Nitrogen use efficiency in intensive cropping systems: From crop to cropping system level

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Introduction

The heuristic value of the term nitrogen use efficiency (NUE) may generally be questioned. This term is used to describe a couple of input/output ratios which are very differently defined, depending on which level one looks at the ratio of nitrogen input and the yield output of the system (Novoa and Loomis, 1981) (Moll *et al.*, 1982) (Huggins and Pan, 1993).These scales are ranging from the primary processes of plant productivity, photosynthesis and respiration, to farm and regional levels. Another problem arises from the fact that for some definitions NUE is steadily decreasing with increasing input level of nitrogen. It should therefore be predefined at which yield level and intensity level of other input resources one evaluates NUE. Using the term NUE often to veils the view on the underlying key processes of efficient nitrogen use in agriculture rather than to sharpen the discussion about it. However, despite of all these shortcomings, NUE has become a standard terminus, which can't be ignored.

The following analysis of NUE based on the approach of (Huggins and Pan, 1993) is an attempt to use definitions of NUE to focus the different importance of processes on the crop and cropping system scale.

NUE at Crop level

We may define nitrogen use efficiency at the crop level NUE_{CL} as the ratio of the actual yield of a crop Y and N supply to this crop $N_{s:}$

$$NUE_{CL} = \frac{Y}{N_a} = \frac{N_v}{N_a} \cdot \frac{N_u}{N_v} \cdot \frac{N_y}{N_u} \cdot \frac{Y}{N_y} \qquad (1)$$

Were N supply is defined as the sum of nitrogen from fertilizer, N_f, the residual nitrate in soil left from the previous crop, N_r, the amount of nitrogen mineralized during the

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crops growing period, N_m, the amount of nitrogen fixed, N_x, and the nitrogen coming from deposition, N_d:

$$N_s = N_f + N_r + N_m + N_x + N_d \qquad (2)$$

According to equation (1) nitrogen use efficiency has several components. We can distinct the uptake efficiency, which is the ratio of nitrogen uptake through the plant per nitrogen supply, (N_u/N_s) the utilization efficiency or nitrogen harvest index (N_y/N_u) and the reciprocal of the nitrogen concentration of the harvested organs (Y/N_y).

It is therefore straightforward to postulate that we may enhance NUE at crop level through lowering the nitrogen content of the harvested organs, through enhancing the utilization efficiency or trough enhancing the uptake efficiency of the crop.

Enhancing uptake efficiency is possible through enhancing uptake efficiency of roots, enhancing total root length and matching N supply and demand of a particular crop. In plant physiological research it is common to express the dependency of the nutrient uptake rate of roots in terms of the Michaelis-Menten kinetic (Epstein and Hagen, 1952). This function has three parameters: I_{max}, the maximum uptake rate of a root under saturated conditions, C_{lmin}, the concentration where influx meets efflux and K_m, the concentration where the uptake rate is just half the value of Imax. Common values of the parameter K_m are in the range of 10 to 50 $mmol \cdot m^{-3}$ (Peuke and Kaiser, 1996) (Kage, 1995). If one extrapolates these values to corresponding nitrate nitrogen values if a defined soil layer, one comes to the conclusion that the uptake rate of a root becomes concentration dependent at very low values. It therefore seems that roots have already a very high uptake efficiency and that very little effect on NUE can be expected on enhancing the uptake efficiency of the roots. However, one has to notice the uptake parameters are usually carried out with very young roots and that root aging may alter the uptake properties of the roots (Henriksen *et al.*, 1992) (Lazof *et al.*, 1992). Delaying root aging may therefore and important trait to enhance the uptake efficiency of the root system and the plant.

We may now look at the possibilities to enhance the uptake efficiency by increasing root length. Results of a simulation study carried out with a very simple single root model (Fig. 1) (Kage and Ehlers, 1996) are showing that a rooting system with a density of 0.2 $cm \cdot cm^{-3}$ is able to take up almost all nitrate nitrogen from an soil layer of 30 thickness during a simulated period of 30 days. A further reduction of root length density may, however, reduce the uptake capacity drastically. On the other hand on has to conclude that enhancing the RLD to much higher values than 0.2

cm·cm^{-3} should have no substantial effect on the uptake efficiency of the crop. Under these conditions not the nitrogen availability but the N demand of the plant usually limits nutrient uptake.

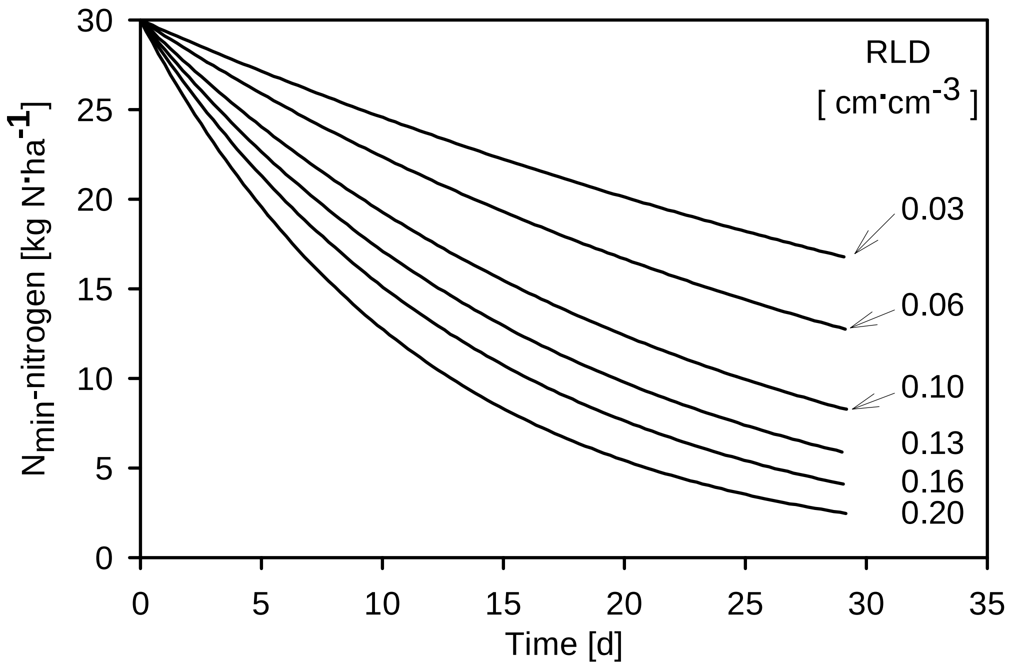

Fig. 1: Simulated depletion of an isolated soil layer of 30 cm thickness by root systems of different rooting density.
Assumptions: roots acting as zero sinks, vol. soil water content 0.2 cm^{3}·cm^{-3}, water uptake rate = 1 mm·dm^{-1}·d^{-1}, root radius 0.02 cm.

The question now arises were we can expect root length densities that may limit the potential uptake rate of a root system. The answer is somewhat specific for different crops. Long term growing deep rooting crops like cereals have at the end of their growing season usually root length densities sufficient for a complete soil exhaustion down to depth of 1 to 1.5 m. Other potentially deep rooting crops like cauliflower are limited in their rooting depth by their short growing period if they are cultivated using transplants. There are also crops which are genetically determined shallow rooting crops, like lettuce and onions (Greenwood *et al.*, 1982). However, the downward movement of the root system is also a function of the environmental conditions including the nutrient allocation in the soil volume.

Cropping system level

At the cropping system level a useful definition of NUE may be ratio of the long term yield to the amount of nitrogen fertilized to a certain field over the long run:

$$NUE_{CSL} = \frac{Y}{N_f} = \frac{N_s}{N_f} \cdot \frac{N_{av}}{N_s} \cdot \frac{N_u}{N_{av}} \cdot \frac{N_y}{N_u} \cdot \frac{Y}{N_y} \qquad (3)$$

In addition to the components of NUE at the crop level (equ. 1) we now have to define two additional components:

- the ratio of N available to N supply (N_{av}/N_s, nitrogen loss ratio)
- and the ratio of nitrogen supply to nitrogen fertilized (N_s/N_f, soil nitrogen fertility).

In this context the amount o nitrogen available is defined as the N supply minus the sum of N losses from the system.

One interesting point of equ. 2 is that at the cropping system level we have some relationships between the components of the NUE at crop and cropping system level. If we have a low uptake efficiency, residual soil nitrate is high which may result in a higher N supply of the following crop. However, also the losses from the system may rise, resulting in an decrease of NUE of the production system. If we have a low utilization efficiency at the crop level, the mineralisation from crop residues higher, which may increase nitrogen supply to the following crop. But also the losses from the system may rise.

As a simple conclusion from this: a low NUE at the crop level only determines a low NUE of the production system only if this already predetermines substantial N losses from the system. Designing cropping systems with high NUE may therefore either be done by using crops with high NUE or by designing the cropping systems which make effective use of residual nitrogen in soil and crop residues.

One possible way to prevent residual nitrogen from being lost is to use catch crops . The main problem of catch crops, however, is their limited uptake capacity for nitrogen when sown too late . This limits drastically their successful use after all late harvested crops.

Another possibility may therefore the use of deep rooting succeeding crops for nitrogen recycling. One possible crop for this task may be winter wheat because of his high rooting depths (high uptake efficiency), his high nitrogen demand (high sink capacity) and his high N-Harvest-Index (high utilisation efficiency). Own results (unpublished data) indicate that this cropping strategy may substantially reduce leaching losses at least on soils with a sufficient water holding capacity under a climate of moderate humidity.

Conclusions

NUE may be very differently defined, depending on the system level one looks at. A comparison of definitions of NUE at different scales, as presented, may help to structure the discussion.

Literature

Epstein, E., and Hagen, C. E. (1952). A kinetic study of the absorption of alkali cations by barley roots. Plant Physiol., 457-474.

Greenwood, D. J., Gerwitz, A., and Stone, D. A. (1982). Root development of vegetable crops. Plant and Soil **68**, 75-96.

Henriksen, G. H., Raj Raman, D., Walker, L. P., and Spanswick, R. M. (1992). Measurements of net fluxes of ammonium and nitrate at the surface of barley roots using ion-selective microelectrodes. II. Patterns of uptake along the root axis and evaluation of the microelectrode flux estimation technique. Plant Physiol. **99**, 734-747.

Huggins, D. R., and Pan, W. L. (1993). Nitrogen efficiency component analysis: an evaluation of cropping system differences in productivity. Agron. J. **85**, 898-905.

Kage, H. (1995). Interaction of nitrate uptake and nitrogen fixation in faba beans. Plant and Soil **176**, 189-196.

Kage, H., and Ehlers, W. (1996). Does root length density limit water uptake of field crops ? Z. Pflanzenernähr. Bodenkde. **159**, 583-590.

Lazof, D. B., Rufty, T. W., and Redinbaugh, M. G. (1992). Localization of nitrate absorption and translocation within morphological regions of the corn root. Plant Physiol. **100**, 1251-1258.

Moll, R. H., E.J. Kamprath, and Jackson, W. A. (1982). Analysis and interpretation of factors which contribute to efficiency of nitrogen utilisation. Agron.J. **74**, 562-564.

Novoa, R., and Loomis, R. S. (1981). Nitrogen and plant production. Plant and Soil **58**, 177-204.

Peuke, A. D., and Kaiser, W. M. (1996). Nitrate or ammonium uptake and transport, and rapid regulation of nitrate reduction in higher plants. Prog. Bot. **57**, 93-113.