.9 g ^{14}N kg^{-1}) ammonium nitrate and ammonium sulphate, were used in 1992 and 1993, respectively.

Measurements

Concentrations of mineral N (ammonium-N and nitrate-N) in the soil solution were assessed every three weeks, from planting until about 9 weeks after emergence, with ceramic cups and porous Rhizon SS tubes (Meijboom & Van Noordwijk, 1992) and divided by the concomittantly measured moisture content to calculate the mineral N quantities per unit soil volume. ^{15}N atom % in the soil solution was assessed at the start and end of each experiment.

Crops were harvested about 9 weeks after emergence and split into stems and leaves. Fresh weight of the fractions and their dry matter content were determined after drying for 24 h at 105 °C. Leaf area of all plants was assessed photoanalytically. Dried material was analysed for total N content and ^{15}N atom %.

Mineral N in the soil solution and total N in leaves and stems were determined with a TRAACS 800 continuous flow analysis system (Bran Luebbe Analyzing Technologies). ^{15}N atom % in soil solution and crops were assessed with a gas specific mass spectrometer (Europe Scientific).

Nitrogen recovery

N-recoveries were calculated according to the difference method (Van Keulen, 1986; Equation 2) and according to the isotopic dilution method (Varvel & Peterson, 1990; Equation 3).

$$\text{N-recovery (\%)} = \begin{array}{l}(\text{SN (or SMN}_{70}\text{) of fertilized crop, kg ha}^{-1} - \\ \text{SN (or SMN}_{70}\text{) of unfertilized crop, kg ha}^{-1}) / \\ (0.01 \times \text{N-rate, kg ha}^{-1})\end{array} \qquad 2$$

$$\text{N-recovery (\%)} = \begin{array}{l}((\text{atom \% }^{15}\text{N in SN (or SMN}_{70}\text{) of unfertilized crop)} - \\ (\text{atom \% }^{15}\text{N in SN (or SMN}_{70}\text{) of fertilized crop))} \times \\ (\text{SN (or SMN}_{70}\text{) of fertilized crop, kg ha}^{-1}) / \\ ((0.01 \times \text{N-rate, kg ha}^{-1}) \times \\ (\text{natural atom \% }^{15}\text{N} - \text{atom \% }^{15}\text{N in depleted fertilizer}))\end{array} \qquad 3$$

with SN= N stored in maize shoot, SMN_{70}= N stored as mineral N in the upper 70 cm soil layer, natural atom % ^{15}N= 0.3663

Results

Roots

Except during the pre-emergence period of the early planted maize crop in 1992 (Experiment 1), ambient temperatures were too high to induce any serious cold stress. In early planted crops, the soil temperature decreased with depth in both years (Figure 2). Root length densities determined in core samples about 9 weeks after

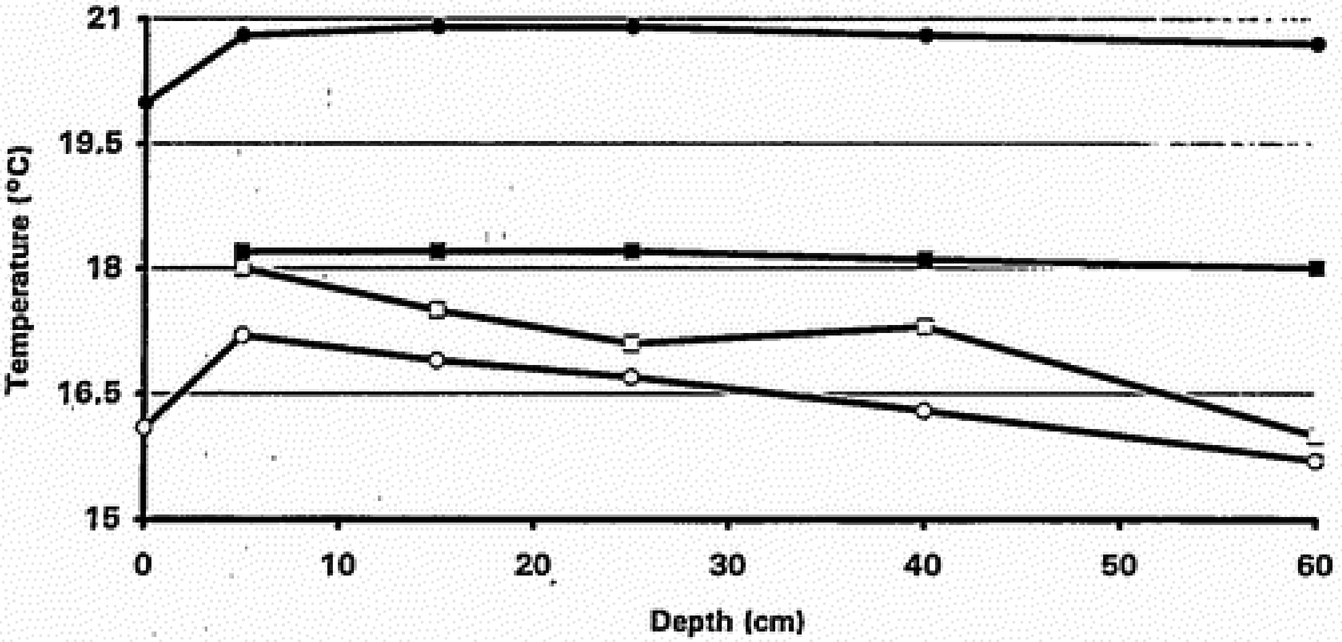


Figure 2. Average daily temperature (°C) at various soil depths (—○— = early planted experiment, 1992; —●— =late planted experiment 1992, —□— = early planted experiment, 1993; —■— = late planted experiment, 1993).

emergence, showed steep gradients in both vertical and lateral direction. Vertical gradients were strongest in the row, lateral gradients were strongest in the upper soil layers. (Figure 3). N-fertilizer placement between the rows resulted in significantly

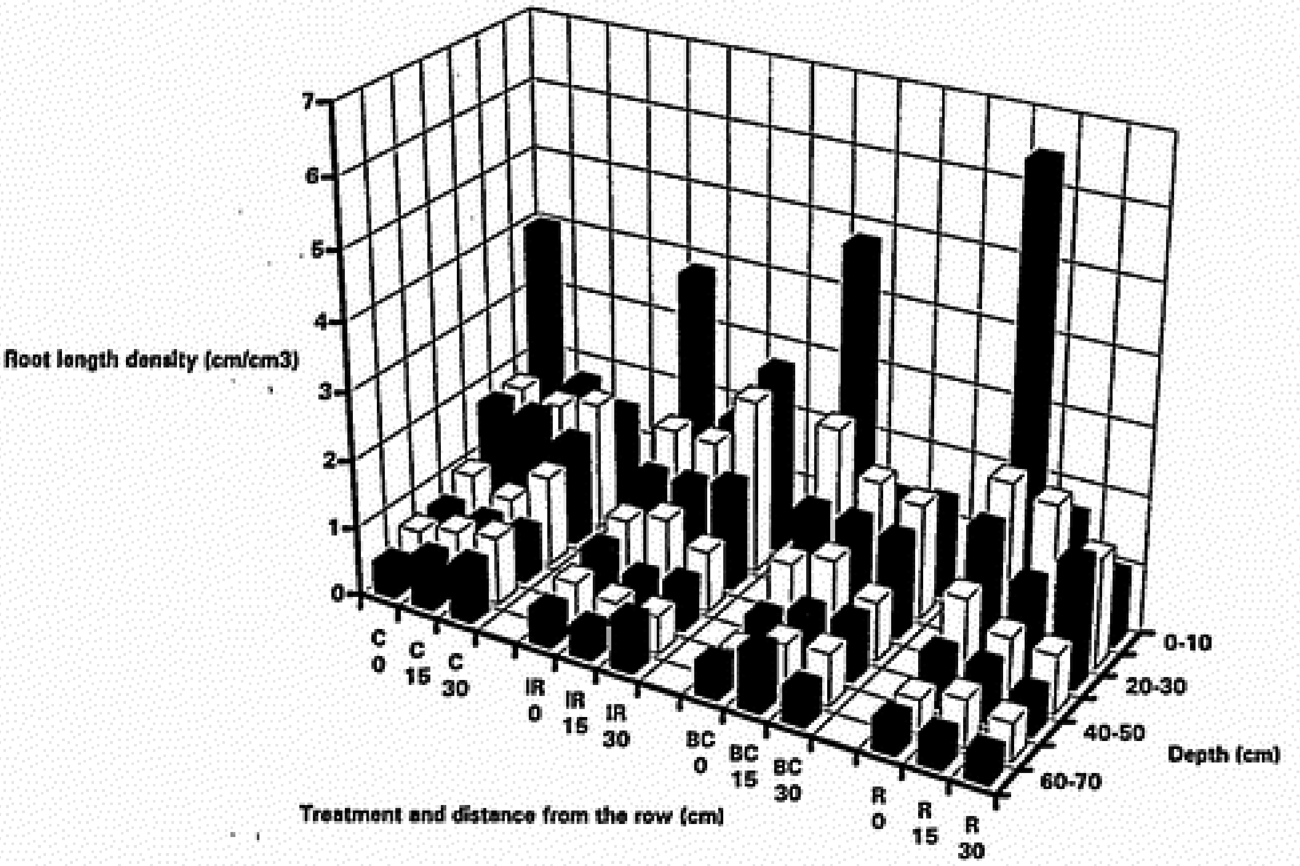


Figure 3. Root length density in core samples about 9 weeks after emergence in relation to depth, lateral distance from the row and N-fertilizer application method (C=control, IR=fertilizer placed halfway between the rows, BC=broadcast fertilizer, R=fertilizer placed near the row).

Table 1. Average root length density (cm cm^{-3}) 9 weeks after emergence in the 0–20 and 50–70 cm soil layers in relation to lateral distance from the row and N-fertilizer application method.

Depth (cm)	Lateral distance (cm)	Treatment:*			
		C	IR	BC	R
0–20	0	2.9 a**	2.9 a	3.6 b	4.4 c
0–20	15.5	1.7 a	1.8 a	1.6 a	1.9 a
0–20	31***	1.7 ab	2.6 a	1.5 b	1.3 b
50–70	0	0.6 a	0.6 a	0.5 a	0.5 a
50–70	15.5	0.8 a	0.5 b	0.8 a	0.6 ab
50–70	31	0.9 a	0.7 ab	0.6 b	0.5 b

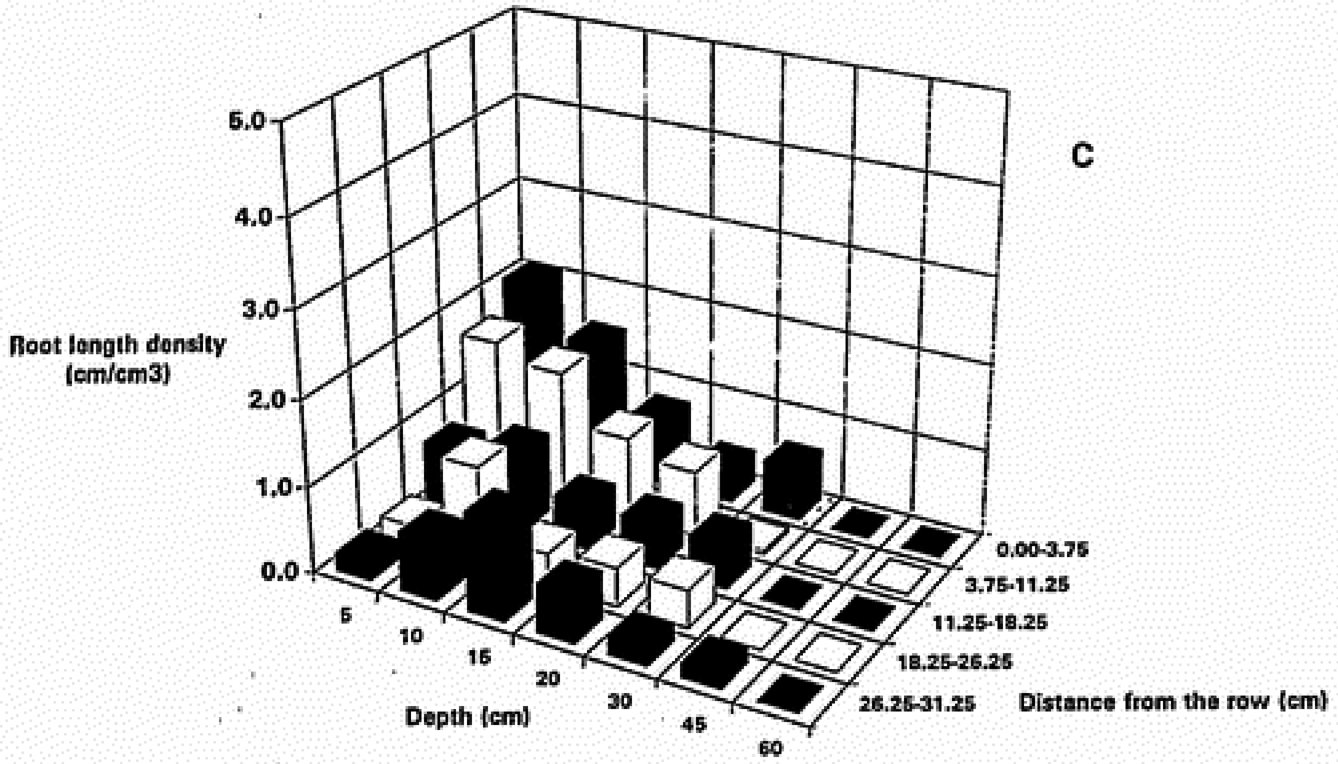
* C=control, IR=N placed halfway between the rows, BC=broadcast N, R=N placed near the row
** different letters within a row indicate significant differences between treatments at the $P<0.05$ level
*** halfway between rows

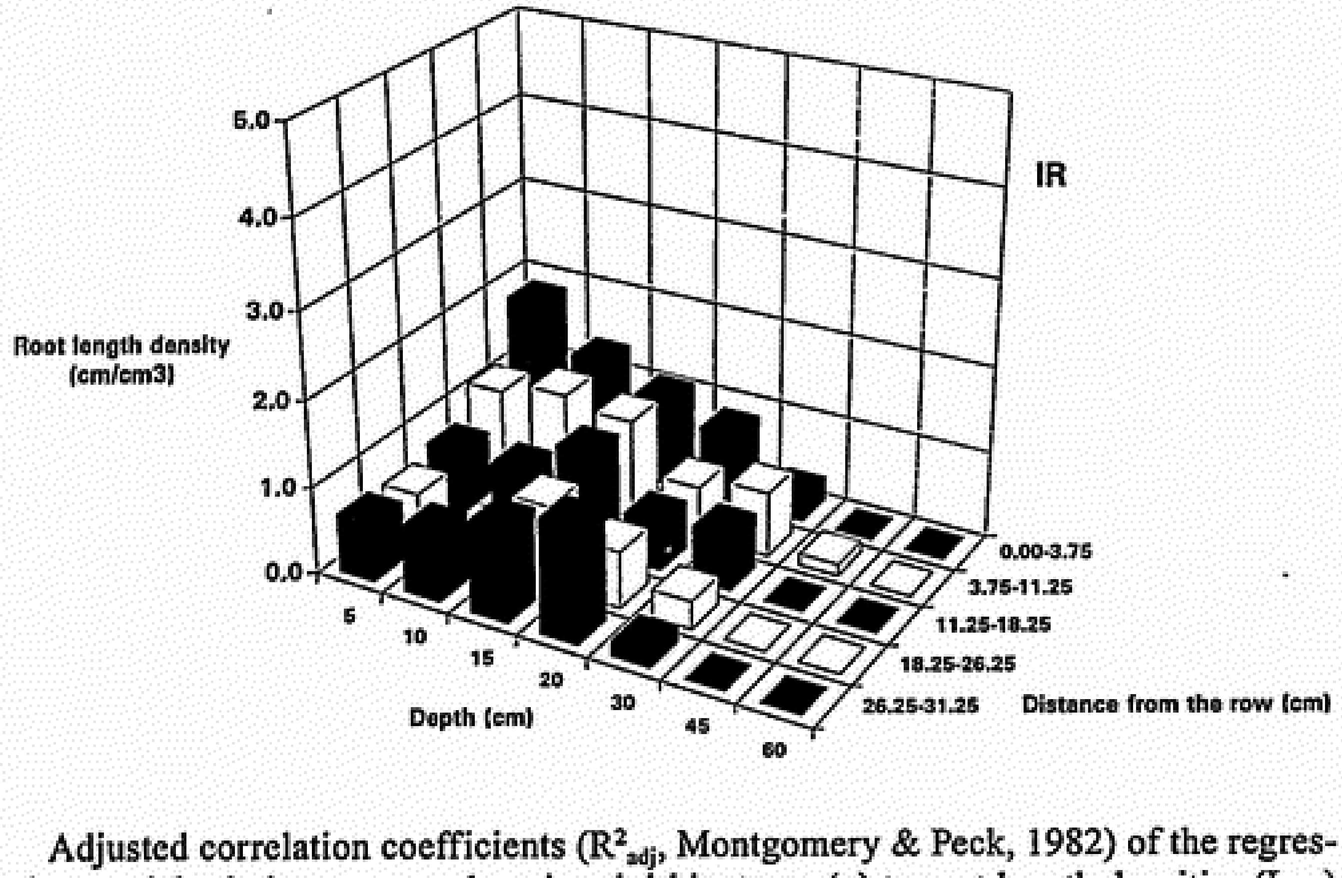
($P<0.05$) larger root length densities in the upper 20 cm soil layer halfway between the rows and lower root length densities in their vicinity as compared to the BC and R treatment. In the upper 20 cm, root length densities of the control treatment were relatively low compared to the BC and R treatment, whereas they were slightly higher halfway between the rows, especially in deeper layers (Table 1).

Table 2. Depth-dependant time lag (LAG, °Cd) and ratio (c, cm °Cd^{-1} cm^{-3}) and R^2_{adj} for the soil compartment-specific relation between thermal time (TT, °Cd, threshold 8 °C) after emergence and root length density of maize during juvenile growth stages.

Treatment	Lateral distance class (cm)	LAG for various depths (cm)							c x 1000	R^2_{adj}
		5	10	15	20	30	45	60		
C	0.00– 3.75	0	108	248	323	281	403	593	5.144	0.67
	3.75–11.25	3	44	179	223	390	452	507	4.283	0.76
	11.25–18.75	219	176	271	274	275	419	418	4.193	0.65
	18.75–26.25	343	119	310	293	297	435	434	4.140	0.41
	26.25–31,25	338	211	87	248	343	350	427	3.704	0.42
IR	0.00– 3.75	0	82	148	199	331	467	500	4.613	0.79
	3.75–11.25	88	45	76	238	195	364	466	3.596	0.74
	11.25–18.75	187	195	77	240	218	426	403	3.540	0.67
	18.75–26.25	177	271	69	172	287	722	487	2.816	0.62
	26.25–31.25	256	235	175	123	360	722	724	4.731	0.61
BC	0.00– 3.75	0	207	262	383	442	667	570	8.380	0.64
	3.75–11.25	3	266	215	338	361	483	513	6.800	0.72
	11.25–18.75	188	166	186	208	311	443	503	4.641	0.60
	18.75–26,25	487	294	187	440	351	425	667	4.668	0.46
	26.25–31.25	414	507	189	448	472	652	722	5.496	0.42
R	0.00– 3.75	0	116	365	394	497	512	520	11.601	0.87
	3.75–11.25	0	77	206	240	315	435	490	6.470	0.75
	11.25–18.75	158	177	227	174	290	380	448	5.139	0.60
	18.75–26.25	269	452	154	275	389	439	447	5.624	0.61
	26,25–31.25	425	378	116	198	261	410	445	4.893	0.42

*C=control, IR=N placed halfway between the rows, BC=broadcast N, R=N placed near the row





Adjusted correlation coefficients (R^2_{adj}, Montgomery & Peck, 1982) of the regression model relating root numbers in minirhizotrons (n) to root length densities (Lrv) in core samples amounted to 0.48, 0.16, 0.11 and 0.29 in the subsequent experiments. Corresponding Lrv/n ratios were 1.13, 1.76, 0.99 and 1.21 ($P<0.01$), respectively. Lrv/n ratios differed significantly ($P<0.05$) among experiments, except for Experiments 1 and 4. Extension of the regression model with a factor accounting for the lateral distance, changed R^2_{adj} with only –0.02 to +0.04 (absolute). Taking depth into account, improved the R^2_{adj} only in the late planted experiment of 1992. As

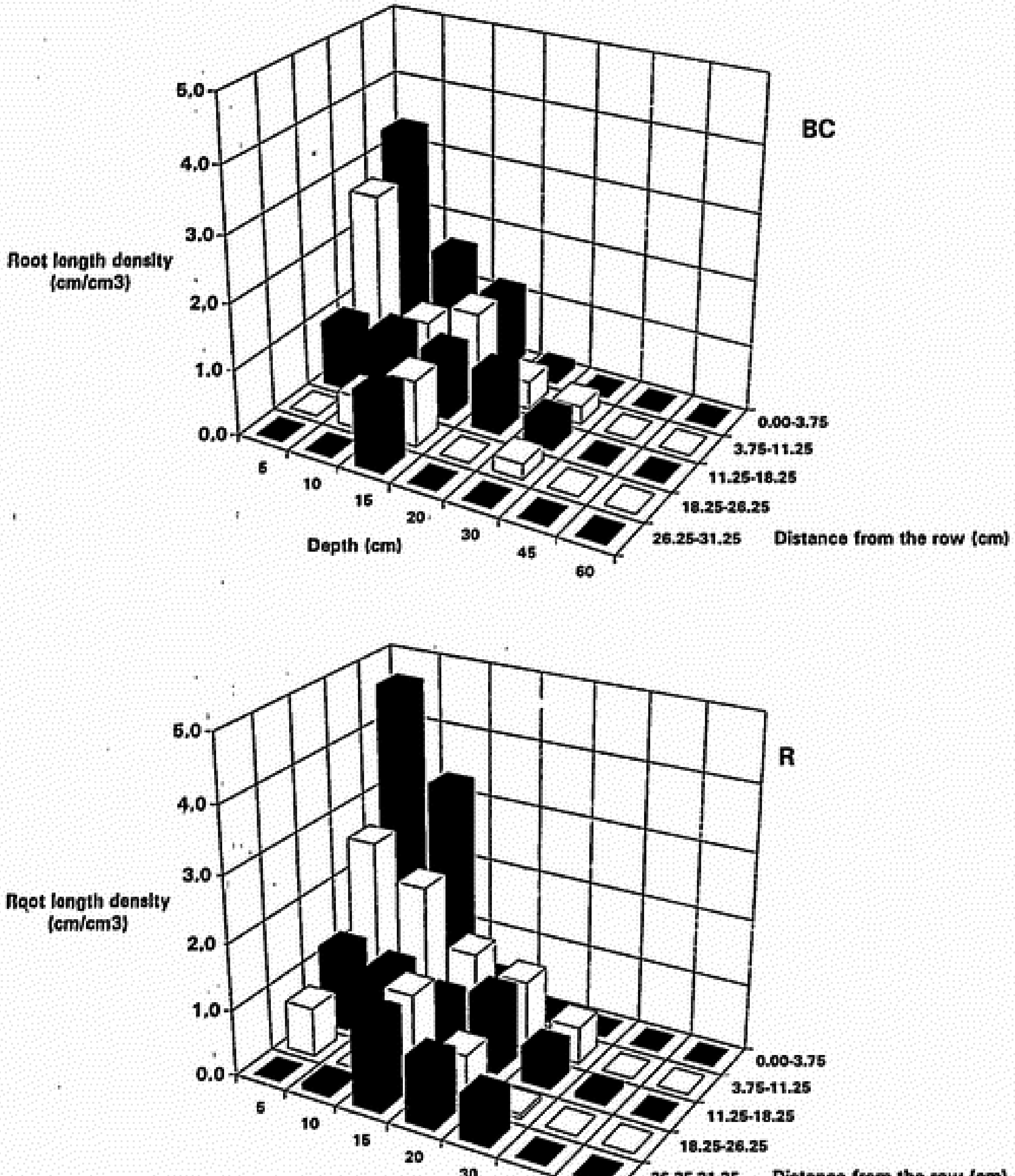


Figure 4. Calculated root length density after 400 degree-days after emergence (base temperature 8 °C) in relation to depth, lateral distance from the row and N-fertilizer application method (C=control, IR=fertilizer placed halfway between the rows, BC=broadcast fertilizer, R=fertilizer placed near the row).

trends between Lrv/n ratios and distance or depth were absent, an identical value for all depths and lateral distances was used for the conversion of minirhizotron observations into root length densities within one experiment.

Highly significant (R^2_{adj} 0.41–0.87) relationships were found between thermal time and the root length density, using the lateral distance as a factor in the model (Table 2). Allowing c_{ij} to vary with depth as well, changed the R^2_{adj} with −0.01 to +0.09 (absolute). Obviously, LAG_{ij} increased with depth and lateral distance. Using calendar time instead of thermal time yielded R^2_{adj}'s that were 0.04–0.07, 0.04–0.11, 0.16–0.19, 0.09–0.22 and 0.11–0.19 lower (absolute) for the consecutive lateral distance classes, respectively.

Figure 4 illustrates the root density distribution at 400 degree-days (e.g. after 50 days with a temperature of 16 °C) after emergence. At that stage the upper 10 cm between the rows was still unexploited in the BC and R treatment and only slightly occupied by roots in the C and the IR treatment. In none of the treatments, roots extended beyond a depth of 45 cm and 26–49 % of the 35 defined compartments were as yet unexploited.

Nitrogen

Mineral N in the upper 70 cm soil layer of the control treatments at the start of Experiments 1, 2, 3 and 4 amounted to 32, 142, 138 and 184 kg ha^{-1}, respectively. In all four experiments the amounts of soil mineral N in the control treatments remained more or less constant during the first 2–4 weeks after planting, indicating that N-uptake by the crop and net mineralisation (= gross mineralisation minus losses including immobilisation) were in balance. Subsequently, uptake exceeded net mineralisation so that N was gradually depleted starting from the upper layers. Balance sheet calculations indicated that the net mineralisation during the full growing period (= shoot N + soil mineral N at harvest − soil mineral N at planting) of Experiments 1, 2, 3 and 4 amounted to 32, −13, 5 and 9 kg N ha^{-1}, respectively.

Depletion also showed a gradient in the horizontal plane, as illustrated by the difference in the dynamics of soil mineral N between positions in the row and between the rows during the period from 30 to 50 days after emergence. In the upper 30 cm, N tended to be taken up preferentially from compartments in the row as shown by the difference in change of the supply of soil mineral N in the row and halfway between the rows (Figure 5A), whereas in the 30–70 cm layer, a tendency for preferential N uptake from compartments between the rows was observed (Figure 5B).

Horizontal soil moisture gradients were not observed in any of the experiments (Schröder *et al.*, 1994).

Leaf area, leaf N concentration and shoot dry matter yield generally showed a positive response to N application, without significant effects of the fertilizer application method. Both R and IR were superior to BC in 2 out 4 experiments with respect to shoot dry matter.

Shoot N yields were slightly larger when N was applied close to the row (R) in 3 out of 4 experiments but the effect was not significant when averaged over experiments (Table 3). N recoveries according to both Equation 1 and 2, were largest for the R-treatment and significantly different from the BC-treatment. Averaged over experiments, shoot N-recovery rankings were similar for the difference and the isotopic dilution method. Absolute values according to the isotopic dilution method were larger in Experiment 3, only.

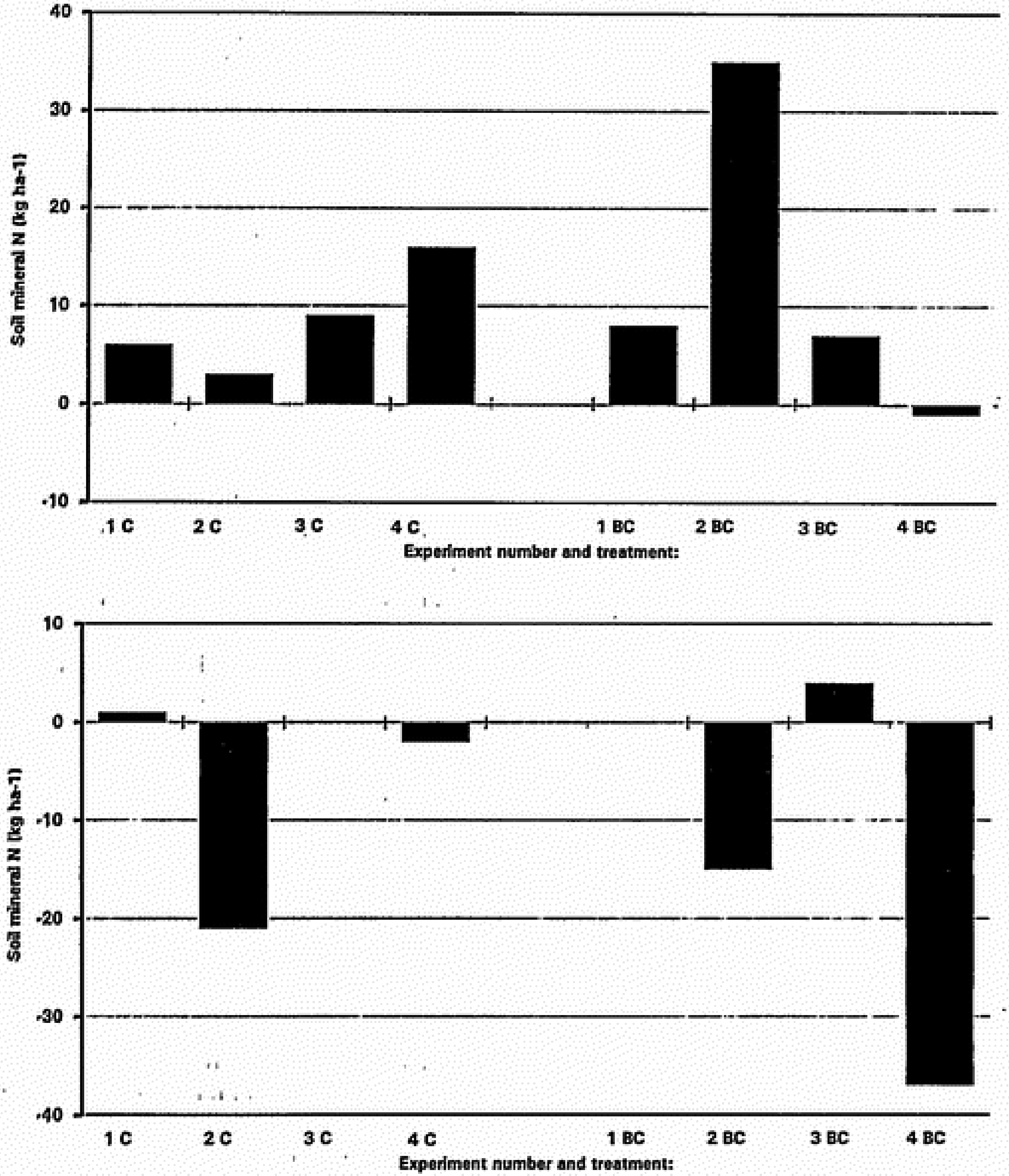


Figure 5. Difference in the dynamics of mineral N in the soil in (A) the 0–30 cm layer in the row and halfway between the rows and in (B) the 30–70 cm layer in the row and halfway between the rows, during the period from 30 to 50 days after emergence (C=control, BC=broadcast fertilizer); note: positive values indicate preferential uptake from below the row, negative values from between the rows.

Averaged over experiments, the fraction of the fertilizer recovered as soil mineral N, calculated according to a given method, hardly varied among treatments. Values of this fraction derived from the isotopic dilution method were always substantially lower than those based on the difference method.

Table 3. Leaf area index (LAI), leaf N concentration and shoot dry matter, shoot N yield and recovery of fertilizer N in maize shoots and in shoots and soil (0–70 cm soil layer) together according to the difference and isotopic dilution methods, about 9 weeks after emergence (averaged over experiments).

Treatment	LAI	Leaf N concentration	Shoot		Recovery (%)			
			DM	N	difference method		isotopic dilution	
	$(m^2\ m^{-2})$	$(g\ 100\ g^{-1})$	$(kg\ ha^{-1})$	$(kg\ ha^{-1})$	shoot	shoot+ soil	shoot	shoot+ soil
C*	3.3 a **	3.29 a	2983 a	81 a	–	–	–	–
IR	3.5 ab	3.42 a	3322 ab	99 b	36 b	96 a	40 a	66 a
BC	3.4 ab	3.40 a	3319 ab	93 b	24 a	85 a	36 a	58 a
R	3.6 b	3.40 a	3599 b	101 b	40 b	103 a	54 b	79 b

* C=control, IR=N placed halfway between the rows, BC=broadcast N, R=N placed near the row

** different letters within a row indicate significant differences between treatments at the $P<0.05$ level

As for the summed recovery of shoot N and soil mineral N, substantial amounts of fertilizer N were not accounted for when the isotopic dilution method was used, especially for broadcast N. Based on the difference method, a large part of the fertilizer N was not recovered in shoot or soil in Experiment 1, whereas a substantial gain in soil mineral N was observed in Experiment 4.

The relative contribution of mass flow to N uptake of maize during the first 9 weeks after emergence can be approximated by multiplying the transpiration rate and the average mineral N concentrations in rooted layers between successive samplings. The results of these calculations indicated that even in fertilized treatments substantial amounts of N must have originated from diffusion or from interception by extending roots, except in Experiment 4 (Table 4).

Discussion

Roots

In 1992 and 1993 we carried out four experiments in the Wageningen Rhizolab to examine whether the recovery of N by maize can be explained in terms of the spatial

Table 4. Accumulation of N in the shoot, calculated contribution from mass flow and from diffusion and interception (kg N ha^{-1}) and the relative proportion of diffusion and interception in the accumulated N.

	Experiment							
	1		2		3		4	
treatment*	C	BC	C	BC	C	BC	C	BC
mass flow $(kg\ ha^{-1})$	12	27	39	71	51	52	64	67
diffusion+interception $(kg\ ha^{-1})$	31	35	88	90	40	30	0	0
diffusion+interception (%)	72	56	69	56	44	37	0	0

*C=control, BC=broadcast N

and temporal distribution of its root system. As low soil temperatures may restrict N availability, two of the experiments were planted in early spring in order to evoke cold stress. We did not obtain stress, however, as the temperature was substantially higher than normal and initial supplies of soil mineral N were large.

The observed ratios between root length density values and the observed number of intersections on minirhizotron walls (Lrv/n), were all substantially lower than 2, the value expected for randomly growing roots (Melhuish & Lang, 1968; Lang & Melhuish, 1970). This may indicate preponderance of vertically growing roots. Chaudhary & Prihar (1974) and Tardieu & Pellerin (1991) found that low temperatures caused a reduced vertical extension of maize roots which would result in a negative relation between temperature and the Lrv/n ratio. In our experiments, however, a positive relation ($P<0.05$) was observed between the Lrv/n ratio and average daily soil temperature. Maybe other factors such as the loss of fine roots during the processing of core samples, may have contributed to the relatively low Lrv/n ratios.

Root lenght densities were closely related to thermal time during juvenile growth stages (ranging from 0 to 700 degree-days). From these relations can be calculated that roots would have penetrated to a depth of 60 cm within 81–101 days after emergence at a temperature of 13°C and within 50–63 days after emergence at a temperature of 16°C, suggesting growth rates of 0.6–1.2 cm d^{-1} which is close to the results of Foth (1962) and De Willigen & Van Noordwijk (1987). At temperatures of 13 and 16°C, respectively, it would take another 16–85 and 10–54 days to achieve a root length density of at least 0.5 cm cm^{-3} at any lateral position at a depth of 60 cm. Likewise, it can be calculated that the first roots arrive at lateral distance of 26–30 cm within 17–38 and 11–24 days after emergence at temperatures of 13 and 16°C, respectively, equivalent to lateral extension rates of 0.7–2.5 cm d^{-1}. These values are in good agreement with the range of 14–50 days after emergence that can be derived from the combined data of Foth (1962), Chaudhary & Prihar (1974), Mengel & Barber (1974) and De Willigen & Van Noordwijk (1987). It must be emphasized, however, that the proposed calculation of root extension rates at different temperatures, is merely an approximation, as specific root lengths are positively related to temperature (Kiel & Stamp, 1992). Consequently, extension rates may be smaller at low and larger at high temperatures.

The lateral extension rate was largest where the supply of soil mineral N close to the plant row was low (C and IR). Probably, N placement between the rows has stimulated lateral root extension (Granato & Raper, 1989). The 15–20 cm layer was first exploited by roots. It took another 18–27 and 10–18 days at temperatures of 13 and 16°C, respectively, before the root length density between the rows was at least 0.5 cm cm^{-3}. For shallower layers, at least 72 and 45 days were needed to achieve similar root length densities at temperatures of 13 and 16°C, respectively. Such a slow exploration of the upper inter-row soil volume may limit the efficacy of post emergence N-dressings if N is applied as a band dressing between the rows (Jokela & Randall, 1989).

Nitrogen

Mass flow alone could not account for the observed shoot N uptake. Consequently, N must have partly originated from interception and diffusion. In agreement with results of Aufhammer *et al.* (1991), Lorenz (1992) and Schröder & Ten Holte (1995), we observed lateral gradients of soil mineral N supplies, indicating that N taken up from a certain compartment was not instantaneously replenished from neighbouring compartments. N depletion of compartments was positively related to root length density.

Horizontal soil moisture gradients were not observed, suggesting a rapid redistribution of soil water. In a field situation where precipitation does not reach the soil surface as evenly as in the Rhizolab (e.g. Ellies & Huber, 1991; Girardin, 1992), this may be different.

N-application generally increased leaf area, leaf N contents and N and DM yields. No significant differences were observed, however, between crops that received N halfway between the row or near the rows. This may have been due to the absence of cold stress even in early planted crops, which may have resulted in a relatively fast root extension. Moreover, root observations indicated that IR applied N, promoted lateral root extension thus compensating for the lack of soil mineral N in the vicinity of the plant. Apparently, there is an interaction between the presence of N and the proliferation of roots. Moreover, the availability of mineral N in our soils was extremely high, probably due to soil manipulation during the incorporation of P and K fertilizers and the filling and emptying of rhizolab units, making the positioning of fertilizer N less relevant. The recyling of the soil from Experiments 1 and 2 with supplies of residual soil mineral N of 28 and 14 kg N ha^{-1} in the upper 70 cm soil layer, respectively, has only slightly increased the availability of N in Experiments 3 and 4.

Drought was avoided in our experiments. This may also explain the absence of significant N placement effects. De Willigen & Van Noordwijk (1995) demonstrated that deficiency of water may reduce the uptake of N through a negative effect on the transport of N in the soil rather than a direct effect on the transpiration. Hence, our results may have been different under dry conditions.

Recoveries derived from isotopic dilution are usually lower than those based on the difference method (Varvel & Peterson, 1990; Timmons & Baker, 1991; Blaylock & Cruse, 1992; Torbert *et al.*, 1992), due to so called added N interactions (Rao *et al.*, 1992). In our experiments, however, both methods yielded similar results. This may imply that isotope substitution has been limited which would have reduced the recoveries obtained with the isotopic dilution method. However, the results of Experiment 4, showing both a larger gain in the supply of soil mineral N than could be explained from fertilizer N input, combined with an average crop plus soil ^{15}N recovery of only 77%, suggested some substitution of ^{15}N in organic matter by ^{14}N from fertilizer. This means that there must be another reason for the fair agreement between recoveries based on the two methods than the absence of isotope substitution. An explanation may be found in an incomplete exploitation of the soil in fertilized crops. This would, by definition, overestimate the contribution of non-fertilizer N to the N uptake of fertilized crops and would underestimate the recovery obtained with the difference method. Indeed, both core samples and minirhizotron observations, generally indicated that the extremes of the profile were slightly better exploited by roots in the control than in fertilized treatments. This coincided with smaller amounts of residual soil mineral N in the extreme soil compartments of the control than in corresponding compartments of the treatment where fertilizer N was broadcast.

In Experiments 1, 2 and 3, net N mineralisation in the upper 70 cm soil layer during the full growing period, was lower in the fertilized treatments than in the control, suggesting losses of fertilizer N during the first 9 weeks after emergence. For the BC treatment, these calculated losses amounted to 28 and 34 % of the applied fertilizer in Experiments 1 and 3, respectively. Leaching into the 70–170 cm layer was not observed (Schröder *et al.*, 1994), so losses were probably due to denitrification and immobilisation. In Experiment 2, losses of BC fertilizer N were limited to 8 %. N-enrichment of the 70–170 cm layer (Schröder *et al.*, 1994) indicated that leaching accounted for the minor losses in that experiment. In Experiment 4 net mineralisation in fertilized treatments exceeded that in the control, suggesting a priming effect.

It was concluded that the DM and N yield of 9 weeks old maize crops responded positively to N. The fertilizer placement method had no effect despite a limited root extension during the early crop stage. Shoot N yields were circa 25 % larger than what is normally observed 9 weeks after emergence under field conditions, indicating that the absence of placement effects was not due to reduced crop demand for N. Apparently, N transport in the soil was not limiting growth under the current soil temperature and moisture conditions.

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