ROOTING DEPTH, SYNCHRONIZATION, SYNLOCALIZATION AND N-USE EFFICIENCY UNDER HUMID TROPICAL CONDITIONS

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SUMMARY

A model is presented with which calculations on the nitrogen balance of a soil can be performed. The processes considered include leaching, transformation of mineral and organic N, adsorption, and plant uptake. Model calculations on the nitrogen balance for conditions of continuous leaching during the growing season in the humid tropics show a reasonable agreement between N uptake as predicted on the basis of observed root distribution and actually measured uptake. Practical possibilities for increasing nutrient use efficiency through better synchronization and synlocalization of nutrient supply in relation to nutrient demand by the crop are discussed.

INTRODUCTION

The traditional upland crop production systems in large parts of the humid tropics rely on a short cropping period followed by a long bush fallow period for soil fertility restoration. This production system is characterized by a low cropping intensity and low crop yields, with little or no input of chemicals. These systems have provided farmers for generations with stable production methods. However, during the last few decades the traditional system is undergoing rapid changes, mainly due to increasing population pressure. This has led to an increase in cropping intensity and shortening or elimination of the much-needed fallow period, resulting in a rapid decline in natural fertility and low yields.

For prolonged or continuous cropping, the loss in soil fertility in the cropping phase must be compensated for by the use of organic nutrient sources and/or fertilizers. Traditional farmers in many parts of the humid tropics cannot afford costly inputs. So-called modern techniques for fertilization are often characterized by low efficiencies, except where they are based on knowledge of local soil, climate and crops. For fertilizer recommendations for tropical countries Janssen et al. (1988) use an apparent N recovery of 20-35%, depending on soil type. With such efficiencies, fertilizer use by small farmers is often not economically justifiable. Therefore, efforts have to be made to reduce dependence on chemical fertilizers by maximizing recirculation of all available waste materials and by maximizing biological N fixation, and/or to increase efficiency of fertilizer use.

In this paper we will use a model for nitrogen uptake by maize in the humid tropics to investigate the effects of rooting depth and method of fertilizer application (synchronization and synlocalization) on the N-use efficiency obtained. The model (based on De Willigen, 1985) will first be tested with experimental data for a location in southeastern Nigeria (Onne). The model is subsequently used to examine the effects of different root distributions, different methods of application of fertilizer and different infiltration patterns of rain water into the profile.

Experiments with N-15 in the humid zone of southeastern Nigeria indicate that recovery of nitrogen given in three split applications during the growing season of maize and localized near the crop is only about 40% (Van der Heide et al., 1985). Low uptake efficiencies under these conditions may be expected, as there is continuous leaching during the growing season. In this respect the situation resembles that in artificial substrates in modern horticulture. In contrast to the horticultural situation, however, the amount of water moving through the profile is not under direct human control. Leaching can only be reduced by increasing surface runoff, with the risk of increased erosion; it may be possible, however, to influence the pattern of infiltration, for instance by ridging or by covering parts of the soil surface with mulch material to create differential infiltration patterns, i.e. zones with increased and zones with reduced infiltration.

By carefully selecting combinations of techniques, higher N-use efficiencies might thus be obtained. Measurements of root distribution have shown maize to be shallow-rooted in this soil, with soil acidity and/or soil compaction as limiting factors for deeper rooting (Hairiah and Van Noordwijk, 1986). A description of the climate and of some physical and chemical properties of the soil in Onne is given by Lawson (pers. comm.) and Pleysier and Juo (1981), respectively. Van der Heide et al. (1985) provide data on maize growth and N-use efficiencies.

MODEL DESCRIPTION

Geometry and time resolution

In the model a two-dimensional cross section of the unit soil area is considered for a maize plant in a row. This rectangular soil area is described by 55 compartments (five "columns" of 11 layers each). Within each compartment the concentration of nutrients and the root density is assumed to be uniform. The first four layers have a thickness of 5 cm, the next four of 10 cm, and the remaining three of 20 cm, the total length of the column thus comprising 120 cm. Because of the high infiltration rate in the growing season (see below) leading to high rates of vertical transport of nutrients, the lateral transfer of nutrients (which will, for the most part, be due to diffusion) plays only a minor role; it is neglected completely in the model. The five columns together cover half the row distance of 1 meter, each column having a width of 10 cm.

The time-interval used in the calculations was 1 day.

Transport and N transformations

Data on precipitation and evapotranspiration are shown in figure 1. The description in the model of water and solute transport, adsorption of ammonium and nitrate, and the biological N-transformations have been

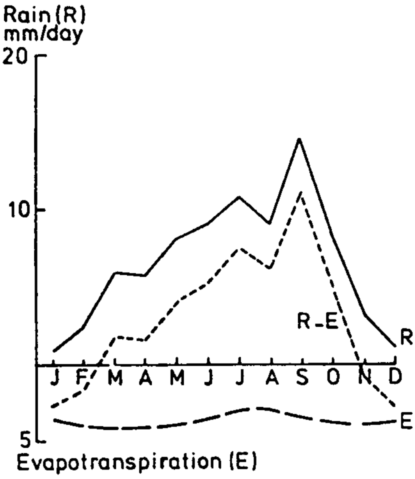

FIGURE 1. Average precipitation (R), evapotranspiration (E) and net precipitation (R-E) at Onne, Nigeria (Lawson, pers. comm.).

discussed earlier (De Willigen, 1985), where details and justification of the chosen description can be found.

Maize growth and N-demand

Potential growth of the crop for the climatic conditions of Onne is calculated as outlined by Van Keulen and Wolf (1986). Gross photosynthesis for a closed crop canopy as a function of irradiance was computed by the model of De Wit (1965). Net photosynthesis is derived from gross photosynthesis, taking into account the extent of soil cover and the respiration (at the average temperature of 26 °C). Distribution of dry matter over the various parts of the shoot (leaves, stems and cobs) was calculated as a function of stage of development, using the data on maize presented by Van Keulen and Wolf (1986). The stage of development was calculated as the sum of average daily temperature, less a base temperature of 10 °C, divided by the temperature sum at silking. The value of the latter has been taken from Allison (1963).

In our model the actual growth rate is calculated by multiplying potential growth rate by a factor depending on the ratio of actual nitrogen content to optimal nitrogen content (figure 2). The optimal nitrogen content is set at 3% in the exponential growth phase and decreases in a linear fashion to 1.3% in the linear growth phase, which starts when the amount of aboveground dry matter reaches a level of 1000 kg/ha. These figures were estimated from experimental data, collected in Onne (Van der Heide, pers. comm.)

The nitrogen demand of the crop follows from its growth rate and the optimum nitrogen content. If the nitrogen content is sub-optimal the demand also includes the amount to be taken up to restore the content to the optimum value.

The amount of nitrogen in the crop at any one moment, N_{pl} in kg/ha, is:

$$N_{pl} = Y_D \, N_c \, / \, 100 \, , \qquad (1)$$

where:

Y_D - aboveground crop dry matter [kg/ha],
N_c - nitrogen content of the shoot [%].

Differentiating (1) with respect to time yields the nitrogen demand:

$$\frac{dN_{pl}}{dt} = \frac{1}{100}\left[N_c \frac{dY_D}{dt} + Y_D \frac{dN_c}{dt}\right] \tag{2}$$

The first term on the right-hand side of (2) represents the uptake rate required to maintain the nitrogen content at N_c, the second term the additional uptake required to restore the optimal nitrogen content, if necessary.

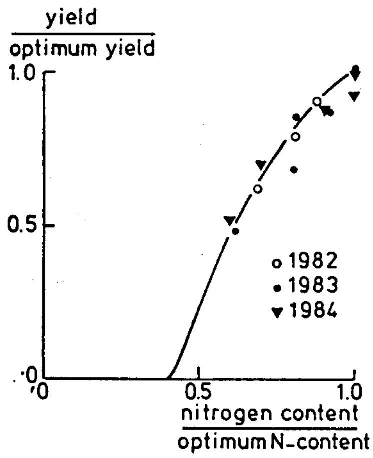

FIGURE 2. Assumed relation between rate of dry matter production and average content of the shoot; points refer to relative yields of maize in three years (data of Van der Heide, pers. comm.).

It is assumed that whenever the nitrogen content is suboptimal, the additional uptake rate is such that optimum nitrogen content can be reached within a week, if the external supply permits, in a first-order fashion:

$$\frac{dN_c}{dt} = \left(\frac{N_{c,o} - N_c}{R_c}\right), \tag{3}$$

where:
$N_{c,o}$ - optimum nitrogen content [%],
R_c - time constant [days].

The crop takes up nitrogen at the required rate if possible, or at the maximum rate allowed by the soil supply and root system. Possibilities for uptake depend on the distribution of roots and of mineral nitrogen in the soil.

Root distribution

Root distribution is not calculated in the model. It is introduced in the model as a forcing function based on data collected by Hairiah and Van Noordwijk (1986) for actual root distribution of maize in 1985. Figure 3a presents schematized data on root density distribution throughout the growing season as derived from vertical root maps and from washed pinboard samples. No maize roots were observed below 30 cm and the majority of roots were found in the top 10 cm, especially later in the growing season.

Root distribution in the topsoil was further investigated by mapping roots in the unit soil area (the reciprocal of plant density) on a horizontal surface at about 5 cm depth at four times in the growing season. Root densities on the maps were scored in a 5x5 cm^2 grid, and were classified into five classes: 0-0.1, 0.2-0.5, 0.6-1.2, 1.3-2.5, and >2.5 cm/cm^3. A cumulative frequency distribution of root densities for each observation date was calculated. With the frequency distribution a description of the horizontal root distribution over the five soil columns distinguished in the model, as it develops in time, was constructed. It was assumed that the lowest root densities will be found midway between the plant rows, and the highest in the immediate vicinity of the plant. From the cumulative frequency distribution curve the average value of root density for which the cumulative frequency is 20% or less can be read. This value is then allotted to soil column 5. The average value found for the cumulative frequency between 20 and 40% is allotted to soil column 4, etc. The distribution in the first layer (depth 5 cm) obtained in this way is given in table 1a. The horizontal distribution in deeper layers was derived from the average root densities given in figure 3. By assuming that in each layer the ratio between the numbers of roots in the soil columns was identical to that in the top layer, root length density in a soil column at a given depth can be calculated from the average root density at that depth. The roots were assumed to be distributed uniformly in each compartment. So around each root a soil cylinder can be constructed, the radius of which is a function of the root density in the compartment. The root system constructed in this way will be indicated by the term standard root system.

To study the influence of root distribution, two root systems in addition to the standard system were constructed: a deeper root system (designated as "deep" in the following) and a horizontally more extended root system ("wide"), both with a total root length equal to the standard root system. The vertical distribution of the deep root system is given in figure 3b, its horizontal distribution is identical to that shown in table 1a. The assumed horizontal distribution of the wide root system is shown in table 1b, its vertical distribution is identical to that given in figure 3a. In the model a value for root density for each compartment on each day is found by linear interpolation between the values given in figures 3 a and b and table 1.

N-uptake

Uptake of nitrogen by the root system is calculated iteratively. First (step 1) the nitrogen demand calculated with (3) is divided by the total root length to obtain the required uptake per unit root length.

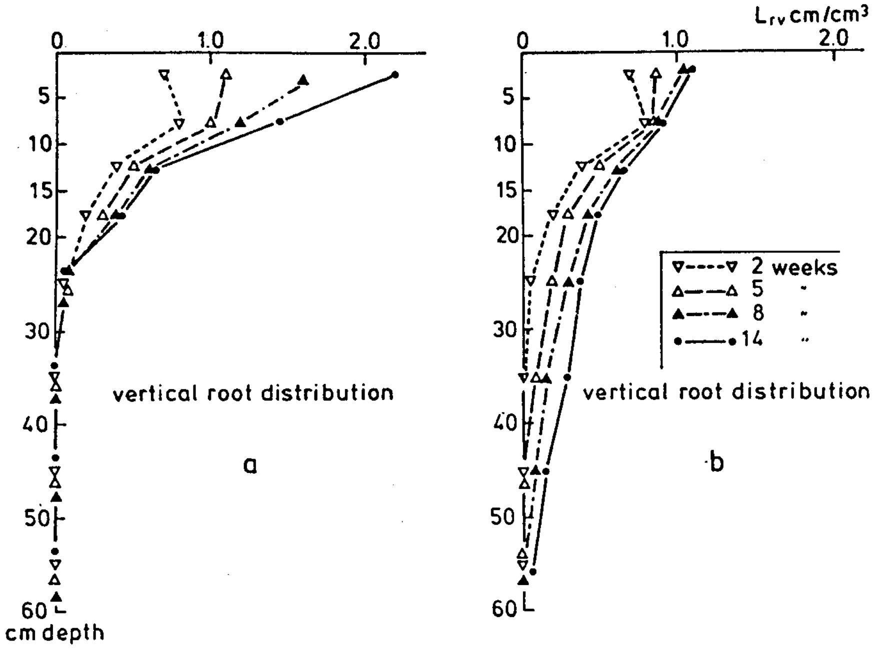

FIGURE 3. a. Root length density of maize as a function of time (weeks after sowing) and depth. Data of Hairiah and Van Noordwijk (1986). b. Assumed root length density distribution of the hypothetical deep root system.

Multiplying this by the root length in a compartment yields the required uptake from each compartment. As explained elsewhere (De Willigen and Van Noordwijk, 1987), the distribution of nutrient concentration around a root can very well be approximated by a steady-rate profile. For such a profile the average concentration C_0 in the soil cylinder around a root, when the concentration at the surface of the root is zero, can be calculated as a function of uptake rate and root density. If the average concentration in a compartment exceeds C_0, uptake from this compartment equals the required uptake. If the average concentration is less than C_0, the roots in the compartment behave as zero-sinks and their uptake can be calculated as a function of the average concentration (De Willigen and Van Noordwijk, 1987). For convenience these compartments will be indicated as compartments of category 1. The total uptake by the root system is the sum of the uptake rates of the individual compartments. If the uptake in each compartment can proceed at the required rate, total uptake equals nitrogen demand and no iteration is required. If uptake is lower than the nitrogen demand, it is checked whether uptake from those compartments where the concentration was sufficiently high to meet the original demand (for that particular compartment) can be raised to increase total uptake, possibly enough to meet the nitrogen demand.

This is achieved as follows. In step 2, first the difference between demand and total uptake, as calculated in step 1, is divided by the total root length of those compartments (category 2) that were able to satisfy the required uptake rate of step 1. This yields an additional uptake rate. The required uptake rate for compartments of category 2, in step 2, now equals the required uptake rate of step 1, augmented with

TABLE 1. Horizontal distribution of root length density in cm/cm^3 at 5 cm depth at four times.

a. Distribution based on observations by Hairiah and Van Noordwijk (1986), used for the standard and deep root system.

Time in weeks from sowing	Distance from plant row in cm (soil column) 5 (1)	15 (2)	25 (3)	35 (4)	45 (5)
2	3.0	0.4	0.1	0.0	0.0
5	3.5	1.5	0.4	0.1	0.0
8	4.0	2.6	1.2	0.2	0.0
14	4.5	3.7	2.2	0.5	0.1

b. Assumed distribution for the wide root system.

Time in weeks from sowing	Distance from plant row in cm (soil column) 5 (1)	15 (2)	25 (3)	35 (4)	45 (5)
2	3.0	0.4	0.1	0.0	0.0
5	3.5	1.0	0.6	0.3	0.1
8	3.5	2.0	1.2	0.8	0.5
14	3.5	2.5	2.2	1.8	1.0

the additional uptake rate. With this uptake rate for each compartment of category 2, C_0 is calculated, and it is examined if the compartment can satisfy the required uptake. If not, roots in such compartments behave as zero-sinks. If all compartments of category 2 can satisfy the required uptake of step 2, total uptake equals demand and the iteration ends. If none of the compartments of category 2 can satisfy the required uptake of step 2, i.e. if in all compartments of category 1 and 2 zero-sink uptake occurs, the iteration also ends. If only a part of the compartments of category 2 can satisfy the required uptake of step 2, iteration proceeds to step 3, etc.

This calculation procedure implies that roots growing under favorable conditions will compensate as much as possible for roots growing under less favorable conditions. It is thus assumed that information about the necessary behavior, as far as uptake is concerned, is instantaneously available throughout the complete root system.

MODEL RESULTS

Dry matter yield and nitrogen recovery under standard conditions

Model calculations for a situation resembling actual experiments in Onne were compared with actual results of N-uptake by the crop as a function of N-fertilization. Maize was grown in a nitrogen fertilizer trial with five treatments: 0, 45, 90, 135 and 180 kg/ha. Row width was 100 cm, plant spacing in the row 25 cm. Nitrogen was given in the form of ammonium nitrate in three split applications and placed about 20 cm from the plant. In our model all fertilizer was added to column 2. As no information was available on the mineral nitrogen content of the soil at the start of the growing season, this parameter was used for roughly calibrating the N uptake without fertilizer addition; an initial amount of 20 kg/ha seems reasonable.

Figure 4 shows the measured and calculated time course of dry matter production of maize, for a fertilization rate of 90 kg/ha (only in this treatment was the time course of dry matter determined). A reasonable fit appears to exist between calculations and measurements.

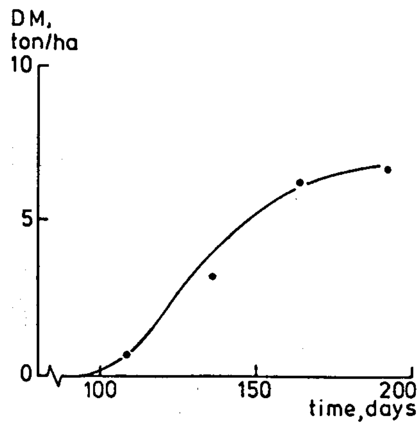

FIGURE 4. Time course of dry matter production of a maize crop at Onne, as calculated (line) and as measured, at an N-fertilization rate of 90 kg/ha. Data of Van der Heide (pers. comm.).

As shown in figure 5, the model also reasonably well describes final nitrogen uptake as a function of application rate in the experiment, although the efficiency of nitrogen use is overestimated. Uptake without fertilizer use is slightly underestimated (calculated 37 kg/ha, measured 41 kg/ha), uptake at intermediate fertilizer application levels is overestimated.

Different root distributions

The model was subsequently used for examination of the effects of root distribution, under various conditions of localization and time-distribution of the nitrogen fertilizer, and for a large range of fertilization rates. Table 2 summarizes the results. It gives the amount of fertilizer required to achieve a nitrogen uptake of 85 kg/ha, which corresponds to a yield of 6.5 t/ha, or about 90% of the potential yield, and the recovery of the fertilizer nitrogen.

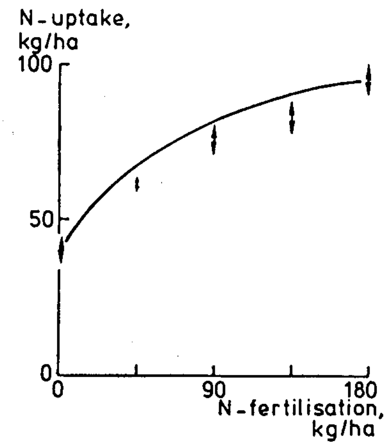

FIGURE 5. Nitrogen uptake as a function of N-fertilization in experiments at Onne; calculated uptake (line) is compared with experimental results, the vertical lines indicate the range of the experimental results. Data of Van der Heide (pers. comm.).

TABLE 2. Application rate of fertilizer nitrogen in kg/ha required to obtain a yield of 6.5 t dry matter per ha (90% of potential yield), and in brackets percentage recovery of fertilizer nitrogen. Br - broadcast, Lo - localization of fertilizer at 20 cm from plant, Sp - fertilizer applied in three splits, Nsp - application at start of growing season.

	Treatment					
	Uniform infiltration				Non-uniform infiltration	
Root system	Br Nsp	Br Sp	Lo Nsp	Lo Sp	Br Sp	Lo Sp
Standard	300(16%)	130(37%)	300(16%)	95(51%)	100(48%)	70(69%)
Deep	90(41%)	75(49%)	90(41%)	50(74%)	75(49%)	45(82%)
Wide	250(18%)	90(49%)	300(15%)	80(55%)	90(49%)	65(49%)

According to the calculations, crops with a deep root system need much less nitrogen fertilizer to realize a yield of 6.5 t/ha than crops with either of the other two root systems. The wide root system usually gives somewhat better results than the standard root system, except where fertilizer is placed and given as a basal dressing.

Uptake without N-fertilization for both the wide and the deep root system was higher than that for the standard root system, viz., 41, 48 and 37 kg/ha, respectively. The wide root system occupies the whole topsoil faster than the standard root system and thus utilizes mineralized nitrogen in column 5 more efficiently; the deep root system recovers nitrogen leached to deeper soil layers in the initial growth period.

Synchronization

Under climatic conditions with a continuous surplus of rain during the growing season, synchronizing the fertilizer supply with crop demand is very important; comparison of columns 1 and 2 of table 2 shows that if all N would be given at sowing, much more nitrogen would have to be applied to obtain a yield of 6.5 t/ha than when it would be given in three equal splits. By further increasing the number of splits, recovery could be improved; labor costs of such spoon-feeding would have to be evaluated as well as the benefits.

Synlocalization

The data in columns 3 and 4 of table 2 show that localization of fertilizer is only beneficial if it is combined with split application. As might be expected, the N recovery of the wide root system improves when N is broadcast. Localization closer to the plant, in the first instead of in the second column, would give higher recoveries, but osmotic problems of high salt concentrations close to the seed may limit applicability of such localization.

Nonuniform infiltration

If it would be possible to reduce infiltration in the immediate vicinity of the plant, for instance by ridging and/or by covering the soil surface with a mulch of plastic or banana leaves, one would expect that higher recoveries could be obtained. To calculate the effect of a modified pattern of infiltration, the average infiltration rate was multiplied by a factor of 0.33, 0.67, 1.0, 1.33 and 1.67 for the five soil columns, respectively. As the last two columns of table 2 show, a considerable improvement of recovery might be obtained in that way, especially when fertilizer is localized. In this case, localization of the fertilizer within 10 cm of the plant would give even better results.

DISCUSSION

As shown in figure 5, the relation between amount of N applied and amount taken up by the crop is curvilinear. If different amounts of nitrogen are applied in a constant number of splits, such a curvilinear response may be expected for conditions of high precipitation surplus, because of the small buffering capacity which protects only a small absolute amount of N against leaching.

Calculated apparent N-recoveries as shown in table 2 give an indication of the prospects for improving N-efficiency in actual practice. To obtain the same production, the amount of N required varies between 45 and 300 kg/ha, with efficiencies of 82% and 16%. The experimental techniques chosen, split application and localization (column 4 in table 2), obviously are much better than broadcast application as a basal dressing (column 1). Further improvement may be possible, however.

With current fertilization techniques, manipulation of rooting depth would have a positive effect on N-recovery. Cultivar selection for tolerance to acid soil conditions may be the safest way to achieve a deeper root development, because increasing soil pH by liming would lead to increased N-mobility and leaching (De Willigen, 1985). Selection for a more rapid colonization of the whole top layer by a more laterally developed root system would only be effective in the case of broadcast fertilizer application. If the N-source consists of decomposing (leguminous) cover crops, localization would not be possible to the same extent as with fertilizer as the N-source.

Manipulating the pattern of infiltration, in combination with localization of the N-source near the plant, would be effective. Split application of fertilizer N might not be required if leaching through the zone near the plant could be reduced. Practical ways of achieving such a heterogeneous infiltration will now be investigated in new field experiments.

A question is how homogeneous the actual infiltration pattern in the field is. Heterogeneity of infiltration is much more important for solutes than for water itself; the whole topsoil will be water-saturated after heavy rainfall, regardless of the infiltration pattern. In practice, infiltration will be influenced by local relief and topsoil structure as well as by characteristics of the plant canopy. Stem-flow, especially for plants such as maize where the leaves may lead a water film onto the stem during rain, may concentrate water around the plant; drip-tips of leaves may have an umbrella effect, increasing infiltration between the plants. Localization of fertilizer at 20 cm from the stem might prove to be the best practice in that situation. Remarkably little research appears to have been done on such aspects of crop canopies.

Mixed cropping of maize and cassava under the conditions at Onne leads to an increased efficiency of N use, at least partly because of the deeper root development of cassava (Hairiah and Van Noordwijk, 1986). Cassava thus utilizes nitrogen leached from the root zone of maize. Alley-cropping (Kang et al., 1985) with certain tree species may have a similar positive effect on N-use efficiency, although selection of trees with suitable root systems requires local research on each soil type. Our analysis shows that detailed information on root length distribution of crops is important for understanding nitrogen use efficiencies in the highly dynamic situation in the humid tropics. In climates where leaching losses are negligible during the growing season, details of root length distribution are less important. There, even a sparse root system can take up all nitrogen (nitrate) at the required rate, at least when the soil is not too dry (De Willigen and Van Noordwijk 1987).

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