Model analysis of environmental relations in a vegetable rotation experiment

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Introduction

Vegetable production systems are typically very intensive whether they are organic or conventional. Real "low input" vegetable systems are not commercially realistic, as growing vegetables is always labour intensive and involve relatively high costs. When many resources are invested in the crop, the farmer will also work intensively to make it successful and high yielding, and this logic applies to organic as well as conventional production. In terms of resource use and environmental effects vegetable systems may be seen as less important, as they cover much smaller areas than arable farming. However, vegetable production have high environmental effects because of the intensive methods used, and it tend be concentrated within limited areas, where the environmental effects become very strong.

Also, vegetable production is interesting because of the large variation in crops, planting times and harvest times. This variation is posing many problems but also allowing a broader range of measures to be employed for reducing environmental effects than in arable farming.

The experiment and dataset used for this model simulation study is interesting because it include not only comparison between organic and conventional vegetable production, but also comparison between quite different approaches to organic production. Further, it is interesting because the set of measured data available showing not only traditionally measured parameters in rotation studies, but also measurements on soil N dynamics and crop root growth to more than 2 m depth in the soil. This set of measurements is unique among crop rotation studies, and allows more detailed comparison of measured and simulated data than most studies.

Short description of experiment and simulation

The data used for this analysis come from the VegQure rotation experiment. This experiment is designed to study effects of organic and conventional cropping systems on a range of topics, from many aspects of quality of harvested products, to effects on biodiversity and natural pest regulation in the fields to yield, productivity, and environmental effects. In the experiment one conventional system (C) is compared to three different organic systems (O1, O2, and O3). The four systems are all stock-less cash crop production systems and have an identical sequence of main crops (an 8-year rotation), but they differ in inputs, and in the use of cover crops and green manures. The C system uses chemicals for crop protection and inorganic fertilizers for nutrient supply. Among the organic systems the O1 system is based on import of animal manure as is widespread in organic vegetable production in practice. In the O2 and O3 systems, much less animal manure is used, and most of the crop nitrogen supply is based on the use of cover crops, mostly including legumes. In these systems cover crops are grown in the autumn after main crops as often as possible, i.e. in 5 out of 8 possible positions in the rotations. In the O2 system the cover crops are incorporated into the soil in the spring before vegetables are grown, but in O3 rows of the cover crops are left to grow as intercrops between the vegetable rows, in an attempt to improve the conditions for natural pest regulation in the field. Only the C, the O1 and the O2 systems are included in the model simulation study of the rotation, as the model cannot simulate the intercrops grown in O3. Further description of the VegQure project can be found at: http://www.vegqure.elr.dk/uk/.

The VegQure is not a part of the QLIF project, but it has been included in this model based analysis of sustainability of organic and low input cropping systems for several reasons. One reason is that the set of parameters measured within the VegQure project is much more detailed on some aspects, than what is measured in other rotation experiments. The rotation has a focus on studying crop root growth, a parameter normally not studied in rotations. Soil N dynamics is studied to at least 2 m depth, as this has been shown to add much more information about N dynamics and how it is affected by crops than the more shallow measurements to 1 m or even less typically used (Thorup-Kristensen, 2006a, Thorup-Kristensen *et al.* 2009). The ability to compare measured and model simulated root growth and soil N content to large soil depths allow us to do a much more rigorous validation of some parts of the model simulations, before we use them to simulate other effects such as N leaching loss which is not directly measured in this experiment. Further, the VegQure experiment includes a comparison between different low-input approaches to grow organic rotations, including an approach where soil fertility management is based mainly on cover crops. This allows analysis not only of whether organic systems are more sustainable than conventional systems, but also of whether changes can be made within organic systems to improve their sustainability, a possibility not present in most rotation studies. This focus of the VegQure experiment is a continuation of work done during previous years on crop root growth and N utilization and on the improved use of cover crops (see e.g. Kristensen & Thorup-Kristensen 2004a,b, Thorup-Kristensen et al. 2003, Thorup-Kristensen 2006a,b).

The VegQure rotation experiment is performed in Denmark at Aarhus University, Department of Horticulture. The project is financed mainly by ICROFS in Denmark (http://www.darcof.dk/), but the QLIF project have contributed to increased level of soil analysis and root studies in the experiment, in order to get better data for the model development made in QLIF WP3.3.4b and to get a better basis for the model based sustainability analysis presented here as an output of the QLIF WP7.1.

The VegQure experiment was initiated in 2005 on an area that had been grown organically without any import of animal manure, but with frequent use of cover crops and green manure since 1996. The model simulations are made with a modified version of the EUrotate simulation model which was developed for simulation of vegetable production systems (http://www2.warwick.ac.uk/fac/sci/whri/research/nitrogenandenvironment/eurotaten). Within this model, soil and crop root simulation had been developed to allow us to work with crop rooting down to 2 m soil depth. Within QLIF WP3.3.4b the model was modified in order to make it better suited for simulation of organic production systems. In short, the ability of the model to simulate N mineralization from crop residues at low soil temperature, and the ability of the model to handle simulations with prolonged periods of N deficiency was modified to allow more realistic simulation of organic and low-input systems. In the model simulation, the model is set up to simulate field treatments as they have been made since 2004, i.e. from before the start of the VegQure experiment, which started in the autumn of 2005. However, data shown in this report cover only results from 2007 and 2008, as in the 2006 data from the VegQure project the important pre-crop effects of the rotation were not yet established. In some figures results are shown as results during an 8 year rotation, though all the data are from 2007 or 2008. This is done by combining data from the different field plots, so that all stages of the rotation can be shown as a continuous set of data.

Model simulation results and validation

The ability of the model to simulate the main results of measured within the field experiment were tested by comparing simulated and measured data of crop root growth, soil inorganic N content, crop growth, and crop N uptake. A critical main check of the validity of the model simulations is presented here by comparing measured and simulated soil N in the November (Figure 1). November data are especially interesting as they show an estimate of N leaching risk during the following winter season, and understanding N leaching is a main objective here. Further, comparing the autumn data constitutes an especially critical test of the model performance. Comparison made in November includes effects of many processes (e.g. crop residue amount and quality, mineralization from crop residues and from soil organic matter, N leaching processes during autumn and N uptake by cover crops).

Comparisons made at other times of the year are more likely to be dominated by the ability of the model to simulate one specific process; in spring it will be dominated by recent fertilizer applications and at harvest time by the differing ability of crop species to deplete soil N reserves, both processes where the VegQure rotation offers a high level of variation which will be relatively easy for the model to predict.

The results of the comparison of measured and simulated soil N data from November show that the model was able to predict approximately 50% of the measured variation in soil inorganic N content in November (Figure 1). This was true for simulation of N content within the whole 0-2 m soil layer considered by the model (r^2=0.54), as well as when looking specifically at the deep soil layer from 1-2 m (r^2=0.44).

The comparison of simulated and measured soil N content show that the model is able to simulate much of the measured variation, but of course also that much of the variation were not predicted. In Figure 2 the data are shown in another way, illustrating strengths and weaknesses of the simulations. It is clear from these figures that the model simulations are able to simulate a lot of the effects of crops and cropping systems, and especially considering the 2007 data the result are very good. In 2008 the model tends to overestimate soil N content in both systems. This is probably due to the dry winter of 2007-08 leading to low leaching losses, an effect which were overestimated by the model. In both years it tends to overestimate soil N content after conventionally grown oats. Measured values were relatively high, in the order of 90 to 100 kg N ha^{-1}, but simulated values were even higher ranging from more 120 to more than 250 kg N ha^{-1}. The reason for this is not known, but the effect on the data is so strong, that the r^2 value for soil inorganic N in the 0-2 m soil layer is increased from 0.54 to 0.73 if oat data are omitted from the analysis.

As a main focus of the VegQure work and the development of the EUrotate model has been the differences in crop root growth, and the ability of some crops to take up N from deep soil layers, results on root growth and on depletion of deep soil N reserves by some crops are also shown here. In Figure 3 measured and simulated root density distribution at harvest of the main crops are shown. The best results were obtained with crops with a relatively short growing season, i.e. onion, lettuce, and oats. With these crops, both measured and simulated data show declining root density with soil depth, and the measured rooting depths (onion < 0.5 m, lettuce < 1.0 m, and oats = 1.5 m) were well predicted by the model simulations. With carrot, cabbage, and rye, the field data showed depth distribution patterns, where the highest root densities were found at some deeper level in the soil rather than in the topsoil. The model cannot simulate such a distribution, it will always show declining root density with depth (Pedersen *et al.*, 2009). However, the model simulations did reproduce the measured result that cabbage had a high root density in the subsoil layers between 1.5 and 2 m, rye a low but significant root density between 1.5 and 2 m, whereas carrot had a very low root density in this layer.

In order to simulate root effects on crop N uptake capacity, the most important part is to simulate differences among crops in rooting depth penetration to larger soil depth, and their ability to build significant root densities in the deeper soil layers. This is due to the fact that the root density needed to allow crops to take up the available N from a soil layer is quite low (Thorup-Kristensen, 2001, Pedersen *et al.* 2009). Root density will only be a limiting factor for N uptake in the deepest soil layers, where roots will have a short time to exploit soil N as they only appear late in the growing season and where root density will be low. The combination of low root density and a short period with active roots in a soil layer will limit the ability of the crop to take up the available N. While there are obvious discrepancies between measured and simulated root distributions (Figure 3) the main differences among crops in their ability to develop their root systems into deep soil layers were well predicted.

In Figure 4 simulation examples are shown to illustrate how crop root growth interacts with other parameters to determine soil N depletion by crops. The carrots show a large system effect, with much lower soil N residues in the O2 system than in the conventional system (C). In the upper parts of the soil volume the difference is due to somewhat higher N supply for the carrots in C than it really need. The main difference is found in the deep soil layers where few or no carrot roots are present. In this soil layer N has been leached down during the preceding winter season in the C system, whereas in O2 a cover crop (grass clover mixture undersown in the preceding oat crop) strongly reduced downwards leaching of soil N. Neither of the carrots takes much soil N from below 0.9 m (12 vs. 14 kg N ha^{-1} in C and O2). In the C system much subsoil N is present, but uptake is low because the crop has its N demand more than satisfied by N supply in upper soil layers. In the O2 system the carrots has a stronger demand for the N they can access in the subsoil, but uptake of N from below 0.9 m is still low because of a combination of low N availability in the subsoil, and that roots grew into the subsoil late, and did only develop a low root density there.

With lettuce the difference between the two systems was smaller (Figure 4). The amount of subsoil N was low and similar among the systems in this example. In the uppermost 0.5 m of the soil the result was much the same as found with carrots, as the high fertilizer N supply for lettuce in the C system also led to the highest amount of N residues left. However, the N supply for lettuce in C was added at the time of planting and some during crop growth, and it was all available to the crop. N supply for lettuce in O2 on the other hand came mainly from cover crop N mineralization during late winter and early spring. This N release started well before lettuce planting, and some N was leached a bit deeper into the soil, and out of reach of the shallow rooted lettuce crop. Therefore, in the 0.5 to 1.0 m soil layer more N was found at harvest of lettuce in the O2 system than in the C system.

With rye the amounts of N found in the soil at harvest were small. The crop had deep rooting during a long period, allowing it to take up most of the soil N down to 2 m depth in the soil. The yield and N demand of the rye crop in the C system was higher than in the O2 system, and the crop had a demand for substantially more N than supplied as fertilizer. This allowed the rye in C to deplete the soil inorganic N more effectively than rye in the O2 system. The result was slightly higher levels of N residues left in the soil after rye in C than after rye in O2.

The three examples illustrate how root growth, pre-crop effects, cover crop effects, yield level, and the balance between soil N availability and crop N demand interact to control the amount of soil N residues left at harvest. Understanding these interactions allow us to develop the cropping systems towards more N efficient systems.

Based on the model analyses presented above, it is concluded that the model can be used to make relevant simulations of the N leaching losses and efficiency of the vegetable cropping systems. Some important discrepancies were observed between simulated and measured data. The main problem was seen in the simulation of the oat crop, and in an overestimation N residues left in the autumn of 2008 most likely due to an overestimation of retention of inorganic N in the soil during the relatively dry winter season of 2007 to 2008. However, still the model did simulate a lot of the dynamics of the rotation, and the r^2 of measured against simulated soil inorganic N to 2 m in November was 0.54, and as high as 0.73 if the oat data were excluded.

Simulation estimates of leaching loss can not be compared directly to field measurements, but the magnitude of the simulated leaching losses in the three systems was also confirmed by field measurements of subsoil (Table 1). Finally, the tests showed that the model was able to simulate the sort of differences observed due to interactions between root growth, N supply for the crop, crop N demand based on yield, and effects of pre-crops through depth distribution of available N.

Model simulated cropping system efficiency

Figure 5 show the leaching dynamics during the rotations. In total the leaching loss was higher in C than in O1 which was again higher than in O2. The difference was quite big, leaching from O1 was almost twice as high as from O2, and leaching loss in O1 and O2 were only 77% and 43% respectively of the simulated leaching loss in C. The field data on subsoil N content, which indicates the extent of the N leaching going on, would indicate that the difference between the systems is much as simulated, though the difference between C and O1 may be slightly less than simulated, whereas the difference between O2 and the two other systems may be bigger than simulated (Table 1).

The leaching dynamics of the C and O1 systems are quite similar, though the losses in O1 are lower for all crops except for rye. The main losses are observed for lettuce, onion and oats, with losses ranging from 56 to 161 kg N ha^{-1}. After carrot the losses were moderate at 30 to 32 kg N ha^{-1}, and after rye and cabbage they were low from -7 to 19 kg N ha^{-1}. Negative values appear because net leaching loss is calculated as the leaching to below 0.9 m, corrected for any N uptake from below 0.9 m. When deep rooted crops take up N from below 0.9 m which has been leached there before the crop was established, it represents a “negative leaching loss” across the 0.9 m boundary.

In O2 not only the amount of N lost by leaching is much lower, the dynamics of loss during the rotation is also very different. By far the main loss occur after onion, with a simulated loss of 129 kg N ha^{-1}, which is as high as the loss observed after onions in C, and represents more than half of the total N leaching loss from the O2 system. Also after carrots the loss in O2 is as high as in C with a loss of 35 kg N ha^{-1}. After oats the loss in O2 is moderate at about 30 kg N ha^{-1}, and after lettuce, rye, and cabbage the practically no loss is observed, the values range from -17 to 8 kg N ha^{-1}.

Model simulated crop N uptake was higher in the C system compared to the O1 and O2 systems, just as observed in the field. However, the model also simulated somewhat higher N harvest in the O2 system than in the O1 system, a difference not observed in the field data. One reason for this may be a too high simulated N release from cover crops, as discussed in the report on development of the EUrotate model from QLIF WP3.3.4b.

When leaching loss was related to N harvest in marketable products, the O2 was the most efficient system with an N leaching loss of only 35% of harvested N, whereas the O1 system was the least efficient with a leaching loss of 72% of harvested N, higher than even the C system with 63% (Table 2). Differences in utilization of N input (fertilizer N + N fixation + atmospheric deposition) for harvested N were smaller but still significant. In the C and O1 system the harvest represented 77% of input, whereas in the O2 system it was slightly above 100%. The very high values were obtained because repeated green manure crops were simulated in the period prior to the studied period. The green manures had built up the mineralization potential, leading to a net release from soil organic pools in all three systems during the period covered in Table 2. Such high harvest of N relative to input would not be possible during longer term simulations, but the significantly better use of N input in the O2 system compared to the two other systems is likely to continue as leaching losses are kept much lower in the O2 system than in the two others.

When calculated on the basis of N input with fertilizers only, the difference between the systems become dramatic, as N harvest represent approximately 90% of input in the C and O1 systems, but as much as 357% in the O2 system. This comparison is relevant because it show the utilization efficiency of the fertilizers available to the farmers. At least in organic production this is a limited resource, and farmers need to make the most of it.

The overall balance calculations show other differences between the systems. One difference is that a build up of soil inorganic N reserves is simulated in O2 while a loss is simulated in C and O1. This effect is followed by a 10 times as large effect on soil C storage, as the C/N ratio in the soil organic matter is close to 10 (data not shown). The difference between O2 and the two other systems is due to the input of C by cover crops. In the O1 system there is some input of C to the system with the slurry applications, but this has less effect on soil C than the effect of larger amounts of crop residues returned to the soil in C.

Another effect is seen in the simulated uptake of N from below 0.9 m. In total it is not very high (11-17 kg N ha^{-1} y^{-1}), but still significant in the calculation of net N leaching loss. The simulated subsoil N uptake is very similar in the C and O1 systems. In the C system there is a high N availability in the subsoil due to high leaching losses, but a low crop demand for the N from the subsoil due to high fertilizer applications for the crops. In the O1 system there is less subsoil N available, but higher crop demand for it, and in total the uptake in the two systems become similar. For all crops except rye, a little bit more subsoil N uptake is simulated in C and in O1 (Figure 6).

In the O2 system the crop demand for subsoil N is relatively high as in O1, but with the intensive use of cover crops the N leaching and subsoil N availability is mostly kept low. The result of this effect is seen in the low subsoil N uptake by O2 oats (Figure 6). This is due to the effect of the fodder radish cover crop grown after lettuce. The fodder radish cover crop prevented N leaching to the subsoil, and took up the N already there. After this, N release from the radish residues occurred in the topsoil, but the subsoil was left with a very low N content, leaving little for oats to take up. With most crops however, the subsoil N uptake was a bit higher in the O2 system than in the two other systems (Figure 6), but the main reason for the higher overall subsoil N uptake in O2 was the use of cover crops, rather than a higher subsoil N uptake by the main crops.

Options for improved N management in rotations

The big differences in efficiency between the C and O1 system on one hand and the O2 system on the other hand clearly point to the possibilities for improvements of the two systems. Cover crops could be included in these systems. , and could strongly reduce the high losses simulated after lettuce and oats. The high and moderate N leaching losses simulated after onion and carrot are not so easy to reduce. In the present simulations the losses after these two crops is actually a bit higher in the O2 system than in the C system. Some of this loss is offset by the higher subsoil N uptake of rye in C2 following these two vegetable crops, but this effect is on average only c. 5 kg N ha^{-1}. Thus, for all three systems there is a clear need for improvement in the N management concerning the onion crop.

The fact that in the O2 system the succeeding rye crop reduces the leaching problem after onion a little indicates some of the possible improvements. Employing deep rooted crops in rotations with shallow rooted crops can strongly improve the N efficiency of a crop sequence (Thorup-Kristensen, 2006a), and in these simulations, anything which will increase the ability of the deep rooted rye crop to take up N left by the onion crop will reduce the total leaching loss from the rotation. Reducing the N fertilization of the rye crop in C will increase its ability to take up subsoil N, as its N demand is not fully satisfied by N applications to the topsoil. Further, the onions are removed from the field in late August, but rye is sown two months later in late October. Advancing the sowing date of rye will increase its uptake of N during the autumn, and it would allow the crop to develop deeper rooting and thereby to take more of the N left in the soil by onions (Thorup-Kristensen *et al.*, 2009).

Figure 7 show simulated effects of reduced N fertilization, earlier sowing of rye, and a combination of both. These measures have a moderate effect on total N leaching loss, reducing it from 219 kg N ha^{-1} in the VegQure simulations to between 182 and 202 kg N ha^{-1}. Effects are not only seen for the whole oat/onion/rye crop sequence, but also for the onion crop itself. This is because with early sowing the rye starts to take up significant amounts of N already during the main leaching period after the onion crop. Both options, reducing rye fertilization and sowing rye earlier may reduce rye yields, but they will still represent a very cheap way to reduce N leaching losses compared to the economic risks involved in reducing fertilization for the onion crop itself.

There are also possibilities for improvements in the period before the onions are grown. It is a clear advantage to grow cover crops before shallow rooted crops, as the cover crops ensure that most of the soil available N is found in the uppermost soil layers. With onion which is probably the most extremely shallow rooted of any common vegetable crop (Thorup-Kristensen, 2006b), it could be important to maximize this effect, but simulations indicated an effect of only 5 kg N ha^{-1} (data not shown). But introducing cover crops into the oat crop grown before onion had a big effect on simulated leaching loss (Figure 7). Leaching loss during the oat/onion/rye sequence was reduced from 219 kg N ha^{-1} to between 107 and 174 kg N ha^{-1}, and the two non-legume covers crops (ryegrass and chicory) clearly had the best effect. Chicory was the best of all because of its very deep rooting, as has also been shown in field experiments (Thorup-Kristensen, 2006a). The legume cover crop (clover grass mixture) reduced N leaching loss in the period between oats and onions as much as the non-legume ryegrass cover crop. The difference appeared in the next autumn/winter season, due to too high N supply for the onions when N released from the legumes were combined with fertilizer N application. This problem could be reduced by reducing N fertilizer application to the onions.

By combining the chicory cover crop in oats grown before onions and early sowing and reduced N fertilization for the rye crop grown after onions, the simulated N leaching loss during the oat/onion/rye sequence was reduced with 70% from 219 kg N ha^{-1} without these measures to only to 67 kg N ha^{-1}. This was done without reducing the fertilization of the high value onion crop. According to the simulation results onion yield was not reduced in any of the simulations, and slightly reduced N availability for onion was only simulated in case of the ryegrass cover crop.

An important point to be seen in Figure 7 is that while N leaching loss during the 3-crop sequence of oat/onion/rye is affected strongly, and in the best combination reduced by 70%, whereas the effect when looking at the “onion phase” alone was only 21%. In the best combination the leaching loss during the “onion phase” was 111 kg N ha^{-1}, whereas the loss during the whole 3-crop were lower at only 67 kg N ha^{-1}. This maybe surprising result was achieved due to the use of deep rooted plants, the chicory cover crop and the rye. During the “oats phase” and the “rye phase” of the sequence they created a “negative leaching loss”, as they took up N that had leached to below 0.9 m, and thereby were able to undo some of the leaching loss otherwise associated with the onion crop.

The reduction in leaching during the “onion phase” was not well related to the effect which could be achieved across the whole 3-crop sequence, and was not a good predictor of the real efficiency of the different options. This result clearly point to the importance of looking at the whole rotation when trying to reduce N leaching losses, rather than focussing specifically on the crop and season when high leaching losses occur.

Discussion

Cropping system effect on N leaching losses

It has previously been concluded that modelling is an important tool for analyzing environmental effects of rotations (Cannavo et al. 2008; Velthof et al. 2009) and for improving organic crop rotations (van der Burgt et al. 2004; Bachinger & Zander, 2007). The present study confirms this by comparing simulated results to detailed measured results on N dynamics in a crop rotation experiment. Though there were some problems in the simulation results, the model was able to predict the general N dynamics of the 8 years of the rotations, and to predict the general differences among the conventional and the two organic rotations. An important aspect of this study is that the model includes soil N dynamics to 2 m depth (Pedersen *et al.*, 2009) and this can be compared to field measurements of soil N and crop rooting also extending to 2 m depth. The results show that deep rooted crops such as cabbage and rye are important, as they can take up N that has been leached to depths where it is normally assumed to be lost by leaching. Also Thorup-Kristensen *et al.* (2009) and Zhou et al. (2008) find that winter cereals can take up N leached deep after previous crops, and Kristensen and Thorup-Kristensen (2004a) and Thorup-Kristensen (2006) found that cabbage can deplete soil N effectively to more than 2 m depth. The important role of such deep rooted crops is not included in other rotation studies, neither experimentally or in simulations. The model simulations indicated the manure based organic system (O1) only reduced N leaching loss a little compared to the conventional (C) system, and similar results have been reported by 6278.

When estimating overall leaching losses and N balances by model simulation, there may be a main problem due to simulation of denitrification losses. In many models denitrification losses are typically simulated to constitute only a few percent of the total N loss from the system, and this is in deed the case with the EU-rotate model used in this study. In some new studies denitrification losses are estimated to be much higher (van Beek et al. 2007; Velthof et al. 2009), and van Beek et al. (2007) even find it to be more than twice as high as the N leaching loss. The reason for this difference in estimates is unclear, but if it is e.g. due to inclusion of subsoil denitrification in the balances, there may not be too much of a discrepancy. N may be lost by leaching from the upper soil layers, and then lost from the subsoil layers by denitrification. Denitrification of N in deep soil layers will occur when nitrate leaches to water logged and often anaerobic soil layers.

One of the conclusions from the simulations was that leaching losses were only moderately lower in the O1 system than in the C system, whereas when employing frequent cover crops the losses were strongly reduced. The result that simply changing from conventional to organic fertilization does not dramatically change nitrogen use efficiency is confirmed by results such as Baeckstrom et al. (2006) who found that NUE was only increased from 44% in a conventional wheat production system to 49% in an manure based organic system during an 11 year study period. Askegaard et al. (2005) found that manure applications in organic rotations did not affect leaching losses, maybe because N application was still below crop N demand, but at the same time they found that including cover crops in the rotation did significantly reduce leaching loss. Comparing Danish farming systems Hansen et al. (2000) concluded that leaching from conventional systems were in the order of 50% larger than from organic systems, and that one of the main reasons for the difference was the more frequent use of cover crops in the organic systems.

Another conclusion from the model simulations is that the amount of N residues left in the soil after crop harvest is strongly dependant on the balance between N availability for the crop and its N demand. This is of course no surprise. It has been shown that N leaching risks can be reduced significantly if soil N availability is measured before fertilization, and the amount of N fertilizer applied then reduced when soil N availability is high already (Hartz 2006; Nendel 2009). However, the result point strongly to the possibility of developing improved fertilizer strategies for reducing leaching losses, where estimates are made of soil N availability before fertilizer is added. The same relationship is the main reason why leaching losses in the slurry based organic system (O1) is only slightly lower than from the conventional system (C). Fertilizer N input in O1 is substantially smaller than in C (37%), but as crop growth is also reduced (20%) so the balance between N availability and crop N demand is not very different and simulated leaching loss only reduced by 23%.

Options for improved N management in rotations

The results of these simulations point towards three main strategies for improving N relations of the cropping systems. A main strategy is to include cover crops in the rotations (see Figure 7). As discussed above this has been shown in several studies to be an efficient way to reduce N leaching losses, and very clear example is shown in Figure 5 of this study where leaching loss after lettuce is high in the C and O1 systems without cover crops, but very low in O2 where a cover crop is grown after lettuce. Sometimes cover crops fit easily into the system as it is, as in the example with lettuce. However, most of the leaching loss tend to occur at certain positions of the rotation (Berntsen et al. 2006; Figure 5), and to achieve the best results it may be necessary to adapt the rotation to allow cover crops at such positions of the rotation (Thorup-Kristensen et al. 2003). Cover crops give the best results when they can be grown directly after crops leaving much leachable N in the soil, but this is not the only situation where they can be used successfully. Often cover crops grown before shallow rooted crops can strongly reduce the N leaching risk after the harvest of these crops

(Thorup-Kristensen, 2006a,b; Thorup-Kristensen et al. 2009; Figure 7). Also if it is not possible to grow a cover crop in an autumn season with a high leaching risk, it is in some situations possible to prevent a lot of N leaching loss by growing cover crops in the next autumn (Hansen et al. 2007), especially if deep rooted cover crops can be grown (Thorup-Kristensen, 2006a; Figure 7).

Another possibility is to change the crop sequence of the crop rotation. Whenever a crop creates a situation where there can be much N in the soil, it is important to grow a crop which can then make optimal use of this N. In the present study, growing oats after lettuce is an example of an inefficient crop sequence. The lettuce leaves much N in the field, and the succeeding oat crop does neither develop the necessary N demand nor the rooting depth needed to allow it to use the N still present in the soil. Growing another crop with higher N demand and deeper rooting at this position would reduce leaching loss (Zhou et al. 2008; Thorup-Kristensen 2006a; Thorup-Kristensen et al. 2009), as seen when winter rye is grown after onion which is also a high risk crop. Sometimes crop choice should be changed, but much improvement may be made just by changing the sequence of the crops already grown.

The third main option is to work on a better relationship between N supply and crop N demand. This is of course related to the possibilities mentioned above. Understanding the general effects of the rotation, and using this to choose optimal crop sequences and to adapt fertilizer application to yield levels and pre-crop effects is important (Figure 7). However, by using soil testing or model simulation to estimate how much N is available make it possible to include not only general effects of the crops and rotation, but also year to year variation as dependent on the interaction between winter season precipitation, crop rooting depth and soil type. This option is easier to use in conventional rotations where the purchase of fertilizer N can just be reduced in years where leaching losses have been low, whereas in organic farming the organic manure cannot just be stored for another year. This leaves less management options in organic farming, but results can still be improved by changing the distribution of manure among crops, and option which will be easier to use in rotations as the O2 system with low manure input than in systems relying more heavily on manure input. In systems where high value crops as vegetables are grown in rotation with cereal crops, improvements may be reached by growing the cereals at below optimum fertilization. This can improve their ability to “clean up” N left by vegetable crops (Figure 7). It can be done at very limited cost as the economic value of the cereals is much smaller than the value of the vegetables.

Apart from these main strategies there are many other management options which can be used. Incorporation time of cover crops, green manures, or crop residues should be optimized to reduce leaching loss of the N released from the plant residues (Drinkwater et al. 2000; Watson et al. 1993). Choice of cover crop species (Thorup-Kristensen, 2001), or advancing sowing time of cover crops or winter cereals (Thorup-Kristensen et al. 2009, Figure 7) may also have important effects. The effects on leaching loss can be quite dramatic, as shown at the bottom of Figure 7, where the overall leaching loss due to an onion crop is reduced strongly by combining such options. The example shows that it is possible to manage the leaching risk of even quite difficult situations using relatively simple measures. Many similar situations can occur, in vegetable rotations especially when N inefficient crops such as leek, celeriac, cauliflower, or broccoli are grown, and harvested too late to allow an efficient cover crop in the autumn after harvest.

In the VegQure O2 system cover crops including legumes were chosen, to help supply more N to the rotation, but with some of the most N inefficient crops, it may be better to use non-legumes to control N losses and then combine it with some more precisely timed application of fertilizers.

Soil organic matter and C balance
A maybe somewhat surprising result of the simulations was that growing frequent cover crops were much more important for building soil organic matter than import of manure. However, this result is in accordance with the results of Dinesh et al. (2009) and Wander et al. (1994), and the result of Luxhoi et al. (2007) that returning straw to the soil was more important than applying manure for maintaining soil organic matter.

The simulations also indicated that the conventional system would have a slightly better effect on soil organic carbon than the O1 system. This result was obtained as the higher yields in the conventional system lead to more return of crop residues. The larger amount of residues was simulated to be more important than the import of manure carbon in the O1 system. This is in accordance with results such as Luxhoi et al. (2007) and Kaur et al. (2008). On the other hand it is contradicted by the results of Khan et al. (2007), who do not find such an effect and theorize that the high N availability in the high N systems will increase the rate of organic matter breakdown, and thereby they can reduce soil organic matter content even though high amounts of residue matter is added. The EU-rotate model does not include equations to simulate such an effect. Before building such effects into models, it should also be tested in more experiments. In the experiment of Khan et al. (2007) the high N plots were placed on plots which had especially high soil organic matter contents from the start due to previous treatments. It is possible that the results obtained are really an effect of this difference in starting point rather than an effect of the treatments made during the experiment.

General conclusions

In total the results presented here show many possibilities for improving cropping systems. They show that though organic systems may generally loose less N by leaching, and protect soil organic matter and soil quality better than conventional systems, larger differences may be found among organic systems than between organic and conventional systems. It may be much more important how a system is designed and managed, than whether it is organic or conventional. Both conventional and organic systems can be strongly improved in terms of N use and losses. However, to achieve this it must be a clear goal of the production system, as it takes continuing attendance and some cost and effort. Such environmental goals are more common among organic farmers than among conventional. In organic farming a better environmental is a general main goal, and reduced N leaching loss may be important also to retain N for the crops. In conventional production the main goal is to optimize production, but also in conventional farming environmental effects can be seen as important. There are conventional farmers who market themselves as environmentally friendly, and many conventional farms are either subsidized of required by regulation to take special care of the environment. The EU water frame directive will make this situation more common among conventional horticultural producers, and force many of them to improve their systems and N use efficiency.

More detailed, the present results point to the active use of rotation planning for reducing N losses and improving N use efficiency. When looking at one crop at a time, and working to optimize fertilization and maybe using cover crops after harvest, the chance to reduce overall N losses is much smaller than when looking at the cropping system as a whole. When working with crop sequences, and strategically placing crops with deep or shallow rooting, crops with high or low N demand, legume or non-legume cover crops and other aspects, much better overall results can be achieved.

The study point specifically to cover crops as a valuable tool for developing better crop rotations. Cover crops help fulfil several of the general goals of organic farming and can also help other systems reduce their environmental footprint; they do not only help reduce N losses. Growing cover crops frequently is an important method for increasing soil C storage, and thereby cover crops help reduce CO_2 release to the atmosphere. Cover crops are of special interest here, as they actually add extra C to the farming system, whereas using manure which can also help increase soil C storage does not add extra C to the system, just returns the C to your field which would otherwise have been added to another field. Cover crops help protect soil structure and quality, and they can add food and cover to soil organisms (Dinesh et al. 2009; Williams and Weil, 2004), and to insects and birds and other creatures living in the agricultural landscape. In this report cover crops and their advantages are discussed in rather general terms. However, there are important differences among the cover crops which can be grown, and by choosing cover crop species and management, the advantages can be improved further.

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