Utilising Differences in Rooting Depth to Design Vegetable Crop Rotations with High Nitrogen Use Efficiency (NUE)

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Abstract

A number of methods involving plant or soil analysis or modelling have been developed to optimise N fertilization of vegetable crops. The methods aim at improving the NUE of each single crop, but do not really consider the crop rotation as such. Various measures can be used to increase the NUE of the crop rotation; measures that can be combined with the methods aimed at optimising NUE of each single crop.

The aims of the paper are to discuss the methods for optimising NUE at the crop rotation level and to present examples of how this can be done. The main methods discussed are 1) how can crops with different rooting depth be optimally placed in a cropping sequence and 2) how can catch crops be introduced to optimise NUE.

Results show that if N left in the soil after harvest on one crop is retained in the soil until spring, it will normally be found in deeper soil layers. Therefore rooting depth of the vegetable crops is important. It is illustrated that by placing deep-rooted crops in the crop rotation preferentially where much N was left in the soil in the previous year can strongly increase the utilisation of the N residues.

It is also shown how catch crops can be used to maintain a high NUE, especially in situations where the farmers choose to grow shallow-rooted vegetables even though much N may be available in deeper soil layers.

INTRODUCTION

During the last decades a lot of research has been directed at optimising nitrogen fertiliser supply for vegetable crops. From the early goal of defining the economically optimum supply, much of the focus has changed to methods aiming at increasing the nitrogen use efficiency (NUE) in order to reduce nitrate leaching without hampering yield. It is clear from the results of this work, that optimum nitrogen supply is strongly variable. When an optimum N fertiliser rate is calculated from a number of experiments, it will cover experiments where less N was needed and other examples where the crops would have responded to even more fertiliser N. The attempts to improve the NUE of vegetable crops have included various approaches to take this variation into account.

The work has included methods trying to measure differences in soil N availability supply, (e.g. the N_{min} (Wehrmann et al., 1988) and KNS method) or nitrogen mineralisation index measurements. Others have tried to estimate crop nitrogen status using methods such as total N concentration and critical N concentration curves (Greenwood and Draycott, 1988), sap nitrate tests, leaf colour or reflectance to estimate crop N status. Models have been used to include both soil and plant parameters (Greenwood et al., 1996).

Thus, a number of very different approaches and methods are in use, but common to them all is that they attempt to optimise the NUE of each single crop, rather than of the crop rotation. Whether mineral N is available in deeper soil layers which cannot be used by the crop, but which could have been used by another crop with a deeper root system is not considered. The fate of the nitrogen inevitably left in soil and crop residues after harvest is not considered either.

A number of cultivation measures can be used to improve the NUE at the crop rotation level, measures that can be used together with the methods developed to optimise NUE of the single crops. The tools to improve NUE at the crop rotation level are for example alteration of cropping sequence, changing the time or the way soil is tilled and the use of catch crops.

All of these methods aim to assure that roots are growing into the soil layers where mineral N is available, or to make sure that the mineral N is kept within soil layers where it can be reached by the crops. Stated shortly, the aim is to assure that roots and available N are present in the same parts of the soil volume at the same time. This paper shows examples of useful approaches to achieve this goal and discusses how they can be used.

MATERIALS AND METHODS

The results discussed in this paper are based on experiments laid out on a sandy loam soil at The Danish Institute of Agricultural Science (DIAS). The experiments concerned nitrogen management in organic vegetable rotation schemes (Thorup-Kristensen, 1999), effects of including catch crops in the rotations and the significance of differences among crops or catch crops in rooting depth. The results on root growth of vegetable crops and catch crops were obtained with the minirhizotron method as described by Thorup-Kristensen and Van den Boogaard (1998). Data for N_{min} (ammonium-N and nitrate-N) were obtained after extracting soil samples for one hour in 1 M KCl (for details, se Thorup-Kristensen and Van den Boogaard (1998)).

RESULTS AND DISCUSSION

Vegetable crops normally leave more N in crop residues and more mineral N in the soil at harvest than do most arable crops. Even though much of this N can be lost by leaching during the following winter season, higher N_{min} (nitrate-N plus ammonium-N) values are normally found in the spring after vegetable crops than after arable crops (Wehrmann et al., 1988). Whereas N mineralised from the soil or added with fertilisers will mostly be available in the uppermost soil layers, mineral N retained from the previous year will mostly be found in deeper soil layers, as the winter surplus precipitation has carried it down the soil profile (figure 1). Therefore, choosing crops with deep root systems is important for the possibility to utilise N retained from previous crops. Large differences in the ability to take up N from deeper soil layers are found among vegetable crops (Burns, 1980; Greenwood et al, 1982; Thorup-Kristensen and Sørensen, 1999; Thorup-Kristensen, 2001).

This means, that when N was left in the field in one year, much of this can be used if a deep-rooted crop is grown next year. If a shallow-rooted crop is grown, the residual N from the previous year will not be used. Thus, to optimise NUE of a crop rotation, deep-rooted main crops should follow crops that leave much N in the field. Crops with shallow root systems should preferably be grown where little mineral N is available in the deeper soil layers, i.e. where little N was available for leaching in the previous autumn.

Figure 2 shows an example of the effect of placing vegetable crops with different rooting depths in different sequences in three fields with variable amounts and depth distributions of N_{min}. For reasons of calculation leek is assumed to have a rooting depth of approximately 0.5 m (Smit et al, 1996), cauliflower a rooting depth of 1.0 m (Thorup-Kristensen and Van den Boogaard, 1998) and white cabbage a rooting depth of at least 1.5 m (Kristensen and Thorup-Kristensen, 2000). In the example, the amount of N_{min} in the top 1.5 m of the soil was 95 kg N ha^{-1} on average on the three fields. Using the worst cropping sequence (figure 2a), where the shallow-rooted leek crop is grown after peas where most N_{min} was present in the subsoil layers, only 52 kg N ha^{-1} of this was within the root zone of the crops. The remaining 43 kg N ha^{-1} was below the root zone and unavailable for the crops. Using the best example (figure 2b) 81 kg N ha^{-1} was within the root zone and only 14 kg N ha^{-1} below. As the data used for this example is taken from an unfertilised organic crop rotation, the amounts of N_{min} in the soil are relatively low. In intensively fertilised production the amounts of N_{min} can be much higher (e.g. Wehrmann et al, 1988) and the possibilities for reducing nitrogen loss by optimising cropping sequence should be even better.

Another possibility to increase NUE at the crop rotation level is to grow catch crops. Whenever the vegetable crops are harvested early enough to allow the effective growth of a catch crop before winter, this can be done to reduce the nitrogen losses. But the perspectives for using catch crops are broader, and interact again with the root growth of the main crops.

For several reasons it will not always be possible or desirable for the farmer to grow deep-rooted crops even if available N is present in deeper soil layers and crops with more shallow root systems may be grown instead. In this situation, measures which can prevent the mineral N from being leached to deeper soil layers, or which can transport N upwards from the deeper soil layers, become important. It will then be optimal to grow a catch crop in the previous autumn, as one of the effects of catch crops is to alter the spring N_{min} profile in the soil. After a catch crop less N_{min} will be available in the deeper soil layers, but more in the upper soil layers, where it can be reached by shallow-rooted main crops (figure 3).

Finally, if neither a catch crop nor a deep-rooted main crop is grown where much N was left in the soil, a deep-rooted catch crop can be grown in the following autumn. If much N was available in the deeper soil layers in the spring, and a shallow-rooted main crop has not been able to utilise this, increased N_{min} can still be found in the deeper soil layers after harvest (figure 4). Some of this can be recovered if a deep-rooted catch crop is grown.

In the example shown in figure 4, onions were grown in the first year, with or without a following catch crop. In the subsequent spring, very little subsoil N was present where catch crops had been grown, but higher levels were found in the soil layers below 0.25 m where no catch crop had been grow. The following crop of peas had a rooting depth of little more than 0.5 m. Therefore, after harvest of the peas, more N was present in soil layers below 0.5 m where no catch crop had been grown in the previous autumn. After pea harvest, a catch crop of fodder radish was established and was found to take up approximately 30 kg N ha^{-1} more where no catch crop had been grown in the previous winter season, compared to fields where rye or ryegrass catch crops had been grown. These results indicate, that even though it was probably the optimal solution to grow a catch crop directly after the onions, some of the nitrogen apparently lost if no catch crop was grown could still be recovered by a deep-rooted catch crop next autumn.

The presented examples show different approaches which can be used to make sure that roots and mineral N are in the same parts of the soil volume at the same time. To summarise, this can be done by choosing deep-rooted crops when nitrogen is found in deep soil layers or by using catch crops to make sure that the mineral N is primarily found in the upper soil layers when shallow-rooted crops are to be grown. The examples show that there are a number of approaches, which farmers can use to achieve a high NUE at the crop rotation level.

The examples shown illustrate the methods in general, but the best way to use them depends on local conditions. One of the most important points is how fast nitrate can be leached out of the different soil layers. On sandy soils with high precipitation, the main focus must be on retaining N in the upper soil layers, as N is soon leached to soil layers where it cannot be recovered. On heavy soils receiving low precipitation nitrate will move slowly through the soil profile (Burns, 1984), and the chance to recover "lost" N at a later time is substantial. On such sites, it is less important to grow catch crops exactly at the time in the crop rotation when most nitrate, prone to leaching, is left in the soil. Growing a deep-rooted catch crop or main crop may then allow recovery of much of the N at a later stage. Thus, strategies for increasing NUE at the crop rotation level must be adapted to the local climate and soil conditions.

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Figures

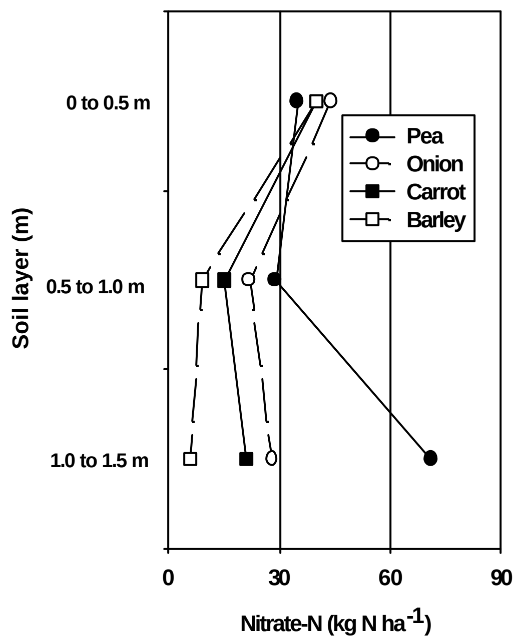

Fig. 1. Spring N_{min} (kg N soil layer^{-1}) as dependent on previous crop. The figure shows the depth distribution of N_{min} in the spring soil (Data from the DIAS organic vegetable rotation (Thorup-Kristensen, 1999)).

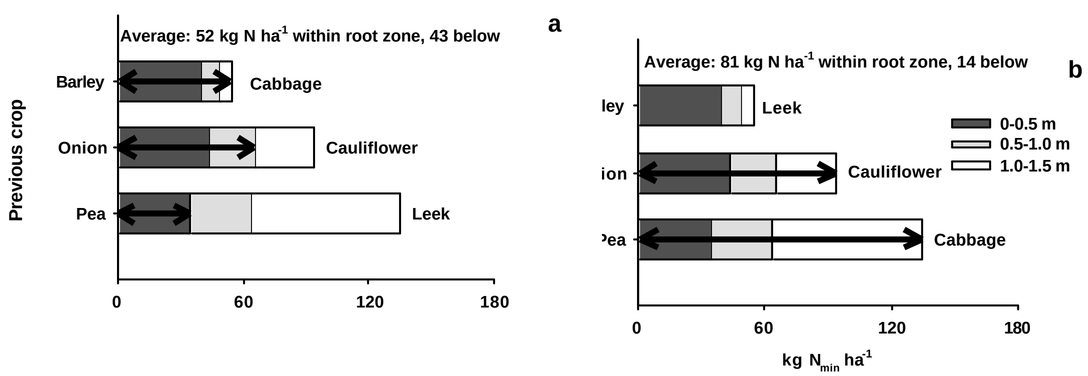

Fig. 2. Examples of utilisation of N_{min} left over from previous crops, as dependent on cropping sequence.

The bars show the amount of nitrogen present in the different soil layers in the pring, and the arrows indicate how much of this is within the rooting zone of the crop. The figure shows two examples of how leek, cauliflower and white cabbage could be placed on the three fields and how this affects the use of the available N. The worst sequence is shown in a), where almost half of the N_{min} is left below the rooting zone of the crops, whereas b) shows the best example where less than 20% of the nitrogen is left below the rooting zone. Se text for further explanation.

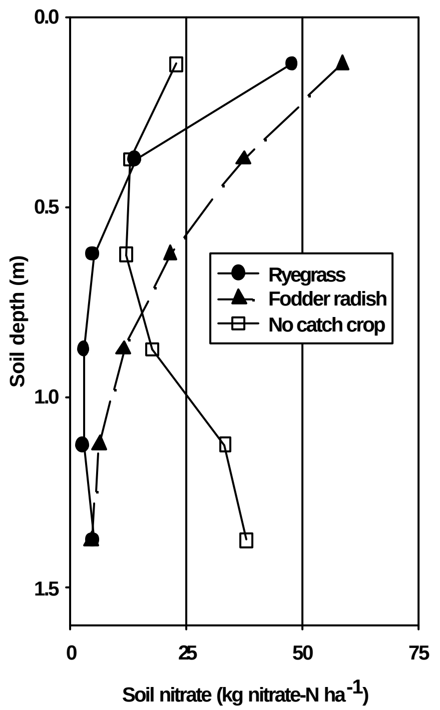

Fig. 3. Example of the effect of two catch crops on the depth distribution of available N in the soil in spring. Both catch crops have caused an increased N content in the upper soil layers and a decrease in the deeper soil layers.
Ryegrass, which remained viable until spring was more effective for redistribution than fodder radish which, was winter-killed. Data are the average of two years experiments with catch crops grown after harvest of green peas.

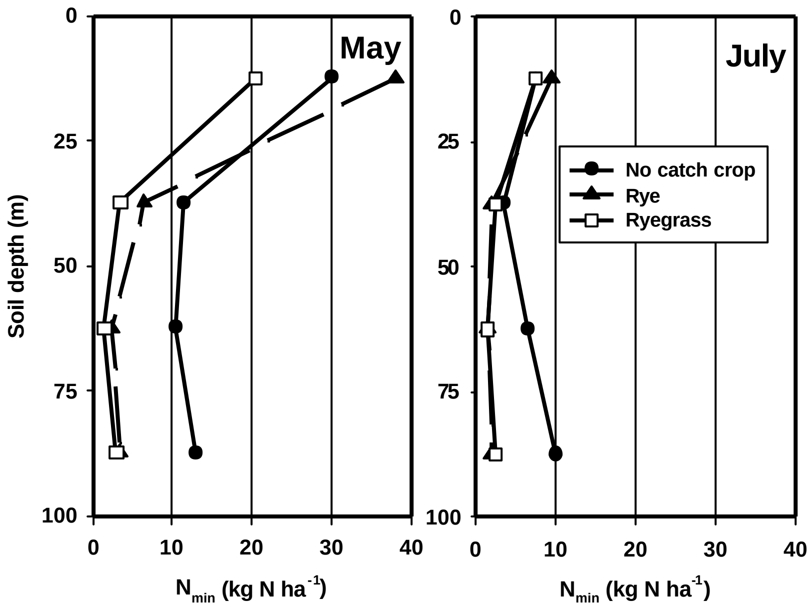

Fig. 4. Nmin before (May) and after harvest of a green peas (July). The pea crop followed an onion crop in the previous year, with or without catch crops (see text for further explanation).