Strict Danish regulations on nitrogen use and how understanding vegetable crop root growth may help us improve nitrogen use efficiency

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Agricultural use of nitrogen fertilizers is heavily regulated in Denmark, and regulations started early compared to other countries (Hansen et al., 2010). Danish agriculture is intensive and the use of nitrogen fertilizer became high at an early stage. Already during the 1970ies and 1980ies it was found that nitrate levels in drinking water wells was rising fast towards unacceptable levels. Even more important for initiating political regulation of nitrogen use was the fact that Denmark is situated among shallow sea areas, which are vulnerable to eutrophication caused by nitrogen. Eutrophication led to excessive algeal growth, and when the algae later die off, to massive oxygen deficiency (Conley et al., 2007). Due to this, it is now common that large areas of the sea around Denmark suffer from oxygen deficiency killing off many fish and other organisms in the sea during the later part of the summer period.

To reduce the problems with eutrophication, heavy regulations have been put on agricultural nitrogen use, and a considerable effort has been made also to reduce other inputs of nitrogen and phosphorus to the sea. For farmers the regulations include a lot of measures such as demands for growing cover crops, regulations on when fertilizer may be applied and which techniques may be used to spread animal manure. The aim of all this regulation is to optimize the nutrient use efficiency and reduce losses to the environment, a goal which has to some extent been reached (Conley et al., 2007; Hansen et al., 2010).

A major part of the regulations deal with nitrogen quotas calculated for each farm, and requirements for detailed accounting of nitrogen fertilizers added to the farm. In principle it is allowed to add only 90% of the optimum nitrogen demand of the crops. This is done by assigning a specific nitrogen quota to each crop species, but also doing some corrections for factors such as pre-crops, winter precipitation and nitrogen loss. The quota is calculated as aforementioned for each field, but in the end, the farmer get a combined quota for the whole farm, and is allowed to redistribute the nitrogen among fields, he does not have to follow the quota for each field precisely, but must do so for the whole farm. All in all, the regulations have had quite some success, and today the total use of nitrogen fertilizers in Denmark has been reduced by more than 30%, apparently without serious yield losses occurring.

For vegetable production, the specific nitrogen demand of each crop is not so precisely known, while several nitrogen fertilizer trials are made in Denmark each year with the main agricultural crops, fertilizer trials with vegetable crops are rarely made. Because of this, and because vegetables are high value crops, the nitrogen quotas for vegetables are not quite as restrictive as for most arable crops. Further, most Danish producers grow their vegetable crops in rotation with arable crops, meaning they can transfer part of their nitrogen quota for the arable crops and use it for their high value vegetable crops instead. All in all, this means that the system is not too limiting for the fertilization of vegetable crops, though it clearly reduce the amount of nitrogen actually used for vegetable production.

Many attempts have been made to improve nitrogen use efficiency (NUE), and of course in Denmark the focus on NUE is strong. There are many different approaches to improve NUE. Many attempts are focused on optimising the single crops and their management and fertilization; important improvements can also be achieved by working with the cropping system as such.

A major assumption behind our use of nitrogen fertilizers is that a specific crop species need a specific amount of fertilizer applied, and this is also a main assumption behind the Danish N quota system. However, this is a strong simplification, and especially in vegetable production systems this is often far from the reality. Many vegetables leave a lot of nitrogen in the field at harvest, in crop residues on in the soil (e.g. Thorup-Kristensen and Sørensen, 1999). Depending on factors such as weather, soil type, time from harvest of one crop to establishment of the next and others, high amounts of nitrogen may still be available in the soil when the next crop is established. When this occurs, the N fertilization of the next crop can be strongly reduced or sometimes even omitted. Working to understand such differences in the need for fertilizer application is one way where we can still significantly improve NUE in vegetable production.

To understand and predict when fertilization can be reduced require understanding of soil processes and how they govern nitrogen mineralization, retention or loss. However, it is also important to understand differences in crop root growth. As nitrate is quite mobile in the soil, nitrogen residues are often leached to deeper soil layers by precipitation or irrigation. To understand whether vegetable crops can actually use nitrogen from deeper soil layers, it is of course important to know whether they are able to develop a deep growing root system.

Results show that the ability to grow deep roots differ strongly among vegetable crops. This is seen as large differences in root depth penetration rates during growth, to different durations of growth (Kristensen and Thorup-Kristensen, 2007; Thorup-Kristensen, 2006a). Even with a fast root depth penetration, a crop need some duration of growth to actually establish a deep root system and also efficiently exploit nutrients from the deeper soil layers.

Studies on a number of vegetable crops have shown that they develop very different rooting depths and have very different abilities to exploit deeper soil layers, and take up the nitrogen found there (Smit and Groenwold, 2005; Kristensen and Thorup-Kristensen, 2004; Thorup-Kristensen, 2006ab). The development of rooting depth seem to be strongly related to temperature sum, and more so than to e.g. biomass production. For a number of cool season vegetables, depth development rates can be related to temperature sum calculated with a base temperature of 0 °C, and it has been found to vary from c. 0.2 mm per day degree for crops like onion, leek and celeriac, to more than 1.5 mm per day degree for some of the brassica crops. Also zucchini, lettuce and chicory crops seem to have rather high rooting depth penetration rates, whereas many species have shown rates in the order of 0.6 to 1.1 mm per day degree. For calculation of growth response to temperature sum it is of course necessary to define maximum temperatures as well as minimum temperatures for growth. However, the studies on vegetable root growth have been made under north European weather conditions, and the data did not include a sufficient number periods with high temperature to allow estimation of maximum temperatures for root growth.

Through the combination of variable rates or root depth development and variable duration of crop growth, large differences in final rooting depth are observed. At one extreme onion is found to obtain rooting depths of only around 0.3 meters (Thorup-Kristensen, 2006a), whereas brassica and zucchini crops with a long growing season have been found to reach 2.5 m rooting depth. Also tomatoes have been found to have deep rooting, in a study we found them to reach 1.08 m within 35 days from transplanting. Very short season crops such as baby leaf salad crops will of course only achieve very limited rooting depth, though even with 3 weeks of growth they will typically reach deeper than the 0.3 m reached by an onion crop, due to the much higher root growth rates of the species grown. The rooting depth of perennial crops such as artichoke, asparagus and others is unknown, but some of them can potentially reach very deep into the soil.

It has been shown that vegetable crops with deep rooting can also take up nitrogen from deep soil layers (Kristensen and Thorup-Kristensen, 2004; Thorup-Kristensen, 2006b), but several factors are crucial for this to happen. Root systems in the deeper part of the root zone are normally not very dense, and the roots grow into the deep layers only during the later period of vegetable growth, meaning that there are fewer roots and they are active for a shorter period than in upper soil layers. For a crop like lettuce, this may well mean that even though it can reach c. 0.6 m into e soil (Thorup-Kristensen, 2006a), it's exploitation of the lower half of this layer may be limited as the roots are only active there for a very short period. For crops with longer growing seasons the ability to exploit the subsoil and efficiently take up nitrogen present there is much better.

Another important factor is crop nitrogen status. While crops experiencing limited nitrogen availability will have high nitrogen uptake rates, uptake rates will be reduced as the crop is well supplied with nitrogen, which is normally the case in vegetable production. This means that when more nitrogen fertilizer is added to the soil, the nitrogen uptake rates of the roots go down, and thereby the roots in a soil layer will need more time to take up the available nitrogen. With fewer roots and shorter time available for nitrogen uptake from the subsoil, this can strongly impair the ability to utilise the nitrogen available there. Such relationships are in principle well understood, and they have been clearly shown in field experiments, but the relationships are not well quantified, and certainly not under real field conditions.

Even with the limitations in our understanding of interactions between crop nitrogen status and the ability of the crops to take up nitrogen from deep soil layers, it is clear that it is not enough just to grow deep rooted crops to really improve the NUE of vegetable cropping systems. It will be necessary to improve our prediction on when nitrogen is available there. It is also important then to reduce the amount of nitrogen accordingly to improve the ability of the crop to utilize the nitrogen from the deep soil layers. Important improvements can also be achieved by adjusting the crop rotation, to attempt to grow deep rooted crops where high amounts of subsoil is likely to be available. In some situations growing deep rooted cover crops (Thorup-Kristensen et al., 2003) or growing vegetables in rotation with deep rooted arable crops can allow strong improvements in overall NUE, though these options are more relevant under northern European conditions than in Spain.

There are various techniques which can be employed, from predictions which can be employed by farmers and advisors to help use the possibilities offered by deep rooted crops. Effects can be estimated by simulation models (Pedersen et al., 2009, 2010) or other simpler advisory tools, or by soil sampling and analysis. Several previous studies have shown that fertilization can safely be reduced based on soil analysis of inorganic nitrogen content, and using this sort of techniques in intensive vegetable production systems the input of nitrogen fertilizer and the losses to the environment may be significantly reduced.

CONCLUSIONS

Among the options we have to improve NUE in vegetable cropping systems, using the fact that vegetable crops have strongly variable rooting depths, and this can help to recover nitrogen left by previous crops which have been utilized very little. However, by better understanding of differences in crop root growth and better predictions of soil nitrogen dynamics especially in deeper soil layers, significant improvements can be achieved. Reducing crop N fertilization where significant amounts of N is available in the subsoil, and actually adapting the crop rotation to try to grow deep rooted crops specifically where much N is likely to be available in the subsoil is two of the approaches which can be used.

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