Root and Moisture Distribution of Nitrogen Treatments in a Long-term Fertilization Experiment

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Introduction

Water and nutrients are heterogeneously distributed in both vertical and horizontal planes in the root zone. Soil heterogeneity in a field causes considerable variability in root growth, which results in a variability in the growth characteristics of the above ground parts and yield. Soil water availability influences both the growth rate and spatial distribution of the root system. In turn, the number and location of active roots in a given soil volume markedly affects water uptake patterns, and hence the spatial distribution of soil water (HUCK, 1984).

Additionally, as moisture gradients are created by uptake around the roots, high differences occur between the moisture content of the rhizosphere and that of the bulk of soil (GARDNER, 1968).

Although nutrient and water uptake are closely related to the development of the crop root system, which plays a major role particularly if plants are no longer in an optimum environment, very little information is available currently on root system establishment and functioning in crop stands.

In the development of crop growth simulation models there is a great requirement for quantifying the influence of variations in water and nutrient content of the root environment upon root development and functions, since the sources and consequences of variability in root size and distribution in the soil profile have mostly been neglected due to methodological difficulties.

Under field conditions it is difficult to obtain accurate data on root growth interacting with the changing local moisture and nutrients. Minirhizotron methods have the advantages of requiring no destructive sampling and of allowing the fate of individual roots to be followed by repeated observations of the same root system. These methods are suitable for monitoring root growth, however, the influencing soil properties in the vicinity of roots cannot be accurately estimated on the basis of the bulk soil data because of their areal variability.

Although it has been possible to quantify some root parameters using minirhizotrons in field, the absence of data on the dynamics of root growth pattern with interaction of water dynamics in the root vicinity in field conditions has called for an observational facility. The minirhizotron – capacitannce moisture meter set has been developed to meet these specific research needs (ANDRÉN et al., 1991) as it is a non-destructive technique for studies on root distribution in relation to soil moisture, resulting data sets with a one-to-one correspondence between root numbers and soil moisture.

The objective of the present work was to study the vertical density distribution of maize roots in the soil profile on the basis of local soil moisture availability as influenced by N nutrition, by using non-destructive minirhizotron–moisture meter technique.

Material and Methods

The vertical distribution of maize roots affected by soil moisture has been studied in a long-term fertilization experiment on sandy soil (pH: 7.5–8.0, $CaCO_3$: 3–6 %, O.M.: 0.9–1.1%, total N: 800–1200 mg kg^{-1}, C/N: 7.8–8.0 in the topsoil) in Central Hungary. Four N fertilization rates (0, 150, 300 and 450 kg ha^{-1}) were set up. In 1990 and 1991 maize plants were grown in the field. Previously, starting in 1985 the sequence of the indicator plants was as follows: maize, maize, spring barley, winter oilseed rape, and winter wheat. More precise characteristics of the field and the experiment are presented by NÉMETH & BÚZÁS (1991) and NÉMETH (1996).

In 1990 the 109 cm long, glass minirhizotron tubes were vertically inserted in the maize rows to measure root growth below the row. The diameter (35 mm) of the tubes was chosen to suit the capacitance moisture probe as access tube. Roots growing against the walls of the minirhizotrons were observed weekly, using a viewing unit that contained an illuminated plane mirror + magnifier lens, lowered within the minirhizotron tube in 6 cm deep strata down to 100 cm. Soil moisture was measured immediately after finishing root observation in a given minirhizotron tube, using a capacitance moisture probe (ANDRÉN et al., 1991). By this method the volumetric soil moisture content of a 4 cm weighted radius soil cylinder around the minirhizotron tube can be measured. Thus, it was possible to measure root growth dynamics for the same set of plants over the course of the growing season and, interacting available soil water located in the particular vicinity of the observed roots could be monitored as well. Before the installation of minirhizotron soil nitrate and gravimetric soil moisture samplings were conducted, which were repeated after the experimental period. In 1991 the procedure was the same, but the observation tubes were installed at a 30 degree angle from the vertical to limit roots channeling down the vertical minirhizotron/soil interface.

Results and Discussion

Environmental conditions

In 1990 the season was extraordinarily dry, the total precipitation was only 52 mm for the observation period (5 July–7 Sep), with the major part falling at the end of August. In the following year summer was relatively wet with a considerable amount of precipitation in July. The total precipitation for the observation period in the second year was 252 mm (Figure 1). The distribution of precipitation had a great effect on the amount of water available to the plant.

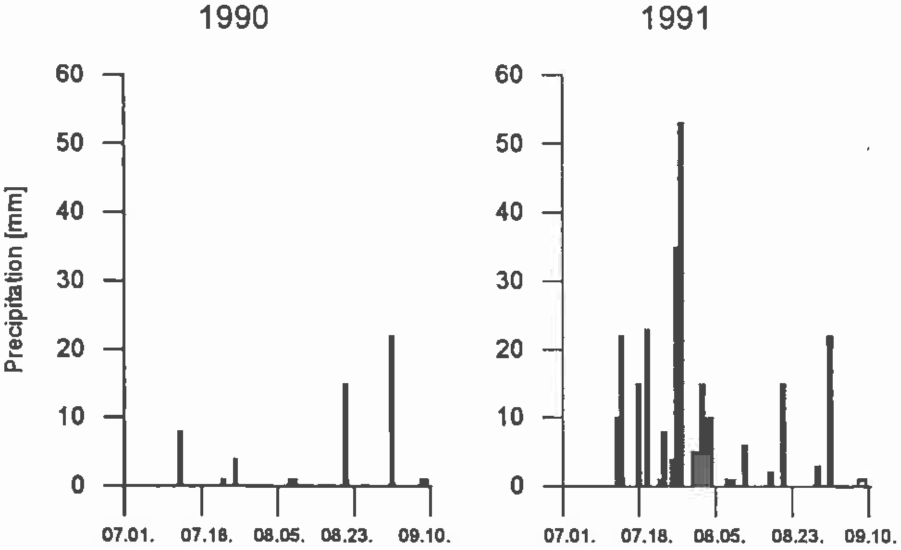

Figure 1
Precipitation during the observation period in 1990 and 1991

In 1990 plant growth was inhibited by water deficiency, whereas in 1991 an optimum water supply in the top soil guaranteed an undisturbed development of the whole plant. The sufficient water supply resulted in increasing yields (by 35, 42 and 55%) with increasing N rates (N_{150}, N_{300} and N_{450}, respectively) (Table 1).

In 1990, in the N_0 treatment the nitrate content was very low along the profile, while in the over-fertilized treatment (N_{450}) a very high nitrate accumulation was found in the topsoil. By the time of harvest the accumulation zone shifted down to the 40-60 cm depth, resulting in similar nitrate contents as in the 0-20 cm layers of the different N treatments. As a consequence of drought the downward movement of nitrate was slow in the profiles (Figure 2).

Table 1

Grain yield in the N treatments in 1990 and 1991

Treatment	Grain yield (t ha^{-1})	
	1990	1991
N_0	2.35	5.08
N_{150}	2.49	6.77
N_{300}	2.33	7.21
N_{450}	2.70	7.89
$LSD_{5\%}$	0.738	1.109

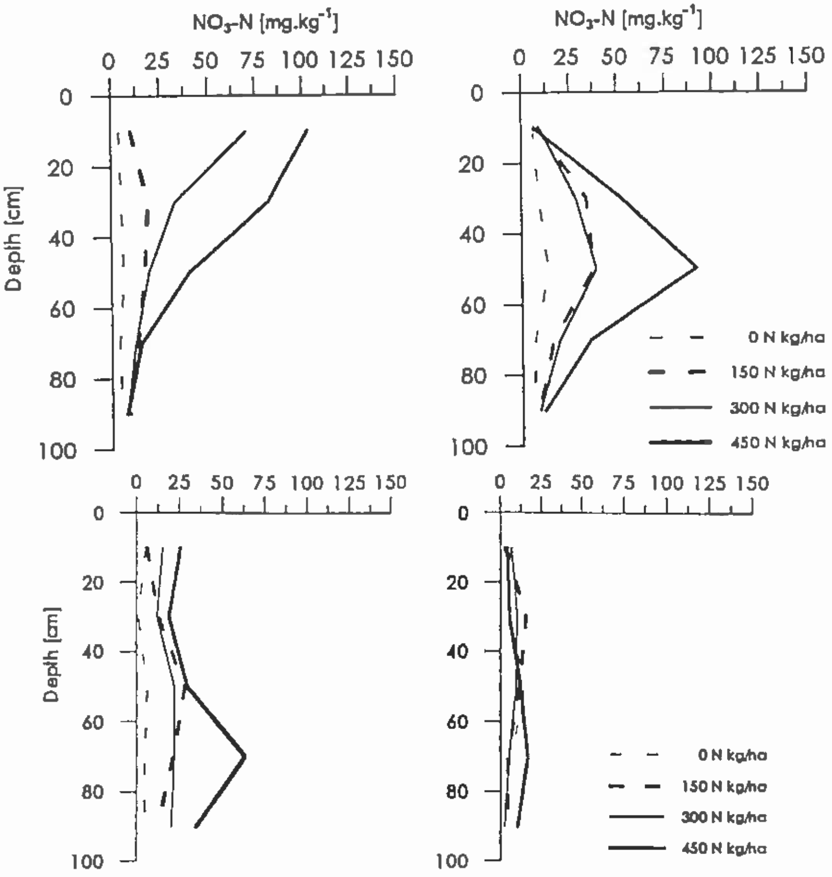

Figure 2

Nitrate-N content in the soil profile in 1990 (upper part) and 1991 (lower part of the figure) in May (left) and September (right)

In 1991 wet conditions resulted in a rapid downward movement of nitrate in the sandy soil profile and plants adapted well with the rapid extension of roots into the deeper layers.

Root distribution

Vertical root distribution reported as total root numbers with depth observed in each 6 cm (1990) and 5 cm (1991) deep layer of the 0–90 cm soil horizon are presented in Figures 3 and 4. Figure 3 compares root countings with depth at the stage of rapid vegetative growth, at silking and at grain filling (full dent stage) obtained in the N_0 and N_{450} treatments.

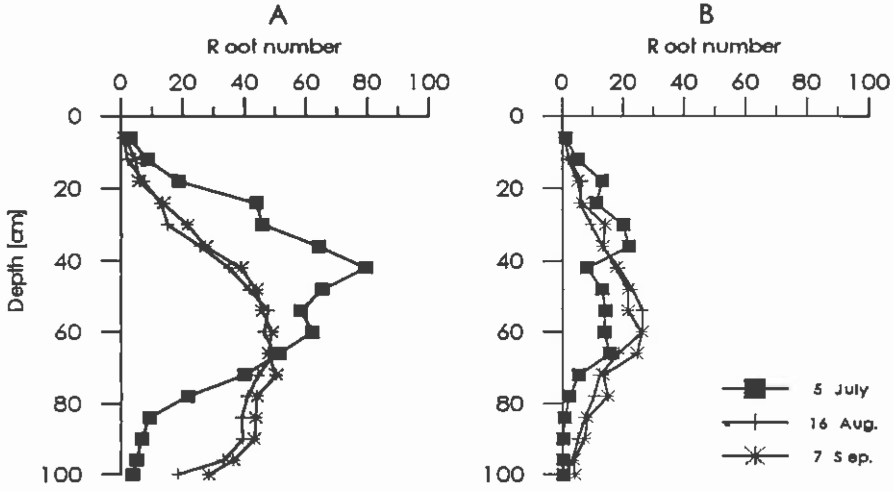

Figure 3
Vertical root distribution in N_0 (A) and N_{450} (B) treatments in 1990

In the 1990 root distribution (Figure 3 and Table 2), each nitrogen treatment resulted in root numbers lower than those in N control (N_0) plots ($p < 0.05$). On average there was a marked decrease in root number with increasing N rates. This is in accordance with the results of AUGUSTIN & MERBACH (1992), who reported that N deficiency caused a strong enhancement of the root growth of wheat plants in quartz sand culture, whereas root growth was inhibited by high N supply.

In contrast, in 1991, the observed root numbers for the N_{300} treatment were the highest throughout the season. No comparison was made between the absolute values of roots counted in 1990 and 1991 because of the difference in minirhizotron installation (vertical and angled) between the 1990 and 1991 studies.

In both years in each treatment the maximum root density zones at first observation shifted downwards during the vegetation period, from 40 cm to 70 cm and from 50-60 cm to 70-80 cm in the first and second year, respectively.

In 1990 during the rapid vegetative growth 64, 77, 70 and 63% of all roots were found in the 30-60 cm depth increment for N_0, N_{150}, N_{300} and N_{450} treatments respectively. In 1991 the value was similar for the N_0 treatment (67%), but only 57, 47 and 52% for N_{150}, N_{300} and N_{450} treatments, suggesting that in an earlier phase, a more rapid downward extension of the root system had occurred, resulting in deeper root penetration.

Generally, root density in the topsoil (plough layer) has a great importance in the nutritional status of the plant, as the concentration of available nutrients is much higher than in the subsoil, and soil aeration is more advantageous for the root activity. Root densities in the 0-30 cm soil layer varied greatly between the years and among N treatments, as indicated in Table 2. When the topsoil dried out, nutrient transport and root activity ceased, no beneficial effect of high root density could be observed.

A characteristic difference among the 1990 profiles was found in deep rooting intensity consistently throughout the season. The greatest percentage of roots (12–45%) below the 70 cm soil depth was observed for N_0, while the lowest (5.5–25%) for the N_{450} treatment (Table 2). In case of the N_0 treatment, approximately 30% of the total root number was found in this depth interval at silking, while this value was 20% for N_{150} and N_{300} and only 10% for N_{450} treatments. These values increased with plant age and almost half of all roots were found below 70 cm at the grain filling stage in the N_0 plots.

Where N was deficient, increased root development led to an increase in N uptake, because larger soil volumes could be exploited. In the early season in the presence of a more or less sufficient water supply, root proliferation was much higher in each soil layer in the control than in the over-fertilized soil.

No such marked differences could be noticed in 1991, when rooting profiles were similar for the four treatments (Figure 4). A marked increase was observed in root numbers below 50 cm in all treatments between 11 June and

Table 2

Root density in the 0-30 cm and 70-90 cm soil layers (% of total root number in the 0-100 cm profile) at flowering stage

	N_0	N_{150}	N_{300}	N_{450}
1990				
0-30 cm	10	13	16	46
70-90 cm	32	17	20	10
1991				
0-30 cm	22	24	22	26
70-90 cm	42	36	41	41

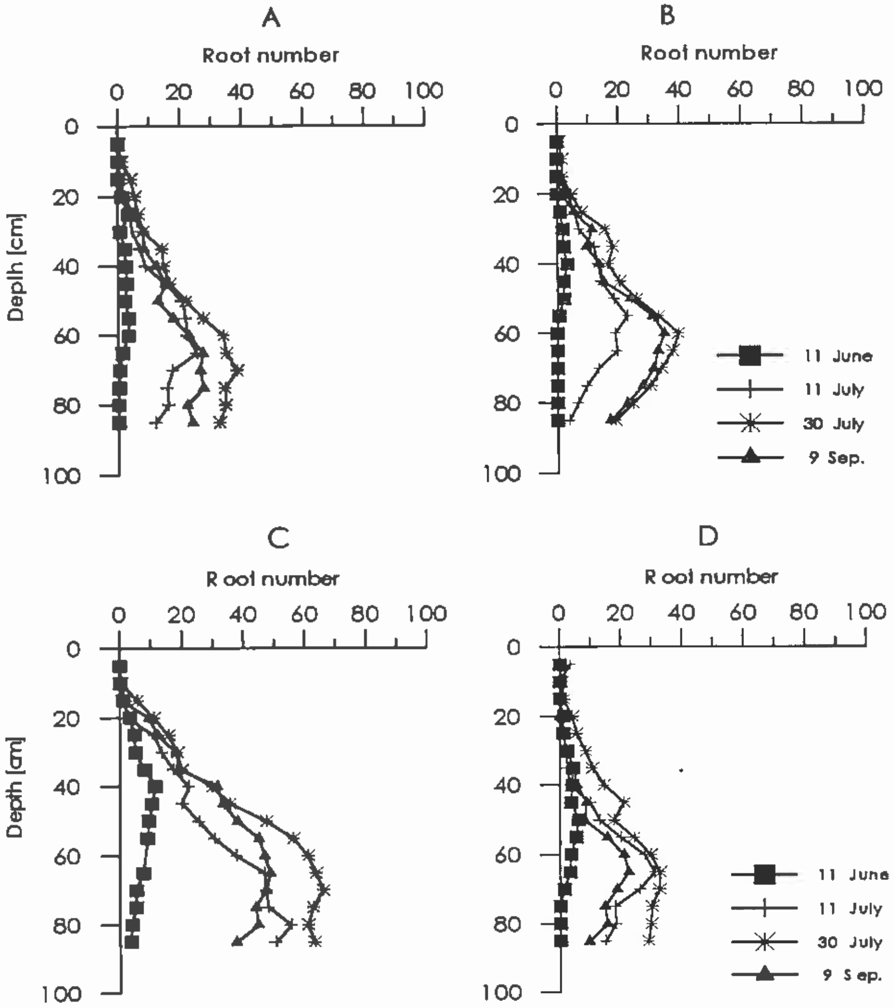

Figure 4
Vertical root distribution in N_0 (A), N_{150} (B), N_{300} (C) and N_{450} (D) treatments in 1991

11 July, in the vegetative growth, then root growth increased in the rewetted upper layers. Root profiles for N_0 and N_{450} treatments were very similar to each other, except for a more expressed lowering of root number for N_{450} at the end of the growing period. From the beginning of the growing period, the N_{300} plants formed more roots than the others, mainly below 40 cm depth. In the N_{300} treatment an extended profile of maximum root number could be found below 70 cm depth, showing a deep rooted zone enlarged beyond the soil depth

that was studied. In general, a deeper root penetration has been found in each plot in 1991 as compared to the dry 1990 season.

Another difference between the 1990 and 1991 profiles is the decrease in root density for the later dates in 1991, which indicates a higher rate of root decay. Root number reached its maximum at about the time of flowering, then decreased markedly in each treatment, as shown in Figure 4. In 1990 the first rains in August after the long dry period led to new root formation, thus no reduction could be observed in root number after silking (Figure 3).

Soil moisture

In 1990 the contrasting root growth patterns in the N treatments affected the response of the crop to available soil water supply. SCHMIDHALTER et al. (1992) reported that mild water stress enhanced root growth in maize seedlings. In our studies N fertilization hindered root growth when water stress became more severe during the season. In the N_0 treatment roots reached deeper soil layers earlier and a density high enough to satisfy the plant minimum water demand was produced. In the N control plot the available water content of the deep soil layers was reduced markedly by the crop water uptake during the observation period, as shown in Figure 5. But under the dry conditions of the upper soil horizon both root surface area and nutrient transport were reduced and

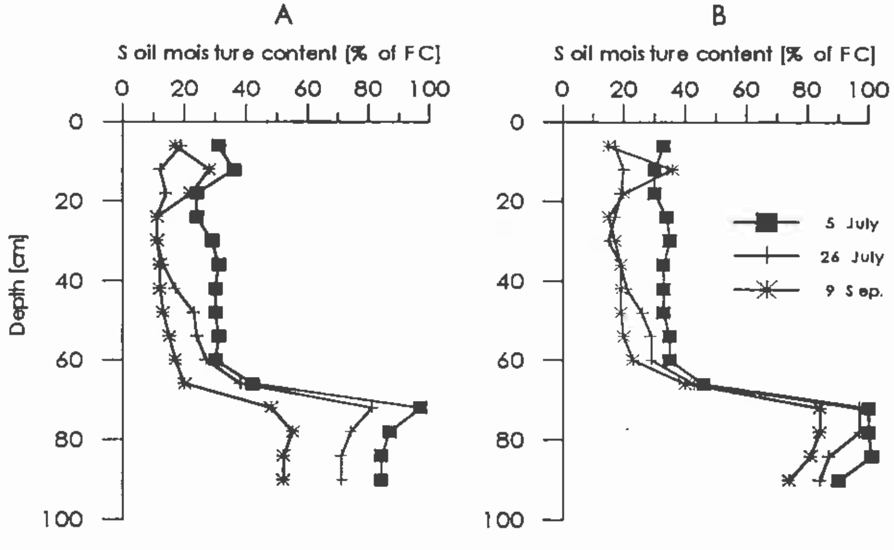

Figure 5
Soil moisture profiles (% of field capacity) around the minirhizotron tubes in the N_0 (A) and N_{450} (B) treatments in 1990

this combined effect led to a reduced yield due to the insufficient water and nutrient supply.

Similar distribution of soil moisture was found in the N_{150} and N_{300} plots. It is noticeable that, although below 70 cm root density was much lower in the N_{150} and N_{300} treatments than in N_0 (see Table 2) the moisture content was somewhat higher in the vicinity of observed roots in the deep layers of the N control plots, suggesting that the water use of plant increased with increasing N supply.

On the contrary, in the over-fertilized soil of the N_{450} treatment, high soil nitrate retarded root growth from the early vegetative stage. As a consequence, roots reached the deep subsoil later and being there in low density could not exploit much water from it (Figure 3 and Table 2.). Thus over-fertilization – due to its retarding effect on root development – increased the severity of the water stress on plant growth. Under these conditions the influence of moisture stress was dominant and no beneficial effect of applied N came out on the yield which was similarly low in each treatment (Table 1). In case of all treatments nitrate in the 0-100 cm profile was not depleted even by the harvest stage (Figure 2).

Differences in root proliferation into the subsoil due to differences in NO_3-N content of soil may influence the effects of water stress. Greater root exploration of soil volume will lead to greater water and nutrient absorption, thereby reducing the risk of water and nutrient stress.

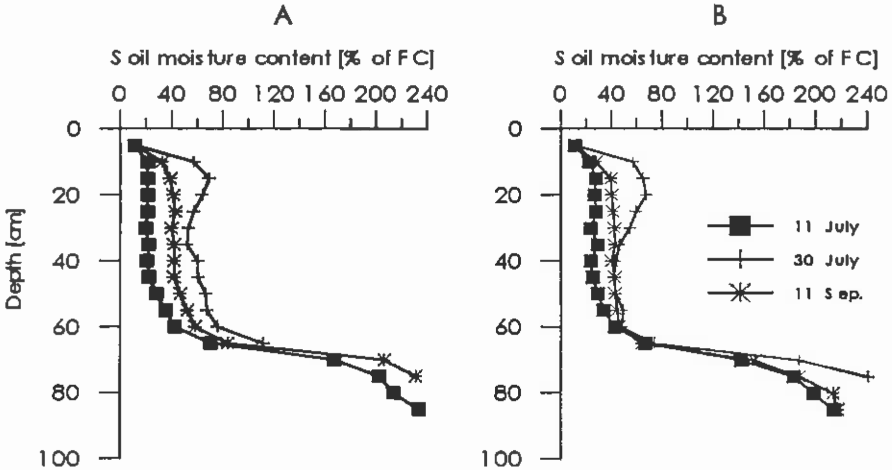

Figure 6
Soil moisture profiles (% of field capacity) around the minirhizotron tubes in the N_0 (A) and N_{450} (B) treatments in 1991

In 1991 the greater summer rainfall resulted in a much higher soil moisture content and an earlier root extension to the deeper layers, presumably caused by the rapid downward movement of water and nitrate in the sandy soil. No retardation of root growth was observed in the overfertilized treatment as compared to the N control, which indicates the decrease of soil nitrate content below the harmful level under the wet conditions of 1991 in the upper root zone.

Soil moisture was higher after silking, due to higher rainfall recorded after 11 July. Soil moisture content increased similarly in the 0–60 cm layers of N_0 and N_{150} plots, but markedly differed below the 70 cm depth in the subsoil layers, which indicates that plants used higher amounts of water from the deeper layers in the N fertilized plots than in the control (Figure 6).

In the case of N_0 there was only a slight reduction of water content in deep layers (mostly between 65 and 70 cm) by early September, while in the N fertilized plots the moisture content at 65-85 cm depth decreased markedly. The first two N rates (N_{150} and N_{300}) resulted in higher water deficit as a consequence of greater root activity in the deeper layers. Water deficit was the highest for the N_{300} treatment with the highest root density in the deeper layers.

Conclusions

Vertical distribution of the root systems varied markedly over the course of the growing season with N treatments and climatic conditions as well.

With progressive production the increased evaporative demand must be met by water supplied from the root system. Under dry conditions, root growth occurs primarily in the deeper, wetter soil horizons. In 1990 – under dry conditions – more time was required for roots to penetrate into deeper layers in N fertilized treatments than in the N control plots.

If water is deficient, maize plants with vigorous root growth are more likely to grow continuously and be productive, since an extended, deeply penetrating root growth can help to avoid dehydration by continuous uptake of water and nutrients. In the extreme dry season of 1990 water deficit was too high and the duration of drought was too long to produce normal yield by this adaptation strategy, as it could be shown for N_0 plants.

In 1991 N fertilization influenced the vertical distribution of roots in a different way. Root density reached its maximum in the N_{300} treatment, with the deepest root extension. Overfertilization caused a marked reduction in root number and root depth as well, while grain yield was the highest in this treatment. In all treatments most of the new root extension occurred in deeper soil layers, where conditions for root growth were more favourable, stored water and N were available for uptake.

N fertilization (with the exception of N_{450} in 1990) increased water use from the subsoil, where more available water was stored.

These results are useful in the assessment of the importance of different factors in growth, water and nutrient uptake, and can be utilized in simulation studies when predicting spatial distribution of active roots over the course of a growing season and accounting for variation in soil water content.

Summary

Expansion of the root system determines the volume of soil available for water and nutrient supply.

A non-destructive technique for studies of root distribution in relation to soil moisture in the immediate vicinity of the observed roots has been used in a long-term N fertilization trial. N fertilization greatly affected the growth and vertical distribution of roots. However, these effects were modified by drought stress conditions.

In 1991 – when water supply was satisfactory – increasing nitrogen rates increased root density and root depth, which reached their maximum value in 300 kg N ha^{-1} treatment, and declined in the 450 kg N ha^{-1} treatment. Under such conditions there is a high risk of accumulation of leached nitrate in the subsoil, where root density is low.

Under drought conditions (in 1990) in the N control treatment water from the deeper soil layers could be exploited by plant due to the high root proliferation in the subsoil, thereby the risk of water stress was reduced. In overfertilized plots high soil nitrate content inhibited root growth, so the severity of the effects of water stress on plant growth increased.

Nitrogen fertilization increased water use from the subsoil, where more available water was stored, with the exception of the N_{450} treatment in 1990.

The results can be utilized in simulation studies when predicting spatial distribution of roots over the course of a growing season and accounting for variation in soil water content.

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