Nitrogen Turnover and Leaching in Cropping Systems with Ryegrass Catch Crops

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Abstract

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This thesis deals with perennial ryegrass (*Lolium perenne* L.) catch crops and their short- and long-term effects on nitrogen leaching and nitrogen turnover in soils. Results are presented from three field experiments on a sandy soil in south-west Sweden, where undersown catch crops were used in cropping systems with and without applications of liquid manure. The effects of different tillage practices on soil mineral nitrogen and leaching were also studied. Two coupled simulation models, which describe water flow and nitrogen transformations and transport in soil, were used for calculations of nitrogen mineralization and soil nitrogen balances. A more detailed study of the residual effects of ryegrass on the nitrogen supply to the subsequent crops and nitrogen leaching was performed in lysimeters, using ^{15}N-labelled ryegrass.

Undersown catch crops efficiently reduced nitrogen losses when mineral fertilizer or manure was applied at normal rates (90-110 kg N/ha). Over five years, undersown catch crops reduced nitrogen leaching by 60%, on average, compared with soil which was conventionally tilled in August-September. Incorporation of catch crops affected nitrogen mineralization mainly during the first growing season following incorporation, when approximately 20-30% of catch crop nitrogen was released. The results emphasize the importance of an early onset of nitrogen mineralization in spring after incorporation of catch crops. This is necessary in order to overcome the soil-depletion effect of nitrogen uptake induced by the catch crop. Simulations showed that incorporation of catch crop material in late autumn instead of spring can result in a time distribution of nitrogen mineralization more suitable for a subsequent cereal crop, but this was not verified by the results of the lysimeter experiment. It seems important to obtain further knowledge of how to improve the degree of synchronization between nitrogen mineralization after incorporation of catch crops and nitrogen demand of the subsequent crops.

According to simulations, the main part of the catch crop nitrogen contributed to a long-term accumulation of soil organic nitrogen (+10 kg N per hectare and year), while it slowly declined in autumn-tilled soil given mineral fertilizer (-30 kg N per hectare and year). However, the accumulation of soil organic nitrogen due to the catch crops was very modest compared with the total amount of organic nitrogen in the soil.

Key words: catch crop, perennial ryegrass, nitrogen leaching, nitrogen mineralization, liquid manure, time of tillage, long-term effect, nitrogen balance

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Contents

Preface

Papers I-IV

This thesis is based on the following papers, which are referred to in the text by their Roman numerals:

I. Aronsson, H. & Torstensson, G. 1998. Measured and simulated availability and leaching of nitrogen associated with frequent use of catch crops. *Soil Use and Management*, 14, 6-13.

II. Stenberg, M., Aronsson, H., Lindén, B., Rydberg, T. & Gustafson, A. 1999. Soil mineral nitrogen and nitrate leaching losses in soil tillage systems combined with a catch crop. *Soil & Tillage Research*, 50, 115-125.

III. Torstensson, G. & Aronsson, H. 2000. Nitrogen leaching and crop availability in manured catch crop systems in Sweden. *Nutrient Cycling in Agroecosystems* (in press).

IV. Aronsson, H. 2000. Contribution of ^{15}N-labelled ryegrass nitrogen to crop uptake and leaching after autumn or spring incorporation in lysimeters. (Submitted to *Plant and Soil*).

Introduction

Nitrogen leaching from arable land usually occurs...

Nitrogen leaching from land to groundwater and surface waters normally occurs every year in regions with a humid climate. The extent to which nitrogen leaching takes place depends on both natural prerequisites such as precipitation, temperature and soil type, and on human activities. Nitrogen losses from growing forests and permanent grassland are often small. However, when the soil is fertilized and cultivated, nitrogen leaching can reach considerable levels, especially in intensively cultivated areas with high precipitation and light textured soils (Johnsson & Hoffmann, 1998). Nitrogen leaching from arable land is regarded as a problem, since diffuse pollution from agriculture is the largest single source of nitrogen emissions to the aquatic environment in many countries (Werner & Wodsak, 1995; Kronvang et al., 1996; Stålnacke, 1996). Large efforts have therefore been made to work out strategies for reducing these losses to acceptable levels.

...but there are possibilities to keep it under control

As pointed out in this thesis and in other studies, important measures for reducing nitrogen leaching from arable soils in cold-temperated humid regions are:

- careful fertilization with commercial fertilizers and manure to minimize the amount of mineral nitrogen in soil when the crop uptake period ends
- avoidance of early autumn soil tillage in order to minimize nitrogen mineralization during autumn and winter
- keeping the soil covered with vegetation, taking up mineral nitrogen in soil during autumn and mild winter periods

As long as commercial nitrogen fertilizer and manure are used in accordance with crop requirements, actual nitrogen fertilization constitutes only a few per cent of the nitrogen leached from the soil during the following winter (Addiscott & Powlson, 1992; Bergström, 1987), while over-fertilization results in increased leaching (Bergström & Brink, 1986; Lord & Mitchell, 1998). It is well-known that the main source of leachable nitrogen is, generally, due to mineralization of soil organic matter outside the crop growing period (Macdonald et al., 1989; Addiscott et al., 1991; Powlson, 1993), and that delaying or excluding tillage operations in autumn reduces the risk of nitrogen leaching (Shepherd et al., 1992; Stokes et al., 1992; Goss et al., 1993; Davies et al., 1996). A crop which is growing during autumn can further reduce the accumulation of leachable nitrogen in the soil during autumn.

Undersown catch crops reduce nitrogen leaching

A catch crop can be undersown in the main crop, simultaneously with, or just after the sowing of this crop. When the main crop is harvested, the catch crop has an established root system ready to take up nitrogen from the soil during late summer and autumn. Nitrogen that otherwise could have been leached is then taken up and incorporated into plant material. The catch crop is then ploughed-in as late as possible in autumn or in spring. In many studies world-wide, it has been shown that the use of perennial ryegrass (*Lolium perenne* L.) as a catch crop is an effective measure to reduce nitrogen leaching in spring cereal crop production (Martinez & Guiraud, 1990; Nygaard Sørensen, 1991; Gladwin & Beckwith, 1992; Thomsen et al., 1993; Lewan, 1994; Francis et al. 1995; Davies et al., 1996; Møller Hansen & Djurhuus, 1997; Shepherd, 1999; Thomsen & Christensen, 1999) .

However, many questions concerning nitrogen dynamics in cropping systems with catch crops remain to be answered. After incorporation into soil, some of the catch crop nitrogen may be mineralized more or less immediately and some will enter the more stable fractions of soil organic matter. More knowledge is needed about how to achieve a satisfactory degree of synchronization between the release of nitrogen from catch crop material and the nitrogen demand of subsequent crops. The build-up of soil organic nitrogen is of special interest if catch crops are used repeatedly. In the long-term this will increase potential nitrogen mineralization and may also increase the risk of nitrogen leaching. Such thoughts were important considerations in this work.

Objectives and outline of the thesis

The main objective of this work was to investigate how undersown perennial ryegrass catch crops affect nitrogen leaching and nitrogen dynamics in soil. Catch crops were studied in three long-term field experiments in which either commercial fertilizer nitrogen or liquid manure at different rates was used. The effects of soil tillage practices on nitrogen leaching were also studied in the field. The effect of incorporated ryegrass on nitrogen leaching and nitrogen supply to the following crop was studied in lysimeters with ^{15}N-labelled plant material. A simulation model was used to evaluate and interpret results from the field experiments and to estimate nitrogen budgets and the amount and temporal distribution of nitrogen mineralization.

The experimental field at Mellby

The field studies were conducted in three ongoing long-term field leaching experiments at Mellby, 25 km south of Halmstad, on the southwest coast of Sweden (56°29′ N, 13°0′ E). Several factors contribute to comparatively large nitrogen leaching loads in this region (Johnsson & Hoffmann, 1998). The autumns and winters are mild and wet, light textured soils dominate and large-scale animal production is common in the area. The region has a mean annual temperature of 7.2 °C and a mean annual precipitation of 800 mm. Conventional spring cereal crop production results in nitrogen leaching of about 45 kg N per hectare and year (Hessel Tjell et al., 1999). The topsoil at the experimental field is a sandy loam (8-9% clay and 5% organic matter) and the subsoil a loamy sand.

Cropping systems with catch crops fertilized with commercial fertilizer and with pig slurry at different rates were studied in two experiments, carried out on tile-drained plots (Papers I and III, respectively). The perennial ryegrass catch crops (*Lolium perenne* L.) were undersown in spring cereals or oil-seed rape each year. In a third experiment which was started in 1993, the influence of different tillage practices on nitrogen leaching was studied (Paper II). Water percolating through the soil was sampled with ceramic suction cups at 60 and 90 cm depth. Mouldboard ploughing in early autumn was compared with ploughing in late autumn or in spring. Late autumn ploughing was studied with and without a catch crop, and with and without preceding stubble cultivation. The effect on nitrogen leaching of straw removal compared with incorporation of straw was also investigated. In addition to measurements of nitrogen leaching, determinations were also made of crop uptake of nitrogen and mineral nitrogen content in soil.

Lysimeter study

The lysimeter experiment (Paper IV) was conducted in Uppsala, Sweden (59°49′N, 17°39′E), using soil monoliths collected at the Mellby experimental field (see above). ^{15}N-labelled perennial ryegrass was incorporated in September 1995 or in May 1996. The fate of ryegrass nitrogen was studied for three years by sampling of the subsequent crops, as well as soil and drainage water.

Modelling approach

Two coupled simulation models (SOIL and SOILN) were used for calculations of nitrogen budgets and the temporal distribution of nitrogen mineralization after incorporation of catch crops in the field experiments (Papers I and III). The soil water and heat model (SOIL; Jansson, 1991) provides driving variables for the soil nitrogen model (SOILN; Johnsson et al., 1987), i.e. infiltration, water flow in the soil and to drainage pipes, soil water content and soil temperature. The

SOILN model includes the major processes determining inputs, transformations and outputs of nitrogen in arable soils. Measurements of drainage, soil water contents, nitrogen concentrations in drainage water, crop uptake of nitrogen and soil mineral nitrogen were used for calibration of the models.

The SOILN model

In the SOILN model, inputs of nitrogen can be in the form of commercial fertilizer and manure added to the topsoil, and atmospheric deposition (Fig. 1). Harvest, leaching and denitrification constitute the nitrogen outputs. Soil organic nitrogen is represented in three fractions: litter (fresh organic matter, microbial biomass and metabolites), faeces (organic fraction of manure) and humus (stabilized organic material). Organic carbon pools are included in the litter and faeces fractions to regulate nitrogen decomposition and mineralization. Decomposition of litter (or faeces) carbon is regulated by a rate constant and a synthesis efficiency constant, which regulates the fraction of carbon lost as CO_2 One fraction of the decomposed carbon is transferred to the humus pool, whereas the remaining part is recycled to the litter (or faeces) pool. The recycled and humified products are assumed to consist of material with a constant C/N ratio. Nitrogen mineralization from the humus pool is regulated by a rate constant. The turnover rates of the organic nitrogen pools and other biological activities are also regulated by the moisture and temperature conditions in each soil layer.

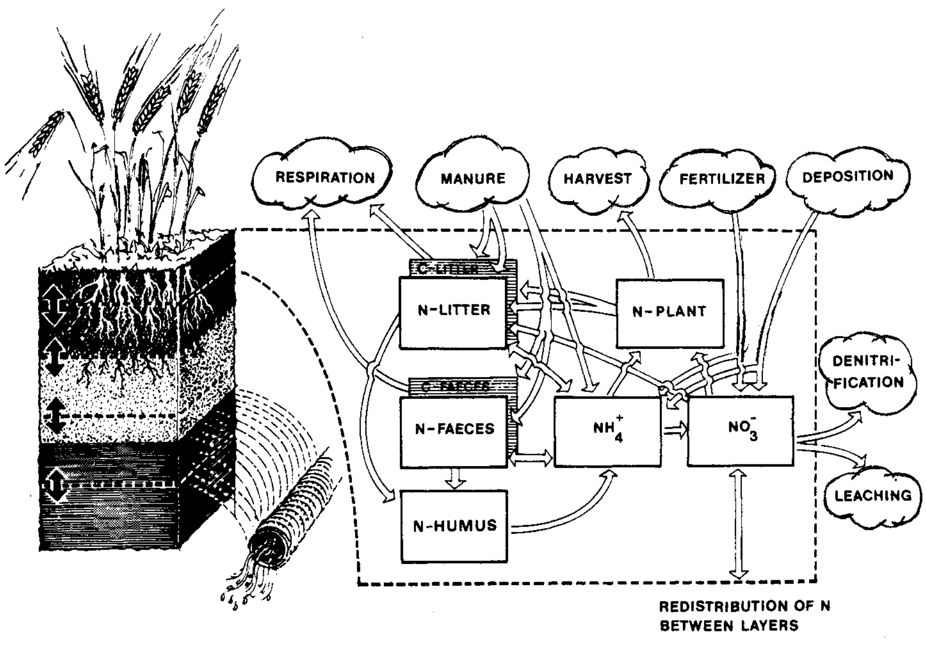


Fig. 1. Structure of the SOILN model. Parts within the broken line represent the uppermost layer of the soil profile. Subsurface layers have the same structure as the surface layer, but have no direct input from fertilizer and deposition (From Johnsson et al., 1987).

Perennial ryegrass catch crops

Nitrogen uptake by catch crops

The amount of nitrogen that is taken up by a catch crop depends on the amount of nitrogen available for uptake and on the capacity of the catch crop to take up nitrogen. The capacity of a crop to take up nitrogen is closely related to the time period available for nitrogen uptake (Christian et al., 1992; Francis et al., 1995). When undersown catch crops are used, the time available for catch crop growth is maximized, since the catch crop is already established when the main crop is harvested.

The main nitrogen uptake by catch crops at Mellby (Papers I, II and III) took place during August - November. During this period, the nitrogen content of the above-ground parts of the catch crop increased, on average, from 8 to 23 kg/ha in plots with applications of commercial fertilizer. If 40-60% of the catch crop nitrogen is assumed to be present in roots (Sjödahl Svensson & Clarholm, 1994) an estimation of the total nitrogen uptake in catch crops would be about 50 kg/ha. In plots with pig slurry applications in spring, there were larger amounts of mineral nitrogen in soil during autumn, which resulted in larger uptake of nitrogen by catch crops (Paper III). In plots with normal application rates of manure (110 kg N/ha), on average 35 kg/ha of nitrogen was found in above-ground plant material. However, at double rates of manure (215 kg N/ha), the nitrogen uptake by the catch crops did not further increase, which suggests that the catch crops did not have further nitrogen uptake capacity under prevailing site conditions. Winter rye sown in the middle of September after potatoes one year (Paper III) reached the same nitrogen uptake as ryegrass in plots with commercial fertilizer. However, larger amounts of mineral nitrogen in soil during autumn, due to manure applications in spring, did not result in increased nitrogen uptake by winter rye.

The results obtained from the experiments at Mellby are similar to other measurements of nitrogen uptake in undersown catch crops in southern Sweden and Denmark (Andersen & Olsen, 1993; Beck-Fries et al., 1993; Wallgren & Lindén, 1994; Ohlander et al., 1996*a*; Møller Hansen & Djurhuus, 1997).

The climate in the southernmost part of Sweden usually permits growth of a catch crop until November, sometimes even longer. In regions with shorter autumns the use of catch crops is of more restricted value. In a field experiment in west central Sweden the nitrogen uptake in ryegrass catch crops during several years was only about half of that found at Mellby (Lindén et al., 1999).

How much do catch crops reduce nitrogen leaching?

Effects of nitrogen uptake and postponed tillage

The effect of a catch crop on nitrogen leaching shows large variation between years and places, depending on, for example, differing precipitation and drainage conditions, variations in amounts of nitrogen in the soil available for leaching, and how successful the establishment of the catch crop was. The use of catch crops has reduced nitrogen leaching by 50% or more in several studies (Martinez & Guiraud, 1990; Nygaard Sørensen, 1991; Gladwin & Beckwith, 1992; Thomsen et al., 1993; Lewan, 1994; Francis et al. 1995; Davies et al., 1996; Møller Hansen & Djurhuus, 1997; Shepherd, 1999; Thomsen & Christensen, 1999).

At Mellby, catch crops (grown until spring) reduced nitrogen leaching by 60%, on average (30-80%, corresponding to 20-50 kg N/ha and year) over five years, compared with soil which was stubble cultivated in August - September and ploughed in November (Paper III; Fig. 2). When the effect of catch crops was studied separately, i.e. in comparison with spring ploughed soil (Paper I), the reduction in nitrogen leaching was 40 and 50% (10 and 18 kg N/ha and year), respectively, during two years when establishment of the catch crop was successful. During three earlier years on the same experimental plots, Italian ryegrass (*Lolium multiflorum* L.) as a catch crop reduced leaching by 80% compared with soil tillage in early autumn (Lewan, 1994).

The effect of catch crops on nitrogen leaching is often, as was done in Paper III, compared with soil which is cultivated in early autumn. The reduced leaching is then both an effect of nitrogen uptake by the catch crop, and of reduced nitrogen mineralization due to delayed tillage (Shepherd et al. 1992; Goss et al., 1993; Lindén et al. 1993; Sørensen & Thorup Kristensen, 1993; Davies et al., 1996; Lindén et al., 1994). That soil cultivation in early autumn can lead to increased nitrogen mineralization, and thereby substantial accumulation of leachable nitrogen in the soil during autumn, was shown in Paper II, where different times for ploughing were studied. When tillage was postponed until November or March, the risk of nitrogen leaching decreased due to lower nitrogen mineralization (Stenberg, 1998*a*) and uptake of nitrogen in weeds during autumn. Simulations reported in Paper III and results from the lysimeter study (Paper IV) also showed that nitrogen mineralization increased after stubble cultivation in August - September.

From the present work it is hazardous, but tempting, to draw general conclusions about the relative contributions of postponed tillage and growth of catch crops in reducing leaching. A rough estimation for conditions in southern Sweden with spring cereal crops is that postponing tillage (stubble cultivation or mouldboard ploughing) from early autumn until spring and growing undersown perennial ryegrass as a catch crop reduces nitrogen leaching, on average by 50-70%. About

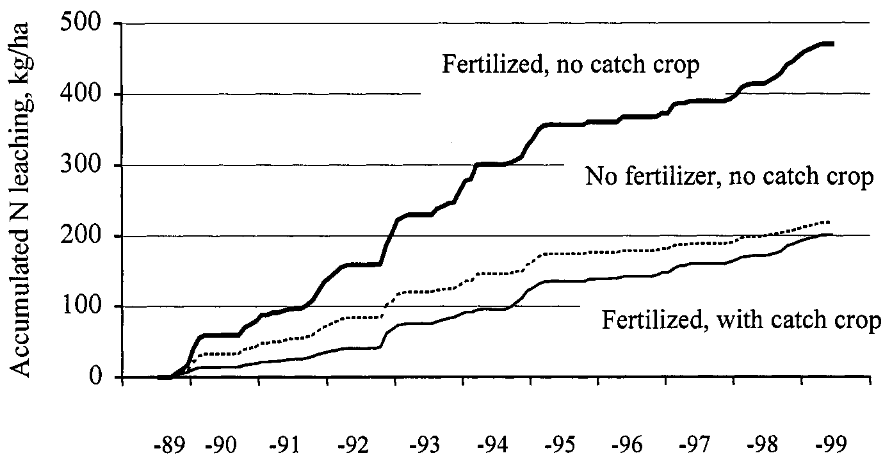


Fig. 2. Ten years with catch crops at Mellby, instead of tillage in August - September, saved 275 kg/ha of nitrogen from being lost through leaching. 100 kg N/ha was applied as commercial fertilizer each year. The total amount of nitrogen which had leached from catch cropped soil after ten years was slightly less than from unfertilized soil without catch crops.

1/2 to 2/3 of the reduced leaching seems to be due to the nitrogen uptake of the catch crop, and the rest to delayed tillage.

Catch crops on soil with pig slurry applications

In the manured cropping systems at Mellby (Paper III), the reduction in nitrogen leaching by ryegrass catch crops was almost as high as in systems with applications of commercial fertilizer, when normal rates of pig slurry were used. When double rates of manure were applied, more nitrogen became available than the catch crop could take up and the reduction in nitrogen leaching was only about 30% (compared with 60% in plots with normal rates of fertilizer). Similar results were found by Thomsen et al. (1993) and Thomsen & Christensen (1999) who studied catch crops in manured cropping systems.

Undersown catch crops compared with crops sown in autumn

Undersown catch crops are more effective in reducing nitrogen leaching than crops sown in autumn. There are two main reasons for this: firstly, with undersown catch crops, the time for catch crop growth is maximized, since it is already established when the main crop is harvested; secondly, the establishment of the undersown catch crop does not require cultivation of the soil in autumn, which itself increases nitrogen mineralization.

At Mellby, winter rye sown on 18 September after potatoes (Paper III), reduced nitrogen leaching considerably in plots with applications of commercial fertilizer. However, it was less efficient than ryegrass on manured soil with larger amounts of mineral nitrogen, probably because winter rye had a lower nitrogen uptake capacity under these conditions than ryegrass. Winter rye has been shown to reduce nitrogen leaching considerably in some studies (Shepherd et al, 1992; McCracken et al., 1994; Davies et al., 1996; Shepherd, 1999), but Francis et al. (1995) emphasized that sowing must be done as early as possible. The reduction in nitrogen leaching by winter cereal crops was not satisfactory in the studies made by Francis et al. (1995), Hessel Tjell et al. (1998) and Shepherd & Webb (1999) due to low uptake of nitrogen during autumn.

Impact of catch crops on soil water balance

When a soil that would otherwise have been uncropped is covered with vegetation during autumn and winter, water losses may increase due to transpiration, which may result in reduced drainage. In the present studies, however, neither measurements nor simulations showed any clear differences in drainage between uncropped and cropped soil. According to simulations, the reason was that the increase in transpiration due to catch crop growth was compensated for by a decrease in evaporation from the soil when it was covered with the catch crop. Similar results were found by Møller Hansen and Djurhuus (1997). Other authors have reported 30-40 mm lower drainage output from catch cropped soil compared with fallow (Lewan, 1993; Davies et al., 1996; Shepherd & Webb, 1999). Rogasik et al. (1992) and Allison et al. (1998) related water use to dry matter production of plant material and reported that for each tonne of dry matter produced per hectare, the consumption of water is 20-40 mm.

Considering the climatic conditions in the present experiments, where the mean annual drainage was about 350 mm, the effect of catch crops on aquifer recharge was probably negligible. The effect of catch crops on nitrogen leaching was at least up to 90% caused by nitrogen uptake by the catch crop and delayed tillage, and only to a minor extent caused by reduced drainage volumes.

Catch crops and main crop yield

When two different crops are grown together, they will compete for resources such as water, nutrients and light. The ideal catch crop should be strong enough to grow vigorously after the harvest of the main crop, but it should not affect the yield of the main crop. Time of undersowing and seed rates might influence the growth of the catch crop until the harvest of the main crop. Kvist (1992) and Ohlander et al. (1996*a*) concluded that delayed undersowing clearly reduced the growth of catch crops until the harvest of the main crop, but due to increasing risks of producing an uneven stand and of damaging the main crop, they recommended undersowing to be done sometime between the day of sowing and emergence of the main crop. Kvist (1992) recommended ryegrass seed rates of 6-

12 kg/ha, to ensure good growth during autumn without reducing main crop yields to any large extent.

Undersowing of perennial ryegrass in spring cereals does not, generally, cause any significant main crop yield reductions. In the present experiments, where seed rates of 7-9 kg/ha were used, there were no significant effects of catch crops on main crop yields (Papers I, II and III). This agrees well with results of other Scandinavian studies, where yield reductions have been absent or less than 3% (Andersen & Olsen, 1993; Jensen, 1991; Ohlander et al., 1996*a*; Wallgren & Lindén, 1994). However, in several other experiments Italian ryegrass (*Lolium multiflorum* L.) reduced yields by of 5-20% (Andersen & Ohlsen, 1993; Lewan 1994; Lyngstad & Børresen, 1996; Ohlander et al., 1996*a*).

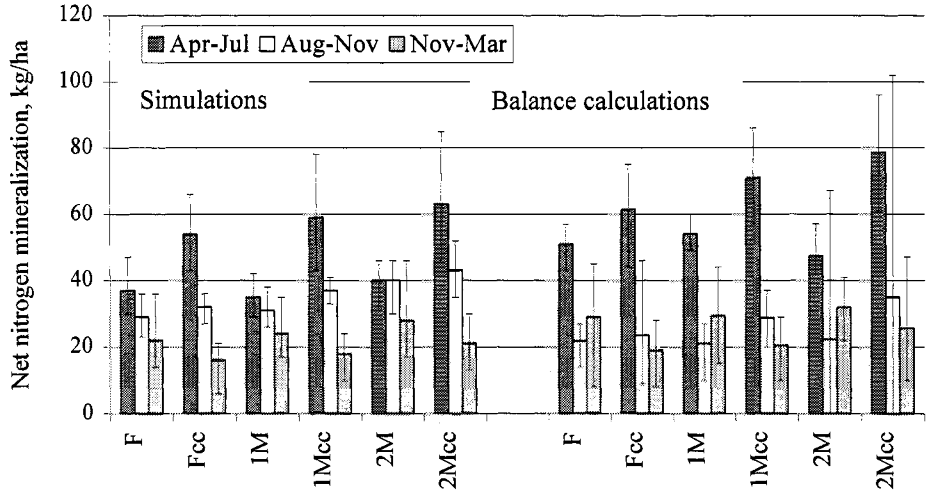
Ohlander et al. (1996*b*) and Stenberg (1998*b*) found that perennial ryegrass catch crops could be undersown in spring in growing winter wheat crops without negative effects on winter wheat yields. However, the establishment of the catch crops was not always successful.

Catch crops and weed control

Repeated stubble cultivation during autumn is often an effective way to get rid of perennial weeds. In cropping systems where tillage is delayed as much as possible in autumn, or even until spring, the problems with perennial weeds might increase. Under such conditions, use of chemical weed control can be necessary (Cussans, 1992). At Mellby, growth of couch-grass (*Elymus repens*) increased on soil which was ploughed in late autumn or spring, which negatively affected crop yields (Paper II). However, a catch crop growing during autumn reduced problems with couch-grass infestations. That catch crops suppress the growth of weeds has also been reported by Ohlander et al. (1996*b*), Breland (1996) and Stivers-Young (1998).

Mineralization of catch crop nitrogen...

Many efforts have been made to quantify and to describe the temporal distribution of nitrogen mineralization after incorporation of plant material. For natural reasons, the results differ widely. Climatic conditions during autumn and winter affect microbial activity in soil. The quality of plant material, e.g. C:N ratio and lignin content, largely influences whether there will be net nitrogen mineralization or immobilization after incorporation of plant material. The general consensus has been that net mineralization occurs within a few days for plant material with a nitrogen content above 2-2.5% (Stevenson, 1986), which corresponds to a C:N ratio of about 20.



F= Commercial fertilizer (100kg N/ha), no catch crop
Fcc= Commercial fertilizer (100 kg N/ha), with catch crop
1M = Manure (110kg N/ha), no catch crop
1Mcc=Manure,(110 kg N/ha, with catch crop
2M= Manure (220 kg N/ha), no catch crop
2Mcc= Manure (220 kg N/ha), with catch crop

Fig. 3. Simulated net nitrogen mineralization agreed well with that estimated by balance calculations for the same period (Hessel Tjell et al., 1999). Bars represent yearly mean values for 1990-1994, including minimum and maximum values during that period.

...is largest during the first year after incorporation

A catch crop preserves in organic form, nitrogen that otherwise might have been leached or denitrified as inorganic nitrogen. This increases the nitrogen mineralization potential of the soil. The ryegrass catch crops at Mellby had a nitrogen content of approx. 1.8% in plots with applications of commercial fertilizer and 2.4% in manured plots. Incorporation in spring seemed to result in a more or less immediate net mineralization of nitrogen. According to simulations, nitrogen mineralization increased by 10-20 kg/ha during April - July. This was supported by estimations of net nitrogen mineralization based on balance calculations (Fig. 3) made for the same experimental field during the same period (Hessel Tjell et al., 1999). When ^{15}N-labeled ryegrass material containing 4% nitrogen was incorporated in lysimeters (Paper IV), 14% (6 kg N/ha) was recovered in above-ground material of the first crop following incorporation, which suggests that net mineralization of catch crop nitrogen was considerably larger than 14%. During the second and third year, 2.5% and 1.5% was recovered, respectively. Other studies also show that incorporation of plant material affects nitrogen release in soil mainly during the first year and to a minor extent during subsequent years (Goswami et al, 1988; Jensen, 1992; Thomsen, 1993; Thomsen & Jensen, 1994).

According to a number of reports, 10-40% of organic nitrogen in catch crops was estimated to be released during the first year after incorporation (Marstorp & Kirchmann, 1991; Bremer & van Kessel, 1992; Jensen, 1992; Rogasik et al., 1992; Thomsen, 1993; Thomsen & Jensen, 1994; Thorup-Kristensen, 1994; Wivstad, 1997; Thomsen & Christensen, 1999).

Nitrogen supply to subsequent crops

Although several studies show that nitrogen mineralization increases after incorporation of catch crops, the effect on the yield of a following crop has been reported as slightly negative (Martinez & Guiraud, 1990; Jensen, 1991; Davies et al., 1996) none (Andersen & Olsen, 1993; Breland 1996), or positive (Lewan, 1994; Lyngstad & Børresen, 1996).

At Mellby, there were no clear effects of catch crop incorporation on crop yields, despite increased simulated net nitrogen mineralization (Papers I and III). This may partly be due to the fact that the new catch crop, which was sown after incorporation of the preceding one, affected the main crop. However the two main reasons seemed to be:

1. depletion of soil mineral nitrogen in spring

2. nitrogen mineralization occurred too late to be fully available for the crop.

Depletion of soil mineral nitrogen in spring
The effect of grass catch crops on the nitrogen supply to a following crop differs from the effect of green manure crops in the sense that catch crops do not add nitrogen to the soil, but first assimilate their nitrogen from the soil itself. The total effect of catch crops on the nitrogen supply to the subsequent crop (N_{eff}) was properly described by Thorup-Kristensen (1993) by the following equation:

$$N_{eff} = N_{upt} \cdot m - N_{upt} \cdot r$$

where N_{upt} is the nitrogen uptake by the catch crop, m is the fraction of catch crop nitrogen which is mineralized in time to be utilized by the following crop and r is the fraction of late autumn soil mineral nitrogen retained within the rooting zone after winter leaching. Thus, $N_{upt} \cdot m$ is the fertilizer effect of the catch crop material, and $N_{upt} \cdot r$ is the soil depletion effect from the nitrogen uptake of the catch crop. If there is to be a positive net effect of catch crop incorporation on nitrogen supply compared with bare soil, nitrogen mineralization during the growing season must be larger than the depletion of soil mineral nitrogen in autumn and winter. During years with intensive leaching, most of the soil mineral nitrogen will be leached if a catch crop is not grown. The nitrogen effect of the catch crop during the following growing season will be dominated by mineralization of catch crop nitrogen. However, during winters when a lot of mineral nitrogen would have been retained in the soil even if a catch crop had not been grown, the soil depletion effect might result in negative effects of the catch crop on nitrogen supply to a following crop.

As mentioned previously, model simulations at Mellby showed that net nitrogen mineralization increased by on average 10-20 kg N/ha during April - July, after incorporation of catch crops in March-April (Papers I and III). However, in these plots the deficit of soil mineral nitrogen was 10-30 kg/ha in spring, compared with plots without a catch crop, cultivated in autumn. Thus, the total amount of nitrogen available for the following main crop (N_{eff}) was, in general, slightly negatively affected by the catch crop.

Timing of nitrogen mineralization
According to simulations at Mellby (Papers I and III), catch crop incorporation in spring affected nitrogen mineralization mainly during April - July, and only to a minor extent during the following autumn. However, the dynamics of nitrogen release did not seem to be synchronized with the nitrogen uptake demand of the cereal crops; i.e. nitrogen release occurred too late to be fully available for the crops. This was observed as increased nitrogen leaching during one winter after catch crop incorporation in the preceding spring, compared with soil without a catch crop (Paper I). Catch crops were grown every year, but during that year the establishment of the catch crop more or less failed. Other authors also report increased nitrogen leaching during the winter after incorporation of catch crops in the preceding spring (Lewan, 1994; Shepherd & Webb, 1999; Thomsen & Christensen, 1999). According to earlier simulations at Mellby, Blombäck (1998) concluded that about 30% of the catch crop nitrogen released was leached during winter (9-12 months after incorporation) if a new catch crop was not grown. However, in the lysimeter study (Paper IV) the amount of ryegrass nitrogen leached over a three-year period after incorporation was less than 3%.

How can nitrogen supply to subsequent crops be improved?

To maximize the positive effects of catch crops on nitrogen leaching and nutrition of subsequent crops, it seems important to improve the degree of synchronization between the release of nitrogen from incorporated plant material and the nitrogen demands of following crops. There might be more than one way to do this:

1. to grow crops with a long growth period after incorporation of catch crops
2. to use catch crops which results in fast decomposition and mineralization early during the growing season
3. to adjust the time of incorporation to control the temporal distribution of nitrogen mineralization

The nitrogen uptake by cereals mainly takes place during the early part of summer (May - June) and ceases by the end of July (Kätterer, 1995). Crops with a longer growth period might better fit the dynamics of nitrogen mineralization after catch crop incorporation in spring. Nygaard Sørensen & Thorup-Kristensen (1993) found that incorporation of a catch crop positively affected the yield of white cabbage, which grew until November, while the yield of barley was unaffected. Torstensson (1998*a*) suggested that a winter crop with high nitrogen uptake capacity (e.g. winter rye) would be suitable during autumn after ley incorporation in spring, and that crops with long-lasting nitrogen uptake, such as potatoes and sugar beet may also be good choices as crops following incorporation of catch crop residues. However, sowing of a winter crop usually requires soil cultivation in August - September which may increase nitrogen mineralization during autumn.

A possible way to control nitrogen release after incorporation in spring is to choose plant material with properties which result in a fast release of nitrogen after ploughing in spring. The C:N ratio of incorporated material might be influenced by using grass and legumes or Brassica species in a mixed stand. Meisinger et al. (1991), summarized the literature and concluded that several Brassica species performed well as catch crops over a broad range of climates, but that legumes, in general, were less effective than grass or Brassica catch crops. Winter rape as a catch crop reduced nitrogen leaching substantially in a lysimeter study in Sweden (Bertilsson, 1988). Karlsson-Strese et al. (1996) defined hypothetical criteria for an ideal undersown catch crop and screened a large number of plant materials for their suitability as catch crops. Later work showed that chicory *(Cichorium intybus)* might be a suitable catch crop both with respect to nitrogen leaching and nitrogen supply to subsequent crops (Rydberg, 1998).

When the catch crop is ploughed into the soil, decomposition of the plant material begins. Time of ploughing might therefore be one possibility to influence the time distribution of nitrogen mineralization. Model predictions with the Mellby soil indicated that late autumn incorporation might be somewhat preferable with respect to mineralization dynamics (Fig. 4), compared with spring ploughing (Paper III), without introducing an obvious risk of nitrogen leaching. However, in the lysimeter experiment (Paper IV), which was conducted in central Sweden, time of ryegrass incorporation (autumn or spring) did not significantly affect the recovery of ryegrass nitrogen in drainage water and in a following barley crop. In this experiment the soil temperature was close to or below zero during most of the winter. In studies presented by Wallgren & Lindén (1994) and Lyngstad & Børresen (1996) incorporation in autumn resulted in more positive residual effects on grain yields than spring incorporation. However, in the experiment presented in Paper II, late autumn ploughing (in the middle of November), both with and without a catch crop, was found less effective against nitrogen leaching than spring ploughing without a catch crop.

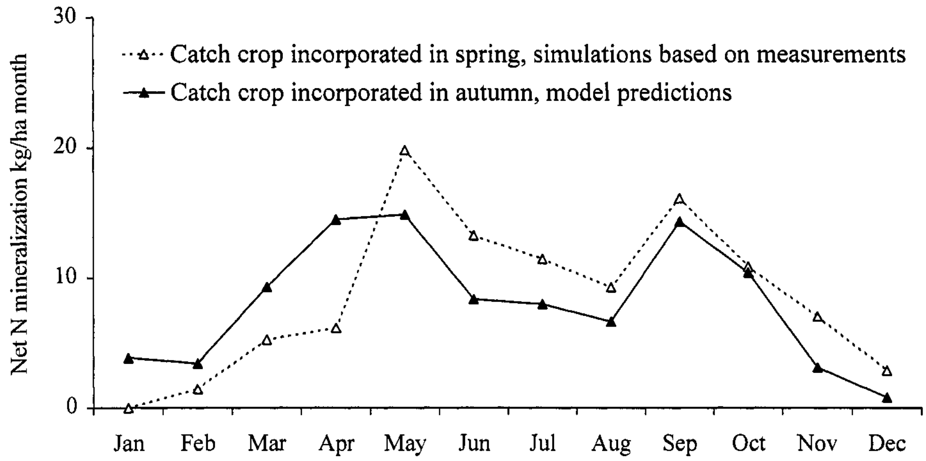


Fig. 4. Model predictions at Mellby indicated that when catch crops are incorporated in November, the release of nitrogen can start early in spring (Paper III).

Furthermore, in an experiment on a sandy soil in west central Sweden, incorporation of catch crops in November resulted in somewhat larger nitrogen leaching during winter compared with soil where the catch crop was left undisturbed until April (Lindén et. al., 1999). Thorup-Kristensen (1993) and Møller Hansen & Djurhuus (1997) recommend that incorporation of catch crops should be done in spring, while Nygaard Sørensen & Thorup-Kristensen (1993) and Davies et al. (1996) recommend late autumn ploughing. However, in practice, the time period available for ploughing may be restricted by various conditions, e.g. on heavy soils where there is an increased risk of soil compaction when ploughing under wet conditions in late autumn or unfavourable seedbed conditions after ploughing in early spring.

In conclusion, growing catch crops which are ploughed early in spring seems to be a very safe and effective way to reduce nitrogen leaching in regions with mild and wet winters. However, if nitrogen mineralization during the following growing season does not coincide with crop demand, there is a risk that some of the nitrogen will be lost during the subsequent winter.

Long-term effects on soil organic nitrogen and nitrogen release

The organic matter content of a soil is a result of its history. It changes slowly in response to alterations in the cropping system. Eventually it reaches a new level in balance with soil management (Johnston et al., 1989). The soil at Mellby has a long history of animal production and manure applications, which has resulted in an organic matter content of about 5%. The simulated organic nitrogen content showed a slightly positive trend (+15 kg N per hectare and year) when manure was applied every year (Table 1). However, in plots with commercial fertilizer, tillage in early autumn and removal of straw, the soil organic nitrogen content slowly declined (-30 kg N per hectare and year) (Paper III). Other studies also showed that cereal production with straw removal resulted in a small decrease in soil organic nitrogen (Persson & Kirchmann, 1994; Kätterer & Andrén, 1999) or balance between inputs and outputs of nitrogen (Johnston et al., 1989; Paustian et al., 1990).

Measures against nitrogen leaching seemed to be important in conserving soil organic nitrogen at Mellby (Papers I and III). Spring ploughing instead of tillage in early autumn resulted in less negative development of soil organic nitrogen, and use of catch crops altered degradation of soil organic matter to a small accumulation (+10 kg N per hectare and year), especially in combination with manure applications. The simulated trends for soil organic nitrogen were confirmed, when compared with measurements of total nitrogen content in soil samples taken in 1988 and 1995 (Torstensson, 1998*b*).

Table 1. Simulated annual means of nitrogen balance from 1990-1995 at Mellby (kg N/ha and year). The amount of NH_4-N in manure remaining after estimated ammonia volatilization was used in the balance calculation. The total amount is given within parentheses.

Nitrogen balance	Treatment					
	F	Fcc	1M	1Mcc	2M	2Mcc
Inputs of N						
Commercial fertilizer	97	97	48	48	48	48
Manure						
NH_4-N (net)	-	-	75	75	120	120
(Total NH_4-N in man.)	-	-	(78)	(78)	(146)	(146)
Organic N	-	-	35	35	68	68
Deposition	20	20	20	20	20	20
Sum of inputs	**117**	**117**	**178**	**178**	**256**	**256**
Outputs of N						
Harvest	72	71	81	85	91	96
Leaching	61	23	65	27	84	57
Denitrification	14	14	21	20	30	29
Sum of outputs	**147**	**108**	**167**	**132**	**205**	**182**
Change in plant N	-	-2	-	-9	-	-12
Change in mineral N	-3	+1	-4	-1	-5	+1
Change in soil organic N	**-27**	**+10**	**+15**	**+56**	**+56**	**+85**

F= Commercial fertilizer, no catch crop
Fcc= Com. fertilizer, with catch crop
1M = Manure, no catch crop
1Mcc=Manure, with catch crop
2M= Manure, double rate, no catch crop
2Mcc= Manure, double rate, with catch crop

The field experiments (Papers I, II and III) showed the effect of different treatments in their extreme forms, i.e. when catch crops or manure applications were used one year after another. In a crop rotation where catch crops or manure are used less frequently, their effects on the accumulation of soil organic nitrogen would be smaller.

Short-term and long-term effects on nitrogen mineralization

When ploughing-in a catch crop, some of the catch crop nitrogen will be released as inorganic nitrogen during the first months following incorporation. Most will, however, be incorporated into the soil organic matter, and may therefore affect nitrogen mineralization in the long-term.

The mean annual uptake of nitrogen in catch crops at Mellby was about 50 kg/ha (including roots). According to simulations (Papers I and III) and the lysimeter study (Paper IV) about 20-30% (10-15 kg/ha) of the catch crop nitrogen was released during the growing season following incorporation. The lysimeter study showed that during the second and third growing season after incorporation, crop uptake of catch crop nitrogen was small. Therefore, 70-80% of the catch crop nitrogen (35-40 kg/ha) likely contributed to a more long-term build-up of soil organic matter. This agrees well with the relative difference in nitrogen balance between catch cropped soil and soil with tillage in early autumn (Table 1).

The effect of catch crops on net nitrogen mineralization may be divided into: 1) a dominant "first-year effect" occurring every year a catch crop is ploughed into the soil, and 2) a small "long-term effect" due to increased organic nitrogen content of the soil. Ten successive years with catch crops in south Sweden might influence nitrogen mineralization as presented in Fig. 5. After ten years, with a catch crop every year, the long-term contribution of catch crops to nitrogen mineralization is probably small (5-10 kg N/ha) when considering the total amount of organic nitrogen in the soil. The assumption behind the long-term effect in Fig. 5. was that the organic nitrogen in soil which derived from the incorporated catch crops was twice as available for mineralization as the native soil organic nitrogen (Legg et al., 1971). The soil at Mellby contains about 8000 kg N/ha, of which 1-2% may be mineralized each year (Stevenson, 1986). Simulated net nitrogen mineralization was on average 100 kg per hectare and year, which corresponds to 1.3% of soil organic nitrogen.

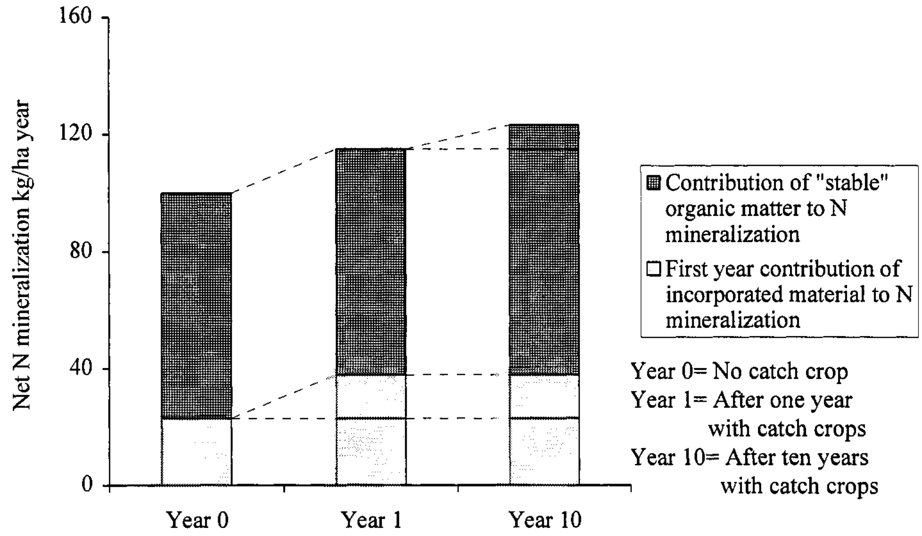


Fig. 5. Catch crops affect nitrogen mineralization, mainly during the first year after incorporation, but repeated use of catch crops will slowly increase the nitrogen mineralization potential of a soil (Based on results from Papers I, III and IV).

Long-term effects on nitrogen leaching

Although it is modest in the short-term, increased nitrogen mineralization due to accumulation of soil organic nitrogen might in the long-term result in increased leaching losses. At Mellby two plots have been treated in the same way since 1984: one with commercial fertilizer and one with liquid manure (pig slurry), both without a catch crop. Nitrogen concentrations in drainage water from the manured plot were higher than those in from the plot with commercial fertilizer during the last three years (Fig. 6). However, due to the large variation in leaching between years, caused by varying weather conditions and different crops, it is probably too early to confirm it as a long-term effect of manure applications. The amount of nitrogen applied in manure varied somewhat between years, which was probably of more importance for nitrogen leaching than for long-term effects on nitrogen mineralization. However, according to Dilz et al. (1990), more than ten years of manure applications can be supposed to result in clear long-term effects on nitrogen mineralization.

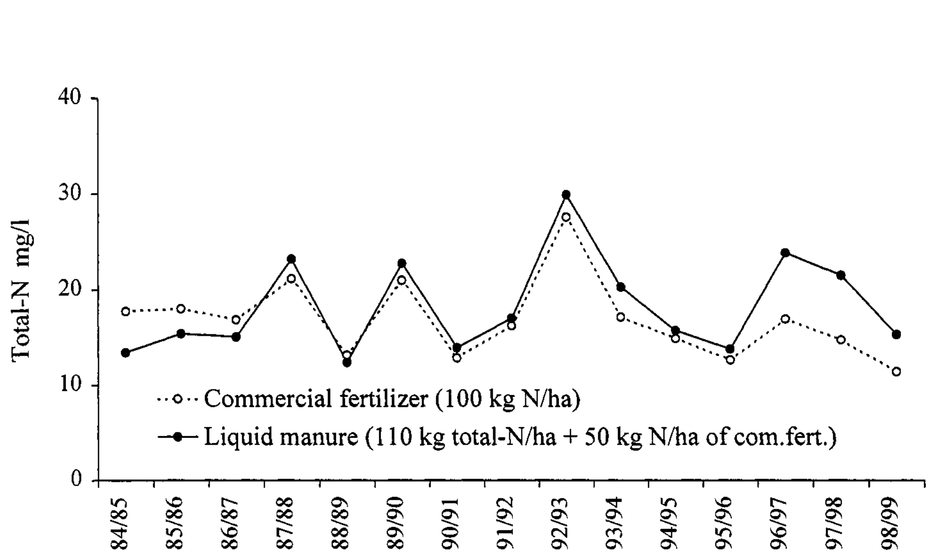


Fig. 6. When surveying results from fifteen years of manure applications at Mellby, no clear long-term effects of manure applications on nitrogen concentrations in drainage water were observed.

Catch crops in the future

Results from the long-term field experiments at Mellby confirm that avoidance of early autumn soil tillage in combination with undersown perennial ryegrass as a catch crop is one of the most reliable and powerful measures against nitrogen leaching in crop rotations dominated by spring cereals. For example, in a five-year crop rotation in an experiment in southernmost Sweden, nitrogen leaching decreased by 30% when ryegrass catch crops were introduced in two of the crops (Hessel Tjell et al., 1998). Ryegrass has also a sufficient nitrogen uptake capacity to reduce leaching under conditions with excessive amounts of mineral nitrogen in the soil, e.g. after manure applications. With current knowledge, it is possible to establish undersown catch crops successfully, without causing yield reductions of the main crops. However, the use of catch crops in practical farming is still modest in Sweden, although many crop rotations provide possibilities to introduce them and subsidies are available to compensate for possible economical losses related to growing catch crops. In the future, undersown catch crops will be more important for reducing nitrogen losses from arable land in the southern part of the country (SJV, 2000).

Nitrogen uptake by a catch crop and excluded tillage in autumn conserve nitrogen in the soil, of which some is released during the following growing season while the main part contributes to long-term accumulation of soil organic nitrogen. However, the experiments at Mellby show that the accumulation of soil organic nitrogen in catch crop systems is modest in comparison with the total amount of organic nitrogen in the soil, and the mineralization potential of the soil increases very slowly. However, at Mellby, the use of catch crops stopped the negative trend for soil organic nitrogen, which was found in plots without a catch crop and with early autumn tillage.

Results from the present work emphasize the importance of an early start of nitrogen mineralization in spring after incorporation of catch crop residues. This is necessary in order to overcome the soil-depletion effect of nitrogen uptake induced by the catch crop. Simulations showed that incorporation of catch crop residues in late autumn instead of spring can result in better synchrony between nitrogen delivery and nitrogen demand of a subsequent cereal crop, but this was not verified by the results of the lysimeter experiment. It seems important to obtain further knowledge of how to improve the degree of synchronization between nitrogen mineralization after incorporation of catch crops and nitrogen demand of the subsequent crop, in order to reduce the need for fertilizer input and to minimize nitrogen leaching from the cropping system. The possibility to control nitrogen release from plant material is even more important in crop rotations with legume based green-manure crops and leys, which usually have a large dry matter production and high nitrogen-fixing capacity.

In the future, old knowledge and new findings will hopefully enable us to further characterize how different catch crop species and soil cultivation practices affect nitrogen dynamics of the soil under different conditions. This will facilitate the choice of a suitable catch crop and management strategy for a specific situation.

Concluding questions

The conclusions of the present work can be summarized in the following questions and answers:

Why choose undersown catch crops?
It is one of the most powerful and reliable measures against nitrogen leaching in wet climates where temperatures are mostly above freezing. When undersown in the main crop in spring, the time available for catch crop growth after harvest of the main crops is maximized and tillage in early autumn, which in general stimulates nitrogen mineralization, is avoided.

Where to use undersown catch crops?
In Sweden, the use of catch crops is in general of most value in the southern part of the country, where the soil may be unfrozen during the main part of autumn and winter. In crop rotations dominated by annual crops, catch crops offer an opportunity to keep the soil covered with vegetation during winter, which is especially important in regions with high precipitation and light textured soils,

i.e. where there is a large risk of nitrogen leaching. On sandy soils, catch crops may be incorporated in late autumn or early spring without damaging soil structure.

How much do undersown catch crops reduce nitrogen leaching?
By 50-70% in southern Sweden, compared with leaching from soil cultivated in early autumn.

Do they reduce main crop yield?
Perennial ryegrass does usually not reduce crop yields.

How does incorporation of catch crops affect nitrogen mineralization?
Mainly during the first growing season after incorporation, when 20-30% of catch crop nitrogen may be released.

Why then is nitrogen supply to the subsequent crop sometimes negatively affected?
In soils with a catch crop there is often a deficit of mineral nitrogen in spring due to nitrogen uptake by the catch crop during autumn and winter. Furthermore, when the catch crop is incorporated in spring, mineralization of catch crop nitrogen may occur too late to fully meet the nitrogen requirement of the subsequent crop.

How can nitrogen supply to the subsequent crop be improved?
Incorporation of the catch crop in late autumn instead of spring may give an earlier onset of nitrogen release in spring. However, more knowledge is needed about how different catch crop species and cultivation practices affect nitrogen dynamics of the soil under different conditions.

How do catch crops affect soil organic nitrogen and mineralization in the long-term?
The use of catch crops results in a small accumulation of soil organic nitrogen, which will very slowly increase the nitrogen mineralization potential of the soil. After ten years of catch crops, nitrogen release from soil organic nitrogen may have increased by 5-10 kg per hectare and year.

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