Nitrogen Dynamics in Crop Sequences with Winter Oilseed Rape and Winter Wheat

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Cover: Winter oilseed rape and poppies in the south of Sweden
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Abstract

With the aim of improving fertiliser nitrogen (N) strategies and reducing N leaching, seasonal changes in soil N supply in crop sequences with winter wheat after winter oilseed rape were examined through field experiments. Break crop effects on wheat after oilseed rape, compared with after peas and oats, were determined as regards residual N, yield and optimum N rate (Opt-N). The impact of residues of the previous crops on net N mineralisation-immobilisation during autumn and winter was studied in field incubation experiments. The influence of spring N fertilisation on winter wheat yields was investigated. Nitrate leaching under winter oilseed rape, peas and oats, and under subsequent wheat was quantified, and measures against leaching were studied. Opt-N to winter wheat was 25 and 15 kg ha^{-1} lower after winter oilseed rape and peas, respectively, than after oats, despite a yield increase of 700 kg ha^{-1} after both. The uptake of soil N by wheat until maturity was 26 and 20 kg N ha^{-1} larger after oilseed rape and peas. Net N mineralisation (Nnet) between spring and maturity was higher after oilseed rape and peas than after oats. Nnet corresponded to 84% of the uptake (or supply) of soil N. The variations in wheat yield at optimum, together with either uptake of soil N or Nnet, explained 70% of the variation in Opt-N. Thus predicting wheat yield and supply of soil N, or Nnet, after previous crops is crucial for the calculation of Opt-N. Due to the large N uptake of winter oilseed rape during the autumn, N leaching during the following winter was lower than during the winter with subsequent winter wheat. More soil mineral N was found at harvest of winter oilseed rape and peas than after oats, affecting later leaching. Above-ground residues of oilseed rape, peas and oats incorporated into soil in September caused N immobilisation during autumn and winter, with the shortest duration for peas. Thus the residue N did not increase leaching risks. Perennial ryegrass as a catch crop undersown in spring in oilseed rape and peas reduced N leaching during winter, whereas direct drilling of winter wheat did not. Fertilisation of oilseed rape above Opt-N enhanced leaching by 0.5 kg N ha^{-1} per kg fertiliser N. It was concluded that optimising the spring N rate to winter oilseed rape was the most important measure against leaching under subsequent wheat.

Keywords: Shoot increase, optimum N fertiliser rate, residual N effect, C:N ratio, topsoil, root residues, ryegrass catch crop, direct drilling, excess N fertilisation

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Dedication

To myself, for finally being ready…

"Nulla tenaci invia est via".
Ingen väg är ofarbar för den ihärdige

Contents

List of Publications

This thesis is based on work contained in the following papers, referred to by Roman numerals in the text:

I Engström, L & Lindén, B. 2009. Importance of soil mineral N in early spring and subsequent net N mineralisation for winter wheat following winter oilseed rape and peas in a milder climate. *Acta Agriculturae Scandinavica Section B – Soil and Plant Science* 59, 402-413.

II Engström, L & Bergkvist, G. 2009.The effects of three N strategies on tillering and yield of low shoot density winter wheat. *Acta Agriculturae Scandinavica Section B – Soil and Plant Science* 59, 536-543.

III Engström, L & Lindén, B. 2010. Temporal course of net N mineralisation-immobilisation in topsoil following incorporation of crop residues of winter oilseed rape, peas and oats in a northern climate. (Manuscript submitted)

IV Engström, L., Stenberg, M., Aronsson, H. & Lindén, B. 2010. Reducing nitrate leaching after winter oilseed rape and peas in mild and cold winters. Agronomy for Sustainable Development. Published on line: 24 September 2010. DOI: 10.1051/agro/2010035.

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The contribution of Lena Engström to the papers included in this thesis was as follows:

I Was responsible for the scope, aim and planning of the study together with co-author Börje Lindén. Lindén was responsible for the general aim and planning of the field experiments. Engström was responsible for the field experiments and all data analysis, and conducted the soil and plant sampling in the field together with Lindén. Wrote the manuscript assisted by the co-author.

II Was responsible for the scope, aim, planning of the study, some of the field sampling, assisted by Lindén, and all data analysis. Wrote the manuscript assisted by the co-author Göran Bergkvist.

III Was responsible for the scope, aim, and planning of the study together with co-author Börje Lindén. Was responsible for the experiments, preparation of soil and plant material, fieldwork, with the assistance of Anna Nyberg, and all data analysis. Wrote the manuscript assisted by the co-author

IV Was responsible for the scope and aim together with the co-authors. Engström was responsible for the field experiments and participated in the field sampling. Performed N leaching calculations, assisted by Maria Stenberg, and all further data analysis. Bo Stenberg helped with the multiple variance analysis. Wrote the manuscript assisted by the co-authors.

Abbreviations

N	Nitrogen
Opt-N	Economically optimum N rate
GS	Growth stage
Nnet	Net N mineralisation between spring and maturity of winter wheat, without N fertilisation

Introduction

In Sweden, winter oilseed rape (*Brassica napus* L.) is an economically important crop for farmers. Between 2000 and 2009 the acreages of oilseed rape has doubled to about 100 000 ha. In comparison, cereals are grown on about 1 million ha and peas on 34 000 ha of a total area of 2.6 million ha cultivated soil. The average yield of winter oilseed rape is 3300 kg ha^{-1} and mainly used for oil production. 50% of the oil produced is for human consumption and 50% for fuel. The byproduct, the rape seed cake, is used for animal feed. Winter oilseed rape is grown from Skåne in the south (55°N) up to the southern parts of the provinces of Värmland, Västmanland and Uppland (59-60°N). In the southernmost regions of Sweden, *e.g.* Skåne, the climate is maritime and winters mainly mild, normally with continuous drainage during winter, but further north the frequency of cold winters with longer periods of frozen ground and snow cover increases.

A crop rotation with a period of 5-6 years between brassica crops is recommended, in order to prevent inoculums from soil-borne pathogens *e.g.* Club root (*Plasmodiophora brassicae*) and Verticillium wilt (*Verticillium longisporum*) to multiply to levels affecting yield (Wallenhammar, 1999). In crop sequences with winter wheat after winter oilseed rape, it is important to gain maximum benefit from break crop effects such as increased yield potential and nitrogen (N) supply. Improved efficiency in N use after break crops reduces costs for the farmer and diminish the negative impact on the environment, *e.g.* through reduced nitrate leaching and denitrification. The focus of this thesis is the use of winter oilseed rape as a break crop, its effect on yield of and N supply to a subsequent winter wheat crop and on N leaching in this crop sequence. Oilseed rape is compared with field peas and oats as alternative break crops.

N leaching after establishment of winter oilseed rape

In Sweden, winter oilseed rape is mostly preceded by cereals, leaving rather small amounts of unused mineral N in soil at harvest. Moreover, N-mineralisation in autumn is limited by the short and cool autumns compared to more southern cropping regions (Hessel-Tjell, 1999). As winter oilseed rape compared to cereals has a higher demand for available N at establishment (Augustinussen, 1987; Razoux Schultz, 1972) the amount of soil mineral N after cereals is likely to be insufficient for optimum growth. Therefore yield increases are generally obtained by fertilising with N at sowing (Biärsjö & Nilsson, 2007) and therefore the application of 30-60 kg N ha^{-1} is recommended after cereals (Yara AB, 2009). In addition, as winter oilseed rape has the capacity to take up large amounts of leachable N during the autumn, it is one of few crops that is allowed to be fertilised with farmyard manure before sowing in the autumn, according to the Swedish environmental regulations. However, the recommended N fertilisation rates at sowing are being questioned due to the risk of leaching if circumstances, for example late sowing or bad growing conditions, limit N-uptake.

N leaching after harvest of winter oilseed rape

Under northern European conditions, winter oilseed rape is commonly followed by winter wheat. However, the accumulation of soil mineral N at maturity and in late autumn (November) after winter oilseed rape is generally larger than after cereals (Ryan *et al.*, 2006; Sieling *et al.*, 1999; Christen *et al.*, 1992). This is also the case after peas (Jensen, 1996; Jensen & Haahr, 1990). Moreover, the uptake of N in the autumn by winter wheat is comparatively small at high latitudes, about 20 kg N ha^{-1}, or less following late sowing (Lindén *et al.*, 2000). Consequently, N leaching is often high during the autumn and winter after oilseed rape (Knudsen et al., 2002; Hessel-Tjell *et al.*, 1999; Sieling *et al.*, 1999; Christen *et al.*, 1992).

The application of excess N to winter oilseed rape in springtime can result in large amounts of residual soil mineral N at harvest, increasing the risk of N leaching (Henke *et al.*, 2008; Sieling *et al.*, 1997; Shepard & Sylvester-Bradley, 1996). When N is applied to cereals in excess to the needs of the crop, leaching increases exponentially (Bergström & Brink, 1986). However, the impact on leaching after excess N fertilisation of winter oilseed rape has not been fully investigated in Sweden, nor has the impact of N leaching after oilseed rape been compared experimentally with the impact of N leaching after peas.

Impact of crop residues on the supply of plant-available soil N and on N leaching

Winter oilseed rape has a high N demand but a low N harvest index. Of the total N uptake by above-ground crop only 50-70% accumulates in the seeds and is thus removed at harvest (Trinsoutrot *et al.*, 2000a). The corresponding figure for oats and peas is about 80%. The N remaining in the crop residues is normally incorporated into the soil by post-harvest tillage. However, most of the N in above-ground crop residues of winter oilseed rape and peas is relatively unavailable to the following crop due to the high C:N ratios of the residues, causing N immobilisation (Justes *et al.*, 1999; Jensen *et al.*, 1997). Thus, the increased accumulation of mineralised N in soil after winter oilseed rape and peas can only be partly attributed to N in the residues of the above-ground crops (Ryan *et al.*, 2006; Trinsoutrot *et al.*, 2000a; Kirkegaard & Sarwar, 1999; Jensen *et al.*, 1997). The contribution of below-ground crop residues to increased supply of plant-available soil N is unclear, but there is an indication N release from plant roots is an important source of plant-available N (Mayer *et al.*, 2003a; Gordon & Jackson, 2000; Jensen, 1996; Janzen, 1990).

The duration and intensity of N immobilisation after incorporation of oilseed rape or pea crop residues may influence both supply of soil N to the next crop and N loss. For instance, in northern Europe, close to the northern limit of cultivation for winter oilseed rape and peas, the lower temperatures probably prolong the duration of mineralisation-immobilisation processes. The duration of these processes after different crops can be determined by the change in soil mineral N over time in field experiments or following incorporation of residues in buried open cylinders in the field (Trinsoutrot *et al.*, 2000a). However, due to N leaching, there is a risk that the results would only demonstrate the net effects of the soil mineral N transformations involved.

Soil mineral N transformations described for warmer climatic regions, and in laboratory studies (Bruce *et al.*, 2006; Mayer *et al.*, 2003a; Trinsoutrot *et al.*, 2000a; Jensen *et al.*, 1997) may only be partly relevant for north European conditions. However, it is difficult to study effects of naturally fluctuating soil temperatures realistically in laboratory incubation studies. Moreover, disturbed soils and milled or finely chopped crop residues is frequently used in incubation studies, which compromise studies on the natural course of N transformations. Crop residues in a form similar to those produced by normal combine harvesting are preferable, if the purpose is to study N processes as influenced by farming practices. The evaluation of the impact of crop residues on the supply of plant-available soil N and leaching in different climate regions requires relevant research data.

Break crop effects on yield and optimum N rate to winter wheat

Winter oilseed rape and peas are effective break crops in a cereal-dominated rotation because of certain positive effects on yield potential of winter wheat, including reduced incidence of root disease, improved soil structure, and increased supply of plant-available soil N, or a combination of these effects (Angus *et al.*, 1994; Chan & Heenan, 1991). The increased supply of plant-available soil N, *i.e.* the residual N effect, is assumed to increase yield potential of wheat, and if large enough, can reduce optimum N fertilisation rate (Opt-N rate) (Engström & Gruvaeus, 1998).

Increased yield potential and soil N supply have to be considered when calculating the rate of fertiliser N to wheat after break crops. In field trials, a larger residual N effect on winter wheat after winter oilseed rape and spring oilseed rape than after cereals has been reported, with Opt-N being lowered by 34 and 14 kg ha^{-1}, respectively (Engström & Gruvaeus, 1998). However, there can be variations over years and between sites. In Denmark, with climate conditions similar to southern Sweden, Knudsen *et al.* (2002) found that Opt-N to winter wheat was lowered by 40 kg ha^{-1} after winter oilseed rape compared with cereals as the previous crop. Whether there is both an increase in yield and a decrease in Opt-N to winter wheat after winter oilseed rape and peas, or just an increase in yield and no change in Opt-N, has been debated among farmers and farm advisors in Sweden.

The difference in break crop effect between peas and oilseed rape has not been clarified, as these crops seldom precede wheat simultaneously in the same experiments. Annual field trials on N application rates to wheat after various previous crops have been conducted at many different sites in Sweden (Mattsson, 2006; Engström & Gruvaeus, 1998; Mattsson & Kjellquist, 1992). In these trials, the previous crop species varied from site to site. Thus, the Opt-N values obtained are a product of both the previous crop and the site. Site conditions are affected by factors such as soil type, soil organic matter content, cultivation history, and weather pattern. To be able to isolate the effects of different preceding crops, *e.g.* winter oilseed rape, peas and oats, on winter wheat, all crops would need to be grown simultaneously at the same site.

N fertilisation strategies to winter wheat after winter oilseed rape

Increased soil mineral N and greater N uptake have been reported on a number of occasions during growth of the crop subsequent to oilseed rape and peas (Ryan *et al.*, 2006; Kirkegaard et al., 1997; Heenan, 1995; Jensen & Haahr, 1990). However, the temporal course of the increased N supply after these crops is unclear.

The recommended fertiliser N strategies for winter wheat generally consider temporal variation in N demand of the crop during growth and development. As growth progresses from sowing to harvest, the wheat crop passes through a succession of phases, each with particular importance for yield (Sylvester-Bradley et al., 2001; Kirby, 1988; Darwinkel, 1983). Each phase is influenced by N supply, but the effects are most obvious during the phases of tillering and shoot survival, i.e. when application of fertiliser N is often recommended (Sylvester-Bradley et al., 2001). High N concentrations in plant tissue during the reduction phases for formed yield components (tillers, spikelets, and flowers) can mitigate this reduction and stimulate production during the formation phase (Hay & Porter, 2006). N generally improves yield through increasing ear density and number of grains per ear, *i.e.* number of grains per m^2, whereas grain weight is less affected by N (Dougherty, 1978; Darwinkel, 1983; Siddique, 1989; Gooding, & Davies, 1997).

The N fertilisation strategy generally recommended for winter wheat in south-west Sweden includes N applications split over two or three occasions. The total amount of N is adjusted to the estimated average yield of a particular field, and most of the N should be applied as a main application in time to be plant-available at the end of tillering and before the beginning of stem elongation (Albertsson, 1999) i.*e.* growth stage (GS) 30 (Zadoks *et al.*, 1974). In Västergötland (south-west Sweden), N application is usually carried out 2-3 weeks before GS30 (between 15th and 25th April), so the N is dissolved and available to the plants at GS30, thus avoiding reduced N availability if May is dry, which is common in the area. If a crop is assumed to respond well to N or high protein content is desired, a second application of N is done at GS37-47.

Wheat canopies with low shoot density (<500 shoots per m^2) at the beginning of growth in spring (GS20-21) are generally fertilised with N in early spring, usually late March or early April. However, the recommendation is not to exceed 40-60 kg N ha^{-1} at this early stage, due to the risk of losing large amounts of N through denitrification or leaching (Albertsson, 1999).

In principle, larger amounts of soil mineral N than normal in early spring and increased soil N release during the growing season should decrease the need for fertiliser N application on winter wheat following winter oilseed rape and peas. An increase in knowledge on the temporal course of increased soil N supply after these crops would make it possible to improve the timing of N applications.

A related question concerns the amount that overwintering soil mineral N contributes to the N supply for the winter wheat, compared with N mineralisation during the actual growing season. N fertilisation of winter wheat in early spring is often questioned in Sweden, as yield increases are seldom obtained in field trials and there is a risk of N losses.

Measures for reducing N leaching

Tillage of soil in early autumn, which incorporates crop residues, kills weeds and loosens the soil before establishing a new crop, increases mineralisation of soil N (Stenberg *et al*., 1999; Wallgren & Lindén, 1994; Dowdell *et al*., 1983). Reduced and delayed tillage in autumn before establishing a crop can maintain N mineralisation at a low level and counteract undesired accumulation of soil mineral N in late autumn and N leaching (Stenberg *et al*., 1999; Djurhuus & Olsen, 1997; Davies *et al*., 1996). Catch crops such as undersown perennial ryegrass (*Lolium perenne* L.) counteract the increased risk of leaching after cereals (Constantin *et al*., 2010; Torstensson & Aronsson, 2000; Hansen & Djurhuus, 1997) due to both N uptake and delayed tillage. However, the cultivation of catch crops after winter oilseed rape and peas is not well investigated in Sweden. An undersown catch crop is able to take up unused soil mineral N already at the time of harvest of oilseed rape or peas. A catch crop sown after harvest starts its growth much later, therefore, the effect is delayed. This is especially important in northern countries, such as Sweden, where there is only a short period between harvest of oilseed rape or peas (August) and sowing of winter wheat (September).

In order to define efficient strategies for reducing N leaching after winter oilseed rape and peas grown under northern European conditions, different management practices need to be simultaneously evaluated at the same site under different weather conditions for the region. Such investigations should include both mild and cold winters, as snow cover and frozen soils affect drainage and N leaching patterns. The effects of N fertilisation of winter oilseed rape, cultivation of catch crops after oilseed rape and peas, and direct drilling on the risk of N leaching are usually studied separately and not in the same experiments, which renders the effects more difficult to evaluate.

Objectives

The overall objective of this work was to identify ways of improving N fertilisation strategies and reducing N leaching in crop sequences with winter wheat after winter oilseed rape. This would be achieved through investigating temporal changes in soil N supply and its impact on yield and N leaching and by comparing winter oilseed rape with peas and oats. The specific objectives were to:

- Quantify the break crop effects of winter oilseed rape, peas and oats on N uptake, Opt-N and yield in subsequent winter wheat (Paper I).
- Describe the influences of overwintered soil mineral N in spring and net N mineralisation during the main growing season after winter oilseed rape, peas and oats on the N supply to subsequent winter wheat (Paper I).
- Determine the effect of the timing of spring fertilisation on winter wheat yields (Paper II).
- Determine the temporal course of net N mineralisation-immobilisation in soil during autumn and winter and the influence of incorporated above-ground residues of winter oilseed rape, peas and oats (Paper III).
- Determine the effects of N uptake by winter oilseed rape on N leaching during autumn and winter as influence by recommended N fertilisation at sowing (Paper IV).
- Describe the impact of increasing rates of fertiliser N applied to winter oilseed rape in springtime on seed yield and N leaching during the subsequent autumn and winter (Paper IV).
- Evaluate the impact of different management strategies for reducing N leaching in crop sequences with wheat after winter oilseed rape. (Paper IV).

Background

Seasonal variations in soil mineral N in south and central Sweden

The amount of mineral N in soil is usually lowest in late summer when N uptake ceases, which generally occurs at maximum crop N uptake (Figure 1), when most of the mineralised N and applied fertiliser N in soil has been used up by the crop. After cereal cultivation in Sweden, only about 15-30 kg N ha^{-1} of mineral N remains within a soil depth of 90 cm. With cereals, this usually occurs at yellow ripeness (Lindén, 1981), but is earlier for winter oilseed rape as it ripens earlier. In field peas, soil mineral N reaches its lowest level during the ripening phase when the plant is turning yellow (Lindén, 1981). It normally remains at a higher level than with cereals because of symbiotic N_2 fixation.

After N uptake ceases during the ripening phase, soil mineral N increases due to continuing N mineralisation in the soil. Under Swedish conditions, this increase normally continues until late autumn in uncropped soils, when the temperature falls to below 0°C, which prevents mineralisation. Due to the increase in soil mineral N during autumn, there is an increased risk of N loss through denitrification (especially in heavier soils) and leaching (particularly in lighter textured soils), especially when drainage rates are high during autumn and winter. Therefore, the amount of soil mineral N usually decreases from late autumn to early spring if the winter is mild with temperatures above 0°C, at least in lighter soils. However, if the ground is frozen for most of the winter, soil mineral N in early spring will be at the same level as in late autumn, or even higher in clay or clayey soils in central Sweden (Delin *et al.*, 2008; Lindén *et al.*, 2006; Lindén, 1981). In early spring, rising temperatures increase soil N mineralisation (Figure 1). Nitrogen fertilisation during spring temporarily contributes to increasing the levels in the soil. However, increasing N uptake by the crop during the main growing season depletes soil mineral N to a minimum level when N uptake ceases at ripening.

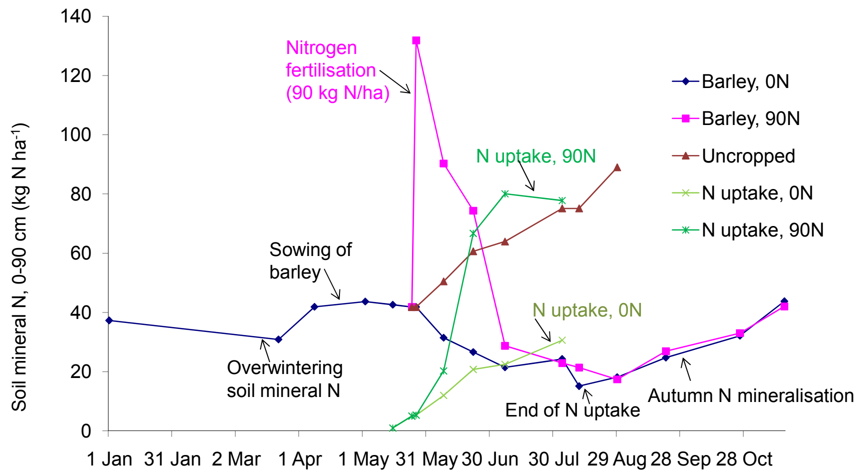

Figure 1. Temporal course of soil mineral N (0-100 cm) in a clay soil with spring barley fertilised with 0 and 90 kg N ha^{-1} and without a crop, at Lanna in southwest Sweden 1983 (Lindén, unpublished). Above-ground N uptake of spring barley with and without N fertilisation is also indicated.

Crop N uptake during autumn

Winter oilseed rape has potential for N uptake during autumn when growing conditions are favourable, sowing is not delayed and the crop is well established. In nine field experiments in southern and central Sweden (Lindén & Wallgren, 1988), the average N uptake was 46 kg N ha^{-1} (range 11-90 kg N ha^{-1}) in late autumn in above-ground parts of winter oilseed rape (n= 6) and turnip rape (n=3), with higher amounts after earlier sowing. In field experiments on a sandy loam soil at Lönnstorp in southern Sweden (Aronsson and Torstensson, 2003), the average N uptake by winter oilseed rape was 54 kg N ha^{-1} in late autumn (range 31-87 kg N ha^{-1}). The crop was sown after barley and fertilised with 30 kg N ha^{-1} at sowing, and the largest N uptake was obtained in a year with early sowing.

In seven field trials with winter oilseed rape in Västergötland, Östergötland and Södermanland, Sweden, between 1996 and 1999, N uptake in late autumn was on average 83 kg N ha^{-1} without application of farmyard manure before sowing and 155 kg N ha^{-1} with farmyard manure applied before sowing (Engström et al., 2000). In these field experiments, soil mineral N (0-90cm) reached low levels in late autumn (28 kg N ha^{-1}).

In south-west Sweden (Engström & Lindén, 2008), five field trials on organically grown winter oilseed rape sown after grass-clover leys and not fertilised at sowing revealed that N uptake in late autumn was 47 kg N ha^{-1} (range 10-76 kg N ha^{-1}). In these trials soil mineral N (0-90 cm) in late autumn was 49 kg N ha^{-1}, whereas it was 89 kg N ha^{-1} in four trials in the same series that were cancelled due to bad establishment. This indicates the importance of a well-established crop with the potential to take up large amounts of N during the autumn to avoid N loss, especially when soil N mineralisation is high *e.g.* after grass-clover leys. Larger amounts of soil mineral N available during autumn generally result in increased N uptake, but conditions during establishment and early growth in autumn appear to affect the final N uptake in late autumn.

On average for these four studies N uptake of winter oilseed rape during autumn was 60 kg N ha^{-1} (range 10-155 kg N ha^{-1}). The greater amounts of soil mineral N available during autumn generally resulted in larger N uptake, but conditions during establishment and early growth in autumn also seemed to affect the final N uptake in late autumn.

Mineralisation of N in soil during autumn is further stimulated by seedbed preparation, including ploughing and harrowing, which increase the potential for N leaching during autumn and the subsequent winter (Stenberg *et al.*, 1999; Wallgren & Lindén, 1994). N fertilisation during autumn, especially by manure applications, is often associated with larger accumulation of soil mineral N in late autumn, and thus, increased N leaching (Lindén *et al.*, 1998). However, as winter oilseed rape has capacity for N uptake during autumn, soil mineral N can be maintained at a low level after manure application (Engström *et al.*, 2000), which reduces N leaching over the next winter.

In order to obtain subsidies intended for reducing N losses from agricultural land in southern Sweden, Swedish environmental regulations require at least 50-60% of the cultivated area on a farm to have a growing crop or remain as stubble (i.e. untilled) during autumn. Crops eligible for subsidies include winter oilseed rape, winter cereals (despite low N uptake during autumn), leys, and catch crops, along with untilled stubble after cereals and oilseed rape. In regions with high N leaching, additional subsidies are available for growing catch crops or delaying ploughing until spring in order to decrease leaching.

Eligible catch crops include grass (mainly perennial ryegrass) or grass-clover mixtures, which are sown at the same time as the main crop, or, by 15 June at the latest. In the most southerly regions of Sweden (Blekinge, Skåne, Halland, and Kalmar), where N leaching is considered highest, white mustard (*Sinapis alba*) and oil radish (*Raphanus sativus* var. *oleiformis*) are also eligible catch crops and are mainly used after sugar beet and potatoes. However, catch crops have to be left in place until 10 or 20 October (depending on region), which makes it impossible to establish a subsequent winter wheat.

Increased yield after break crops

Alternative crops in cereal rotations can increase the yield and protein content of a subsequent wheat crop and are often referred to as break crops. Grain yield potential of wheat after different previous crops varies a great deal, with brassica and leguminous crops known to give the largest break crop effect, but other species can also profitably affect the yield of wheat. However, the magnitude of the response of the subsequent winter wheat varies with seasonal conditions and break crop species. Break crops are often ranked according to the extent to which they affect wheat yields.

In a series with a total of 46 field experiments, carried out in southern Sweden from 1984 to 1988 (Olofsson, 1993), the pre-crops tested were ranked in the following order (from largest to smallest yield of the following crop of winter wheat): Turnip rape (*Brassica rapa* L.) = peas (*Pisum sativum* L.) > oats (*Avena sativa* L.) > barley (*Hordeum distichon* L.) > wheat (*Triticum æstivum* L.). Compared with a previous crop of winter or spring wheat, yield of winter wheat increased by 1200 kg ha^{-1} after spring oilseed rape (*Brassica napus* L.) and peas, by 800 kg ha^{-1} after oats and by 350 kg ha^{-1} after barley (Olofsson, 1993).

In another series of experiments in Sweden, where the effect of various preceding crops on yield and protein content of cereals was studied, Wallgren (1986) found a 1000 kg ha^{-1} increase in yield of winter wheat after spring oilseed rape compared with after barley and winter rye (*Secale cereale*). However, the protein content of the wheat was reduced by 0.2-0.4 %-units after oilseed rape. Wallgren (1986) also found that field beans (*Vicia faba* L.) as the previous crop to spring barley increased both the yield (by 370-430 kg ha^{-1}) and the protein content (by 0.5-0.6 %-units) compared with barley and spring wheat as the preceding crop.

In 90 field trials at different locations in Sweden between 1980 and 1997 (Engström & Gruvaeus, 1998), winter wheat without N fertilisation after winter oilseed rape and spring oilseed rape yielded an average of 2100 kg ha^{-1} and 700 kg ha^{-1}, respectively, more than after cereals. With Opt-N fertilisation, wheat yielded 1100 kg ha^{-1} and 700 kg ha^{-1} more after winter and spring oilseed rape, respectively. There were no differences in protein content. This represented a 25-73% increase in yield of unfertilised wheat after oilseed rape and an 11-18% increase in yield of optimally fertilised wheat. However, in these trials, the wheat after cereals and oilseed rape crops was grown at different sites: this cannot be excluded, even if the large number of experiments probably reduced site effects. Similar results were obtained in 38 Swedish experiments where oats and peas were followed by winter wheat at the same site (Svensson, 1988): peas as the preceding crop caused higher wheat yields at all N levels.

Although cultivation practices and straw treatments vary greatly, studies from outside Sweden report similar results (Christen *et al.*, 1992; Angus *et al.*, 1991; Jensen & Haar, 1990). Peas and winter oilseed rape as a preceding crop have a positive effect on yield of winter wheat, with or without N fertilisation, compared with cereals. In Sweden, the average yield increase after both peas and oilseed rape appears to be 1000 kg ha^{-1}, but the variation is large. The protein content in wheat grain is inconsistently influenced by the previous crop, with both decreases and increases being reported.

Increased soil N supply after break crops

Crop yield is a response to various factors such as nutrients, soil structure, pathogens, soil-dwelling microorganisms, weeds, crop management, and weather conditions during the growing season. In field trials, the effect of preceding crops on crop yield is comparatively easy to measure. However, the reasons for the different responses to preceding crops are more difficult to explain, as they are not entirely clear. The positive effect on yield gained with a non-cereal crop before winter wheat is usually explained by increased amounts of plant-available soil N, suppression of soil-borne wheat pathogens, and improved soil structure, or, a combination of two or more of these effects.

One of the reasons for high soil mineral N levels at maturity and harvest of winter oilseed rape is mineralisation of N in senescing above-ground crop residues shed after flowering and in decaying root residues (Hocking *et al.*, 1997; Shepard & Sylvester-Bradley, 1996). Moreover, winter oilseed rape both ripens earlier than cereals and ceases N uptake earlier, thus, the period of accumulation of mineralised N in soil during late summer and autumn is longer than after cereals. In addition, seedbed preparation for subsequent winter wheat may further stimulate soil N mineralisation.

The high levels of soil mineral N at maturity and harvest of field peas has a different explanation, and is due to a combination of decomposition of more easily mineralised root residues and that peas do not exhaust the soil inorganic N reserves to the same extent as a cereal crop (Mayer *et al.*, 2003b; Jensen, 1996). The N requirement of peas is mainly met by symbiotic N^2 fixation, which can amount to over 200 kg N ha^{-1} (Jensen, 1987). In Sweden, residual soil mineral N at maturity or harvest of field peas amounts to about 35-80 kg N ha^{-1} within the upper 90 cm soil layer (Nyberg & Lindén, 2008; Lindén, 1984), whereas 15-30 kg N ha^{-1} generally remains at maturity of cereals (Delin *et al.*, 2008; Lindén, 1981).

Materials and methods

Field experiments

Studies of break crop effects of winter oilseed rape, peas and oats (Paper I)

In 2000-2004, the break crop effects of winter oilseed rape, field peas, and oats on soil mineral N at different times, N mineralisation during the growing season, yield, and Opt-N in subsequent winter wheat were studied through field experiments at nine different sites in the province of Skåne, southern Sweden (55°06'-55°45'N, 13°04'-14°09'E). At each field site in year 1, the three crops preceding winter wheat were grown simultaneously in three 40 m x 20 m randomised main plots. In year 2, each main plot was divided into eight randomly allocated subplots representing increasing N rates for winter wheat for the determination of Opt-N. Treatment with 0 kg N ha^{-1} was duplicated to allow yield to be determined in one subplot and soil mineral N and winter wheat uptake of plant-available soil N after the previous crop to be determined in the other. The differences in N uptake of the winter wheat without N fertilisation indicated the residual N effect after winter oilseed rape and peas, compared with after oats. Together with soil mineral N, the N uptake data made it possible to calculate net N mineralisation from early spring to maturity of wheat (see below).

Effects of three N strategies on tillering and yield of low shoot density winter wheat (Paper II)

During the period 1999-2002, four field experiments on clay soils at Lanna research station in the province of Västergötland, south-west Sweden (58°21´N, 13°´08E) investigated the importance of N supply in early spring (before stem elongation) on tillering and yield of winter wheat on a clay soil. Winter wheat was sown at normal to late sowing dates (14 September-

11 October) to create normal to naturally low shoot densities. Three N strategies were tested in a randomised block design of 18 m x 1.9 m plots in three replicates. The first N application of the three N strategies was four weeks before the beginning of stem elongation (GS30), two weeks before GS30, and at or shortly after GS30. The experiments aimed to clarify conclusions on the effects of increased soil mineral N in early spring and increased N mineralisation during the main growing season related to certain preceding crops.

Temporal course of net N mineralisation-immobilisation in soil after incorporation of crop residues (Paper III)

An incubation study with soils and above-ground crop residues after winter oilseed rape, peas and oats, which were collected in four of the nine field trials from Paper I, was conducted under natural temperature conditions in a field at Lanna research station. The incubation was divided into two winter periods, 29 August-30 April 2002/2003 and 29 August-30 April 2003/2004. Crop residues of the same size as those produced by normal combine harvesting (as used in the field experiments) were used to study the influence of crop residues on N mineralisation-immobilisation under as realistic conditions as possible.

Reducing N leaching after winter oilseed rape and peas in mild and cold winters (Paper IV)

Nitrogen leaching during growth of winter oilseed rape and during growth of winter wheat subsequent to winter oilseed rape, peas and oats was studied in two field experiments (2004-2006 and 2005-2007) on a sandy soil at Götala experimental farm (58°22´N, 13°29´E) in Västergötland, south-west Sweden. The impact of different management strategies on N leaching was compared to determine methods of reducing leaching after these crops. Nine treatments were tested in a completely randomised block design of 6 m x 30 m plots with three replicates.

The methods used for calculating plant-available soil N including residual N effect and N mineralisation during the growing season of winter wheat and the methods for the incubation study and the N leaching experiments are presented and briefly discussed below. A detailed description of the experimental procedures is presented in Papers I-IV.

Residual N effect and plant-available soil N

The residual N effect of different previous crops on a cereal crop can be determined in field trials by growing the subsequent crop in plots without N fertilisation (0N plots) and then comparing the total above-ground N uptake at ripening (Paper I). The N uptake at ripeness of the unfertilised cereal crop represents the amount of plant-available soil N originating from both soil and preceding crop. Thus, the difference in N uptake at ripeness of the subsequent crop represents the difference in residual N effect of the previous crops. Here, the total uptake of soil N in wheat at ripening was calculated as the sum of N content in grain, straw (Paper IV), and roots (Paper I). It was assumed the roots contained 25% of the total amount of N in the wheat crop without N fertilisation (Hansson *et al.*, 1987).

To determine above-ground N in winter and spring wheat after winter oilseed rape, peas, and oats (Papers I and IV), the total N content in the above-ground plant parts of wheat was determined in crop samples at ripeness (GS87-90) from subplots without N fertilisation. Crop samples were cut at the soil surface from three randomly selected 0.24 m^2 sub-areas within each plot and then dried at 60°C.

The residual N effect on a cereal crop, such as winter wheat, may be calculated as the amount of fertiliser N required for wheat after cereals to obtain the same yield increase as winter wheat after a break crop. However, because of different yield curves with different slopes and maxima, the amount of fertiliser N required for a certain yield level increases differently with increasing fertilisation amounts (Engström & Gruvaeus, 1998). Therefore, the difference in N uptake at ripening by winter wheat without N fertilisation after various preceding crops is a better measure of the influence of break crops on plant-available soil N (Papers I and IV).

In order to determine the influence of preceding crops on wheat yield potential, increasing levels of fertiliser N (0-240 kg N ha^{-1}) were applied to the wheat (Paper I). The use of both these methods allowed the effects on yield potential and on plant-available soil N to be separated.

Net N mineralisation during the growing season

Plant-available soil N during the growing season, determined in 0N plots, could be divided into two parts: overwintering soil mineral N within the root zone in early spring; and soil N mineralised during the main growing season up to cessation of N uptake at ripening.

In Paper I, net N mineralisation (Nnet) was calculated with equation 1:

$$Nnet = Np + ResN_{min} - SN_{min} \qquad \text{(equation 1)}$$

Where:
Nnet = calculated net N mineralisation during the growing season, from early spring to ripening.

Np = total N in above-ground crop at ripening and calculated N content in roots in treatments without N fertilisation. It was assumed that roots contained 25% of the total amount of N in the crop.

$ResN_{min}$ = residual mineral N in soil (0-90 cm) at ripening, without N fertilisation.

SN_{min} = mineral N in soil (0-90 cm) in early spring, before the start of plant growth.

Here, Nnet was defined as:
N mineralisation - N immobilisation - N losses + atmospheric NH_4-N and NO_3-N deposition.

Soil mineral N was determined by soil sampling in early spring, before crop N uptake had started, and by crop sampling at ripening, when N uptake had ceased. In field experiments in Sweden, soil sampling is usually within 0-90 cm depth, but not all mineral N is available to the crop during the growing season partly because the roots do not penetrate the soil completely within the different soil depths. In Equation 1 mineral N at ripening indicates the amount of unused N, thus unavailable to the crop

Field incubation study

The course of net N mineralisation-immobilisation in soil over time, with and without above-ground residues, and under natural temperature conditions was investigated through an incubation study with plastic bottles (15 x 5 cm) (Paper III). The plastic bottles were placed in the topsoil of a field at Lanna research station in Västergötland (Figure 2) by a method developed by Lindén *et al.* (2003) and later used by Delin & Engström (2010). The bottles contained topsoil (0-20 cm, including fine roots) both with and without above-ground crop residues, which were collected in late August (after harvest) in the treatments with winter oilseed rape, peas, and oats in four of the experiments described in Paper I. The incubation equipment was adapted to prevent rainwater from entering the bottles, which would cause losses of N within the bottles. The maximum water-holding capacity (WHC) of the soil was determined according to Jansson (1958). Deionised water was then added to achieve 52% of WHC, which represented the soil moisture conditions frequently occurring in the study region in autumn (50-60% of WHC). The bottles were placed at a depth of 20 cm and covered by a 5 cm layer soil, and with the soil-crop residue mixture at a depth of 15-20 cm. A ventilation tube was attached to the lid of each bottle and extended about 30 cm above the soil surface: the top was bent downwards to avoid entry of rainwater. No substantial changes in bottle weight were observed at the end of the incubation, indicating soil moisture had been stable and the bottles had remained rainproof.

The study was performed under natural temperature conditions in the field and with crop residues of a similar size to those produced by practical farming. However, the soil was cautiously sieved (to remove stones and large woody root residues) and was more intensely mixed than when incorporating crop residues with various soil cultivation methods in the field. This would have stimulated soil N mineralisation more than under field conditions. Therefore, the results should be regarded as a measure of the potential net N mineralisation-immobilisation, as N leaching loss was prevented in the bottles.

In the field trial, the proportions of residues and soil used in the bottles were calculated to correspond with the actual above-ground crop residue:soil ratio (Paper I), and were based on the assumption that residues were mixed by tillage into a 7 cm thick soil layer representing about 25% of a 28 cm thick topsoil layer. The crop residues, including pod walls and stems, were chopped at harvest in the field trials into 2-5 cm lengths, and this size was used in the incubation.

When soil tillage is carried out after harvest and before establishment of winter wheat under field conditions in Sweden, crop residues, generally chopped to 2-5 cm, are evenly incorporated into the upper 5-10 cm of the topsoil. If mouldboard ploughing (to 20-30 cm) is practised, they will be placed in more or less concentrated bands deeper in the topsoil and in clumps. Whatever the method of incorporation, only a small volume of the topsoil (approximately 25%) is in contact with, and directly influenced by, above-ground residues: most of the topsoil (75%) only contains below-ground residues (Paper III).

In order to study the effect on N mineralisation-immobilisation in both fractions of topsoil, soils, with below-ground residues from each of the three previous crops included, were incubated with and without the corresponding above-ground residues (Paper III).

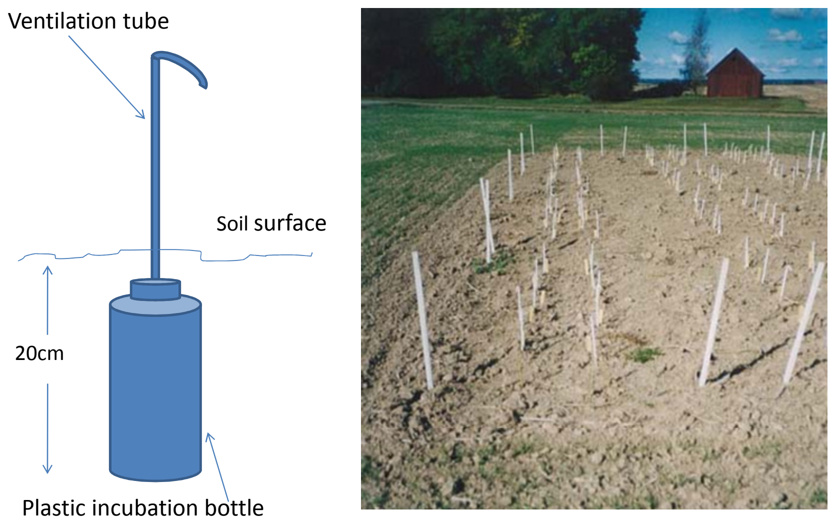

Figure 2. Incubation bottle and positions in the field during autumn and winter (Paper III).

N leaching study

In the experiments on a sandy soil at Götala (Paper IV), nitrate-N concentration (NO_3-N) in soil water was determined plot-wise through sampling soil water with ceramic suction cups (Djurhuus, 1990) installed in triplicate at 80 cm depth in the plots (Figure 3). Sampling was carried out every second week during periods with drainage, usually September-April. Before sampling, a suction of 60-70 kPa was applied for 24 hours. The soil water entering the suction cups by means of suction was collected through plastic tubes in the sampling units that ended above the soil surface..

The daily amount of nitrate-N leached was calculated by multiplying the concentration in the soil water samples by the amount of daily drainage. Daily drainage flow at the experimental site was estimated with data taken from a long-term field leaching experiment on a sandy soil at Fotegården

(58°28'N, 13°21'E), about 20 km from Götala, where water flow was continuously measured and recorded. Precipitation at Götala was assumed to be the same as at Fotegården. The drainage measurements represented the mean drainage from soil cropped with cereals, with and without an undersown catch crop. This approach did not consider possible differences in drainage amounts due to differences in evapotranspiration during autumn among the different treatments, although such differences probably occurred. Under similar conditions, undersown ryegrass catch crops have 0-7% less drainage than soils ploughed in autumn (Torstensson & Aronsson, 2000; Hansen & Djurhuus, 1997).

In N leaching studies with separately pipe-drained plots connected to a measuring station, the nitrate concentration in soil water and drainage volume are determined simultaneously in each plot. The system works on soils with a fluctuating water table at drainage depth, but not on soils with a much deeper water table. At the experimental site, the water table was situated too deep for measuring leaching with this method (Paper IV). The plot size in experiments with pipe-drained plots is normally about 30 m x 30 m (0.09 ha) or 40 m x 40 m (0.16 ha) in Sweden. This is a large area and limits the number of plots, and the number of treatments in an experiment. With ceramic suction cups, the plot size can be kept smaller, *e.g.* 6 m wide: this also reduces soil variation. Suction cups function well on sands or sandy loams, as used at the site in Götala (Paper IV), but not on clays or clayey soils.

At Götala, nine treatments with three replicates comprised one experiment, *i.e.* 27 plots (Paper IV). This was repeated in two experiments positioned opposite to each other and with a sampling unit for the plastic tubes from the ceramic suction cups situated between the two experiments (Figure 3). The plots were long and broad enough (6 m x 30 m) to be divided into two subplots, with application of 0 and 100 kg N ha^{-1} during the winter wheat year. The ceramic suction cups were situated within the first 10 m of each main plot which also was part of the area where 100 kg N ha^{-1} was applied to the winter wheat (Figure 3).

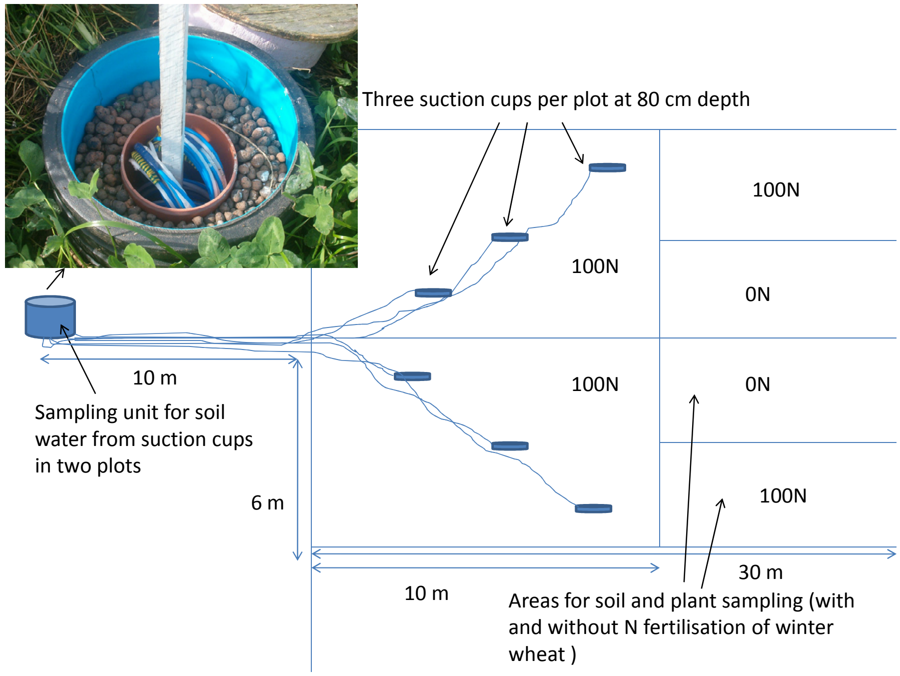

Figure 3. Ceramic suction cups placed in two plots in the field experiments in Paper IV (plot size 6 m x 30 m).

Results and discussion

N dynamics from sowing of winter oilseed rape until early spring

In the experiments on the sandy soil at Götala (Paper IV), winter oilseed rape was fertilised at sowing with 30 and 60 kg N ha^{-1}. Until late autumn N uptake in the above-ground plant parts was 47 or 75 kg N ha^{-1}, respectively, for these rates. In treatments with an oilseed rape crop, soil mineral N in late autumn for both N rates at sowing was 25 kg N ha^{-1} lower than in uncropped tilled soil.

In the mild winter of 2004/2005, with the main drainage between October and March, growing winter oilseed rape reduced nitrate-concentrations in soil water (Figure 4a). N leaching was also reduced (by 40% or 14 kg N ha^{-1}) for the total drainage period (measured July to June), independent of N rate. The good N uptake until late autumn, for Swedish conditions, was a result of a well-established crop. In treatments with a winter oilseed rape crop the nitrate-N concentrations in soil water varied within the range 3.5-13.2 mg nitrate-N L^{-1} (Figure 4a). The concentrations were generally below the European Union drinking water limit of 11.3 mg nitrate-N L^{-1}. However, in treatments with uncropped tilled soil, concentrations were considerably higher, 3.4-39.8 nitrate-N L^{-1} the mild winter.

Increasing the N fertilisation rate from 30 to 60 kg N ha^{-1} at establishment of the oilseed rape did not increase N leaching during autumn and winter. This was attributed to the high N uptake reducing mineral N levels in the soil. Similarly, Engström (2000) found small amounts of soil mineral N in late autumn, after manure application before sowing of winter oilseed rape, due to increased N uptake (165 kg N ha^{-1}) during autumn. However, increased N fertilisation at Götala (60 kg N ha^{-1}) did not increase the yield. Under the present soil conditions with high N mineralisation, N fertilisation might not have been needed at establishment. Nevertheless, the results demonstrated the high N uptake potential of winter oilseed rape in autumn, even when fertilised above its requirements for optimum yield.

Late sowing and dry periods or low temperatures can further reduce crop growth and N uptake during autumn and increase the risk of leaching (Sieling & Kage, 2009; Aronsson & Torstensson, 2003). This emphasises the importance of early sowing for improving the conditions for N uptake (Dejoux *et al.*, 2003).

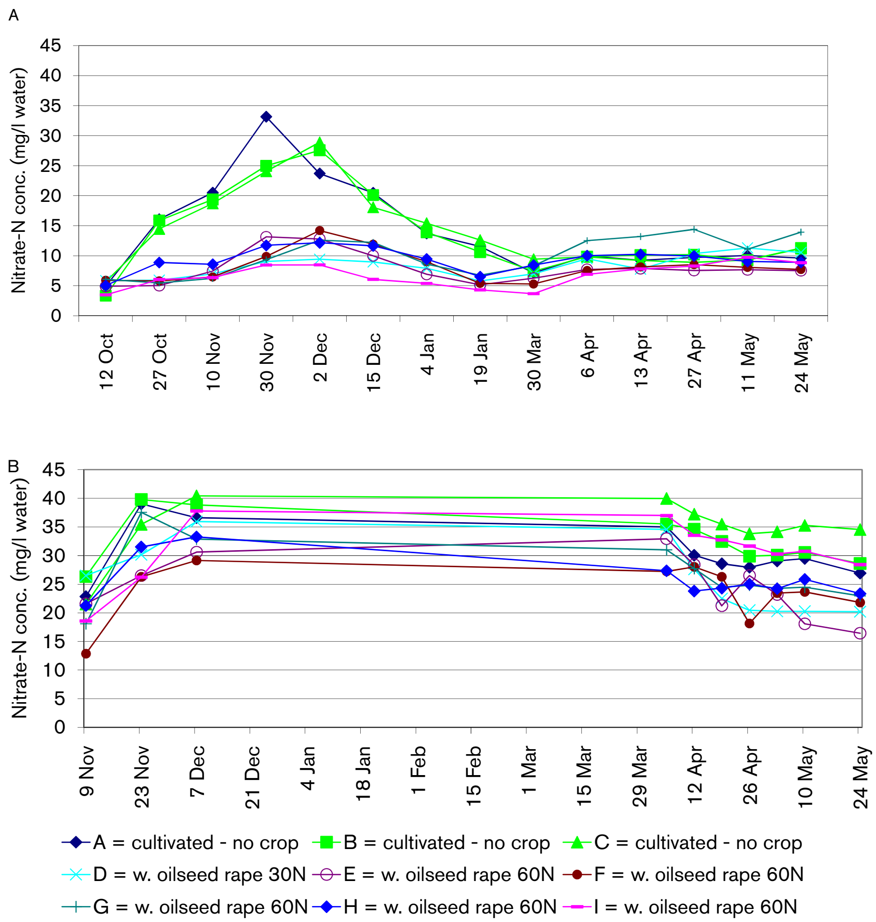

Figure 4. Nitrate concentration in soil water (measured by ceramic suction cups) from July to June in two experiments on a sandy soil at Götala a) 2004/2005 (mild winter) and b) 2005/2006 (cold winter). Winter oilseed rape was sown in August in treatments D-I and in A-C there was no crop after soil cultivation in August. The soil was not cultivated in A-C 2005/2006. The absence of data during winter 2005/2006 is explained by temperatures below 0°C. Due to this, the water in the plastic tubes connected to the ceramic cups was frozen (Paper IV).

After the cold winter of 2005/2006, with the main drainage in March and April, leaching was similar in treatments both with and without a crop: 37 N ha^{-1} and 44 kg N ha^{-1}, respectively (Paper IV). The reason was probably partly due to a dry autumn with low drainage and partly because there was no soil tillage in August in the treatments without a crop. Furthermore, in November, nitrate concentrations were high in soil water probably due to N mineralisation in soil when rewetted after a dry period (Figure 4b). Concentrations remained high until spring, as the soil was frozen from December to March. In addition, the thick snow cover that began to melt in mid-March. This resulted in high overall N leaching during March and April in all treatments. Cold winters with deeply frozen soils reduce N leaching, because of increased surface runoff during snowmelt that reduces water percolation through the soil profile (Gustafson, 1983). Although no N leaching was identified during the cold winter period, the enhanced N losses in March and April appear to contradict earlier findings. The reason appears to be the high coarse sand content of the subsoil in combination with comparatively thick snow cover that protected the soil from freezing below a superficial level. Consequently, excess water might have percolated rapidly through the sand soil layers at snowmelt and thawing.

The N lost during winter from above-ground parts of the winter oilseed rape due to frost was 24 kg N ha^{-1} and corresponded to the increase in soil mineral N from late autumn to early spring. This indicated a contribution of N from decaying leaves during drainage in March and April. The high N concentration in the leaves (4% of dry matter) in late autumn indicated organic N could easily have been released during decomposition. Similar amounts of N loss in biomass over winter due to frost are reported by Dejoux et al. (2000), who through a N^{15} technique, determined that the decomposition of leaves was synchronised to crop N uptake during early spring. However, with high drainage flows in March and April, as after the cold winter of 2005/2006, mineralised N from leaves may be partly lost instead of being taken up again by the crop when growth restarted after the winter.

N leaching under winter oilseed rape was high in spring after the cold winter of 2005/2006. The reason could be that N mineralisation rate on the sandy soil was high when crop uptake was low in late autumn. In the cold winter of 2005/2006, N leaching was 17 kg N ha^{-1} higher than in the mild winter of 2004/2005, despite lower drainage in 2005/2006 (130 mm) than 2004/2005 (214 mm). Thus, measures for counteracting leaching from all light-textured soils with high mineralisation potential need to be considered for all areas and not just those dominated by wet and mild winters.

Soil mineral N from spring to harvest of winter oilseed rape

In Sweden, spring N fertilisation of winter oilseed rape is done as soon as possible at the beginning of growth (March), and usually as a split application, with the second application 3-4 weeks later at stem elongation. During the growing season, soil mineral N decreases to its lowest value, after maximum N uptake, just after flowering (Razoux-Schultz, 1972). Soil mineral N then increases again until ripeness (Paper IV). In the experiments, the increase was on average 56 kg N ha^{-1} after winter oilseed rape (fertilised in spring), 24 kg N ha^{-1} after peas, and 10 kg N ha^{-1} after oats (Paper IV; Figure 5). Thus, the increase was higher for oilseed rape and peas than for oats and explained the higher amounts of soil mineral N at harvest. Soil mineral N was 49 higher at harvest of oilseed rape and 8 kg N ha^{-1} higher at harvest of peas at Götala (Paper IV) and 24 and 16 kg N ha^{-1} higher, respectively, in the trials in Skåne (Paper I).

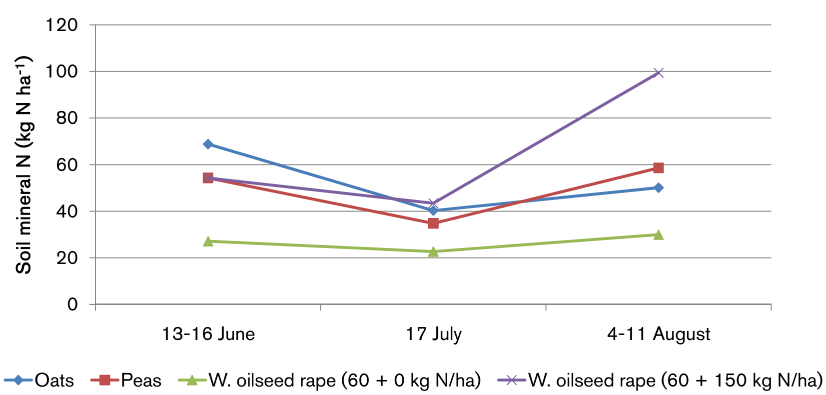

Figure 5. Soil mineral N (0-90 cm) after flowering of oilseed rape and until ripeness of winter oilseed rape (fertilised with 60 kg N ha^{-1} at sowing + 0 or 100 kg N ha^{-1} in spring), oats (fertilised with 100 kg N ha^{-1}) and peas (0 kg N ha^{-1}). Averaged data from the two experiments in Paper IV.

Soil mineral N at harvest may be affected by excess N fertilisation of spring to winter oilseed rape. N rates above 100 kg N ha^{-1} to winter oilseed rape increased soil mineral N by a rate of 0.3 per kg fertiliser N in both experiments (Paper IV: Figure 6b). Similarly, Beaudoin et al. (2005) describe the relationship between soil mineral N at harvest of oilseed rape and excess fertiliser N through a linear function with a slope of 0.4. For N rates below optimum, the data were fitted to a plateau.

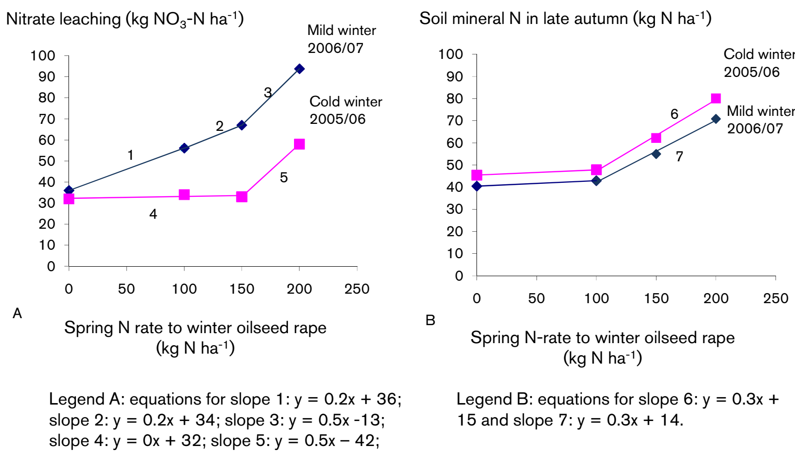

Figure 6. Relationship between spring fertiliser N rates to winter oilseed rape and a) N leaching during autumn and winter under subsequent winter wheat and b) soil mineral N in late autumn (Paper IV).

N dynamics during autumn and winter after winter oilseed rape

Much of the increase in soil mineral N in late autumn after oilseed rape and peas, compared with after oats, had already accumulated in soil until ripening of oilseed rape (Papers I and IV). Soil mineral N at harvest was 53 kg N ha^{-1} after oilseed rape, 45 kg N ha^{-1} after peas and 29 kg N ha^{-1} after oats (Paper I), which corresponded to 78% of the soil mineral N in late autumn after oilseed rape, 64% after peas and 70% after oats. This difference persisted until late autumn, as the net addition of soil mineral N between harvest and late autumn was 15 kg N ha^{-1} after oilseed rape and oats and 20 kg N ha^{-1} after peas. On the sandy soil at Götala, the greater amounts of soil mineral N at harvest of winter oilseed rape and peas, than after oats, levelled out by late autumn, probably due to drainage and leaching (Paper IV). However, soil mineral N was at the same high level in late autumn as at harvest, possibly due to N mineralisation after harvest compensating for N leaching and other losses.

Larger amounts of soil mineral N in late autumn after both oilseed rape and peas generally increased N leaching when the subsequent winter was mild (2006/2007), with drainage from autumn until early spring (Paper IV). N leaching for the total drainage period in the milder winter was similar under winter wheat after optimally fertilised winter oilseed rape and peas, 67 and 63 kg N ha^{-1}, respectively. N leaching was 22 kg N ha^{-1} (oilseed rape) and 18 kg N ha^{-1} (peas) larger than after oats. After the dry autumn and the cold winter of 2005/2006 with frozen ground, the main drainage occurred in March and April and there were no significant differences ($p<0.05$) in leaching between the previous crops.

The highest rate of N to oilseed rape (200 kg N ha^{-1}), which was 50 kg N ha^{-1} above the optimum N rate, caused the highest nitrate concentrations in soil water in both winters (Figure 7). In the mild winter, the greatest N leaching was 94 kg N ha^{-1} and in the cold winter 58 kg N ha^{-1}. This was 49 kg N ha^{-1} more than after oats in the mild winter and 22 kg N ha^{-1} more than after oats in the cold winter. The increase in N rate from 150 to 200 kg N ha^{-1} enhanced N leaching by 26 kg N ha^{-1}, giving a rate of 0.5 kg leached N per kg fertiliser N in both experiments (Figure 6a). Excess N fertilisation to winter oilseed rape caused higher soil mineral N in late autumn than in the other treatments. As no drainage occurred during autumn and the ground was frozen from December until March, the high levels of soil mineral N and high nitrate concentrations in the soil water remained until early spring. Consequently, this caused substantial N leaching when spring drainage occurred in March and April (Figure 7a).

For the cold winter in 2005/2006, N leaching under wheat was 42 kg N ha^{-1}, whereas 58 kg N ha^{-1} leached under wheat during the mild winter in 2006/2007. The nitrate concentrations in soil water during drainage were similar in both experiments and ranged from 10 to 55 mg nitrate-N L^{-1}. Therefore, the reason for higher leaching during the mild winter was probably due to the drainage volume being almost double.

N leaching under winter wheat after oilseed rape was 61 kg N ha^{-1} in the mild winter and 36 kg N ha^{-1} in the cold winter. This was, for a mild and cold winter, 41 kg N ha^{-1} and 16 kg N ha^{-1}, respectively, greater than leaching under winter oilseed rape (20 kg N ha^{-1}) during the mild winter.

However, N leaching under winter wheat after oilseed rape during the cold winter was similar to leaching under oilseed rape (37 kg N ha^{-1}) during the cold winter. Thus, our results showed that there are generally a risk for enhanced leaching under winter wheat after oilseed rape. In addition, in early spring after a cold winter there was a risk of enhanced leaching under both wheat and oilseed rape.

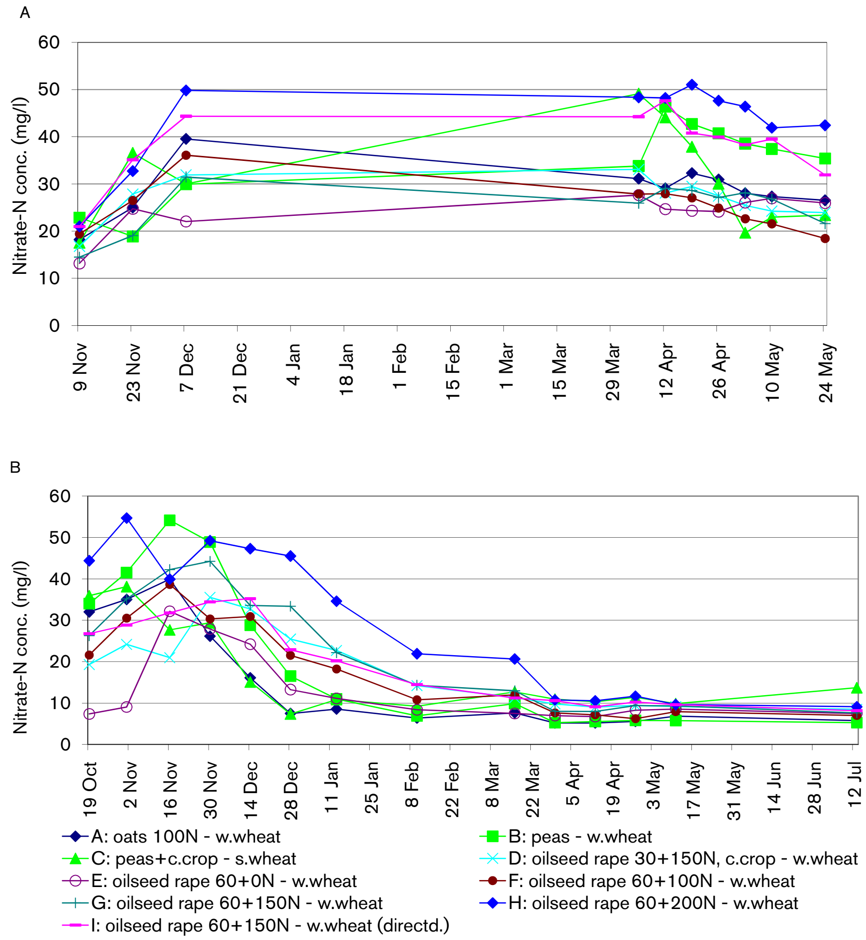

Figure 7. Nitrate concentration in soil water (measured by ceramic cups) from July to June in two experiments on a sandy soil at Götala a) 2005/2005 (cold winter) and b) 2006/2007 (mild winter) with winter wheat in all treatments after winter oilseed rape, peas and oats, except in C with spring wheat. Undersown catch crops (c. crop) after peas and oilseed rape in C and D. Direct drilled (directd.) winter wheat in I. The absence of data during winter 2005/2006 is explained by temperatures below 0°C (Paper IV).

The increased risk of N leaching during the drainage period after harvest of winter oilseed rape, compared with the autumn and winter after sowing the oilseed rape agrees with findings from other studies (Sieling et al., 1997; Sieling and Kage, 2006). The amount of N leached under winter wheat at Götala (Paper IV) was generally high for Swedish conditions. However, similar amounts were found on another sandy soil, in this case in the maritime climate in southern Sweden and with and without dairy slurry application, where annual leaching was on average 59-80 kg N ha^{-1}, as measured over five years (Torstensson & Aronsson, 2000).

The relationship between N fertilisation to cereals and leaching under subsequent cereal crops is described in several studies (Simmelsgaard & Djurhuus, 1998; Lord, 1992; Bergström & Brink, 1986). The conclusion that the slope of the curve is smaller at rates below optimum fertilisation levels and that it becomes increasingly steeper at above-optimum levels, appears reliable. This also accounts for N leaching after winter oilseed rape and is related to the amounts of soil mineral N in late autumn (Figure 6).

Impact of crop residues on N dynamics during autumn and winter

After harvest of winter oilseed rape and peas in Sweden, it is common practice to incorporate the residues during seedbed preparation for the subsequent crop. The decomposition of below-ground and incorporated above-ground residues of oilseed rape and peas affected N dynamics in soil, and therefore, influenced the risk of N leaching and soil N supply to the subsequent crop (Paper III). The incubation study of Paper III indicated that incorporated above-ground residues did not contribute to the enhanced soil mineral N in late autumn after oilseed rape and peas. Thus, the risk of N losses during winter was not increased. Conversely, residues of oilseed rape, peas and oats reduced the amount of soil mineral N available for leaching due to the immobilisation of 7-14 kg N ha^{-1} during the main drainage period (October-March).

Smaller amounts of soil N were immobilised than determined from investigations in warmer regions (Justes et al., 1999), and were probably due to less straw being incorporated (due to smaller yields) and by the cooler winter climate in Sweden, which slows soil microbial processes. However, the incubation study and the corresponding field trials (Paper III) demonstrated that N mineralisation in the soil profile exceeded N immobilisation, despite incorporation of the crop residues. Thus, larger amounts of soil mineral N accumulated in the soil during autumn and winter after oilseed rape and peas, rather than after oats. Soil tillage during incorporation of the crop residues also stimulated N mineralisation (Stenberg *et al*., 1999).

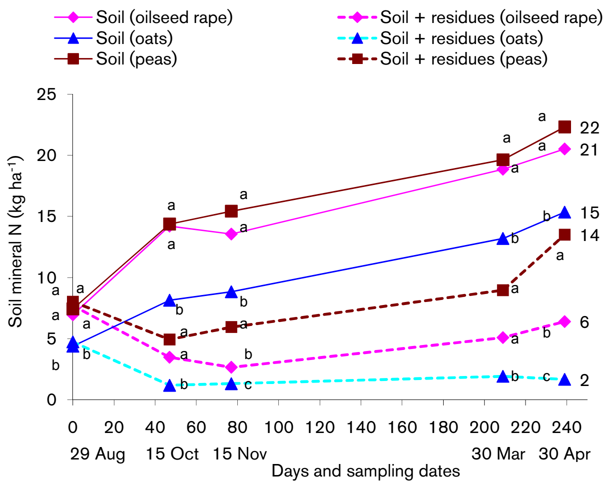

Figure 8. Accumulation of soil mineral N during 240 days of incubation (corresponding to 7cm of topsoil) under field temperature conditions with and without above-ground crop residues. Soil and crop residues were collected after harvest of winter oilseed rape, oats and peas in four field experiments. The letters (a and b) denote significant differences ($p<0.05$) between the preceding crops on a particular sampling date and within a soil treatment: soil or soil + residues (Paper III).

Under field conditions in Sweden, only a small volume of the topsoil (approximately 25%) is in contact with and directly influenced by the above-ground residues (Paper III). Therefore, most of the topsoil (75%) is only in contact with below-ground residues, such as roots and rhizodeposits. In soil with only root residues, the rates of net N mineralisation during early autumn were higher for oilseed rape and peas than for oats. This contributed to the already elevated soil mineral N at harvest of oilseed rape and peas, and these differences persisted until spring (Figure 8). Net N immobilisation in the fraction of soil containing above-ground residues enhanced these differences, as immobilisation was greatest with oat residues and did not decrease during autumn, as it did with oilseed rape and pea residues (Figure 8). Net N immobilisation decreased more rapidly in soil with above-ground residues of peas than with oilseed rape and could explain the greater increase of soil mineral N in the field trials during autumn after peas than after oilseed rape (Papers I and III). This indicated that if no drainage and losses occur during autumn and winter, there is a higher risk of leaching in spring after peas than after winter oilseed rape. This was confirmed by Paper IV, where nitrate concentrations in soil water during spring were higher and there was a tendency for larger leaching after the cold winter after peas, than after optimally fertilised oilseed rape (Figure 7a).

N dynamics after spring under subsequent winter wheat

Soil mineral N decreased from late autumn to early spring but was still 10 kg N ha^{-1} higher after oilseed rape and 6 kg N ha^{-1}higher after peas, than after oats (33 kg N ha^{-1}; Paper I). On the sandy soil at Götala (Paper IV), soil mineral N in early spring also decreased but there were no differences between the crops, possibly due to the high N leaching during the milder winter. Thus, the impact of N losses over winter on the sandy soil was not just environmental, but reduced mineral N availability in early spring for the wheat crop.

During the main growing season (early spring to maturity), net N mineralisation was 19 kg N ha^{-1} higher in wheat after oilseed rape and 13 kg N ha^{-1} higher in wheat after peas, than after oats. This constituted the majority of improved soil N supply after these crops (Paper I). Net N mineralisation represented 83% of the uptake of soil N at harvest for wheat, in treatments without N fertilisation, after oilseed rape, 82% of N uptake at harvest for wheat after peas, and 86% of N uptake at harvest for wheat after oats. The additional contribution of overwintering soil mineral N, calculated as the difference between the uptake of soil N at harvest and net N mineralisation, constituted a smaller proportion (17% after oilseed rape, 18% after peas, and 14%, after oats). This confirmed other findings (Delin & Lindén, 2002) that the small amounts of soil mineral N remaining in early spring in southern Sweden have a minor impact on the need for N fertilisation. The N uptake at harvest of winter wheat without N fertilisation was 118 kg N ha^{-1} after oilseed rape, 112 kg N ha^{-1} after peas, and 92 kg N ha^{-1} after oats. Thus, the residual N effect was 26 kg N ha^{-1} after winter oilseed rape and 20 kg N ha^{-1} after peas.

During the entire main growing season, the uptake of soil N by winter wheat was higher after oilseed rape and peas than after oats (Figure 9). The increased N uptake ranged between 8 and 17 kg N ha^{-1}, with the highest amounts being observed on 30 May after peas and on 1 August after oilseed rape.

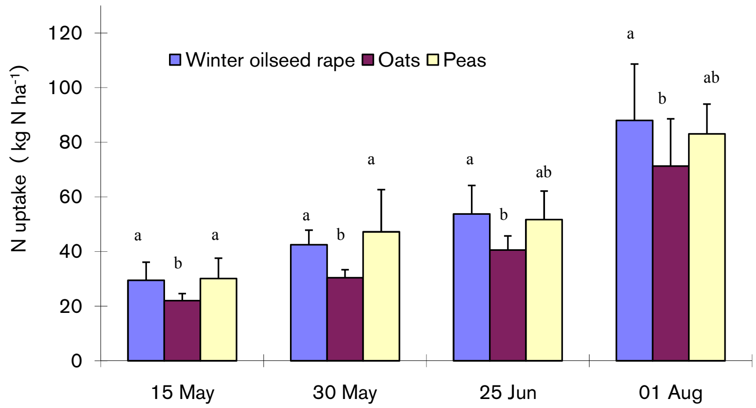

Figure 9. N uptake of winter wheat (without N fertilisation) during the main growing season after winter oilseed rape and peas compared with after oats. The sampling dates corresponded to GS31 (15 May), GS37-41 (30 May), GS61-70 (25 Jun) and GS90 (01 Aug) (Paper I).

The effect of the previous crops on the uptake of soil N by winter wheat during the growing season (Paper I) could be explained by the results of the incubation study (Paper III: Figure 8). The larger N uptake at earlier stages after peas, rather than after oilseed rape and oats (Figure 9), might be related to the earlier decline in N immobilisation in soil with above-ground residues of peas, as pea residues have a lower C/N ratio (Jensen *et al.*, 1997).

In soil with oat residues (Paper III), no increase in soil mineral N was observed at the end of the incubation period in early spring (30 April). Consequently, N immobilisation in soil with oat residues could have continued during the main growing season of winter wheat, whereas it ceased in soil with oilseed rape and pea residues. If the lower level of net N mineralisation in soil incubated with above-ground residues of oats (Figure 8) persisted during the growing season, this could explain the smaller N uptake in winter wheat after oats than after oilseed rape and peas (Paper I).

Measures for reducing N leaching

Application of fertiliser N in spring to winter oilseed rape at the optimum N rate, compared with fertilising 50 kg N ha^{-1} above optimum, reduced leaching by 40% (26 kg N ha^{-1}) in the subsequent winter period (Paper IV).

The optimisation of the spring N rate to winter oilseed rape was thus an effective measure to decrease leaching in both mild and cold winters.

However, the effect on N leaching could be improved with perennial ryegrass as a catch crop undersown in spring and allowed to grow after harvest of the winter oilseed rape until mid-September, when wheat was established. This catch crop reduced leaching by 20% (12 kg N ha^{-1}) during the mild winter (Paper IV; Figure 7b). Thus, the increased N leaching of 22 kg N ha^{-1} after oilseed rape fertilised at optimum N rate (150 kg N ha^{-1}), compared with after oats, was reduced by half. The N uptake of the ryegrass catch crop up to mid-September after oilseed rape was 19 kg N ha^{-1} and the N uptake by the subsequent winter wheat was 9 kg N ha^{-1} up to November. During the cold winter, N leaching was not affected by the catch crops because there was no drainage until early spring (Figure 7a).

An undersown catch crop grown until November after harvest of the peas (followed by spring wheat) reduced N leaching by 24% (14 kg N ha^{-1}) during the mild winter, thus to the same level as after oats. During the cold winter, there was no reduction. Due to N uptake of 30 kg N ha^{-1} by the catch crop during autumn after peas, soil mineral N in late autumn decreased by 17 kg N ha^{-1}, compared with no catch crop.

A catch crop undersown in spring in winter oilseed rape and peas has the advantage of being able to take up unused soil mineral N from the time of harvest of the crops, whereas a catch crop sown after harvest has little effect. This is especially important in northerly regions such as south and central Sweden, where there is a short period between harvest of winter oilseed rape (August) and sowing of winter wheat (September).

Torstensson and Aronsson (2000) report a 35-60% reduction in N leaching for an undersown ryegrass catch crop grown until early spring after spring cereals (with and without application of pig slurry) than in soil ploughed in September without a catch crop. If a catch crop undersown in spring cereals is ploughed down in late autumn (November), the effect is about the half that for incorporation at spring ploughing (Stenberg, 1999). This can be compared with the results presented in Paper IV, where N leaching was reduced by 20-24% when ryegrass was grown after winter oilseed rape until mid-September and after peas until early November. The catch crop did not reduce the yield of the subsequent winter wheat.

Direct drilling of winter wheat in September after winter oilseed rape (at the 150 kg ha^{-1} N rate) did not significantly reduce leaching compared with conventional sowing of winter wheat after oilseed rape; although there was a tendency ($p = 0.10$) for leaching to be 12% lower (8 kg N ha^{-1}) during the mild winter (Paper IV). Soil mineral N in direct-drilled plots in late autumn before the mild winter was similar to the amounts in the other treatments with winter wheat, indicating that direct drilling stimulated soil N mineralisation to the same extent. The reason for this might be that the direct drill used was equipped with a cultivating toolbar and had powerful seed coulters, giving a soil tillage effect through the coulters themselves. Direct drilling in Sweden is mainly performed in this way today. The results from the mild winter agreed with findings by Constantin *et al.* (2010) from north France, where no-tillage decreased leaching by 6 kg N ha^{-1} yr^{-1}, compared with conventional tillage. In addition, this effect on leaching was smaller than the effect of catch crops.

Generally, the results emphasised the importance of accurately adjusting fertiliser levels and strategies. Considering overwintering soil mineral N at spring fertilisation of winter oilseed rape has little relevance in Sweden, as the amounts are generally small (Delin & Lindén, 2002; Papers I and IV). However, increased N uptake in autumn by winter oilseed rape reduces optimum N rate in spring (Henke *et al.*, 2009). Thus, through considering N uptake in late autumn in the calculation of the spring N rate is one way of optimising the spring N rate. Other possibilities include promoting more N uptake during autumn through earlier sowing (Dejoux *et al.*, 2003) and in principle through larger N fertilisation. However, high N rates at sowing cannot be recommended due to the risk of N leaching.

Break crop effects on yield and optimum N rates

The increased yield of winter wheat after winter oilseed rape and peas could not be compensated by increased N fertilisation (Paper I). Therefore, it was not purely a residual N effect, which agrees with several other studies (Jensen and Haahr, 1990; Christen et al., 1992). For instance, plant pathological factors may be involved. For the nine sites (Paper I) with varying crop rotation histories, the average increased grain yield was 700 kg ha^{-1} at Opt-N fertilisation and Opt-N was 25 kg N ha^{-1} lower for winter wheat after winter oilseed rape and 15 kg N ha^{-1} for winter wheat after peas, than after oats.

The higher yield potential of wheat after winter oilseed rape and peas than after oats requires more N and increases Opt-N, whereas more soil N available for the wheat crop reduces the rate (eqs. (i) and (ii) in Table 1). At these nine sites, the average increase in soil N supply was sufficient to cover both the yield increase and lower the optimum N rate.

Table 1. *Relationship between economic optimum rate of fertiliser nitrogen (Opt-N rate, kg N ha^{-1}) expressed as y, the dependent variable, and grain yield level (kg ha^{-1}) expressed as x_1 and total crop uptake of soil N (kg N ha^{-1}) expressed as x_2, or net N mineralisation during the growing season (kg N ha^{-1}) expressed as x_3, as independent variables. The relationships are expressed as adjusted coefficients of determination (R_a^2), n = 27*

Eq.	Relationships between Opt-N rate (y) and…	R_a^2	
i	Grain yield (x_1) and total crop uptake of soil N (x_2)	0.69*	$y = 129 + 0.014\ x_1 - 1.14\ x_2$
ii	Grain yield (x_1) and net N mineralisation (x_3)	0.69*	$y = 104 + 0.015\ x_1 - 1.24\ x_3$

* $P < 0.001$.

These results agreed with those of Engström and Gruvaeus (1998), where winter wheat after winter oilseed rape enabled an average yield increase of 1000 kg ha^{-1} and 34 kg ha^{-1} lower Opt-N, compared with after oats. However, in two of the trials (sites 3 and 5) in Paper I, Opt-N to wheat after oilseed rape was higher than after oats. In one trial (site 5), Opt-N to wheat was higher after peas than after oats (Figure 10). At site 5, soil N supply was lower after oilseed rape and peas than after oats. The reason for this is unclear, but optimum N yield was higher after oilseed rape and peas and could explain the increased Opt-N. Excluding these three trials, the average Opt-N decreased by 37 kg N ha^{-1} after winter oilseed rape (n =7) and by 29 kg N ha^{-1} after peas (n =7), which was in agreement with results from Denmark (Knudsen *et al.*, 2002).

However, in the experiments at Götala (Paper IV), the increases in wheat yield after winter oilseed rape was 700 kg ha^{-1} and 300 kg ha^{-1} after peas, compared with after oats, and the residual N effects (increased uptake of soil N at harvest) were small. This was probably due to the cropping history (*e.g.* with potatoes) and to the large N mineralisation potential of the soil that probably blurred the differences. The large variation observed in yield increases and reduced optimum N rates to winter wheat after oilseed rape and peas (Paper I and IV) indicates that the residual N effect should be estimated at individual sites rather than using general recommendations based on mean values (Figure 10).

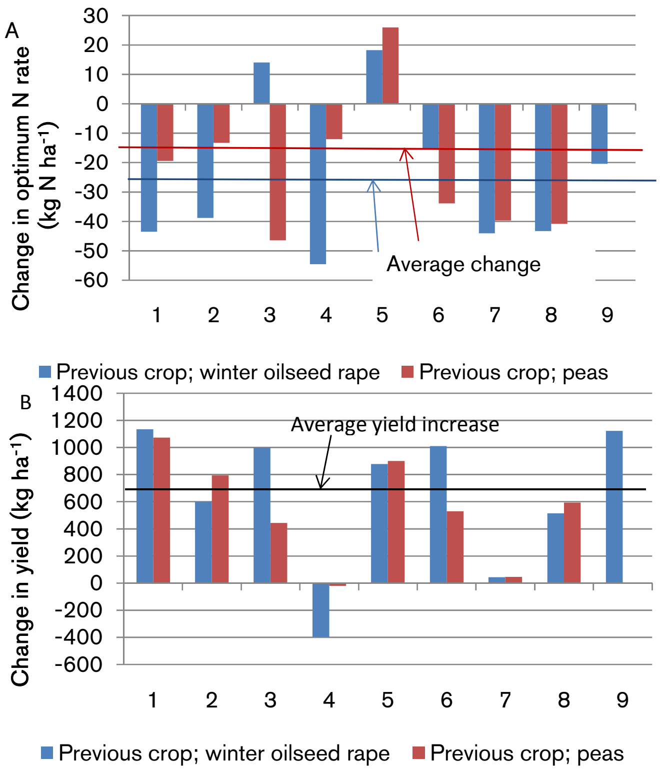

Figure 10. The effect of winter oilseed rape, peas and oats on a) optimum N-rate and b) yield increase of subsequent winter in nine field trials in southern Sweden (Paper I).

N fertilisation model for winter wheat based on break crop effects

The optimum N rate to a cereal crop can be seen as a function of:

- 1) Yield level at optimum N fertilisation (affected by the previous crop) and its corresponding need for N, and
- 2) Plant-available soil N (affected by soil and previous crop).

If the yield level increases at the optimum, *e.g.* when growing winter wheat after peas or oilseed rape, the need for fertiliser N will increase, and *vice versa* (Table 1). If plant-available soil N increases, the demand for fertiliser N will decrease. Thus, the change in plant-available soil N should be deducted from the amount of fertiliser N required for changing yield level. The difference indicates the change in optimum N rate. However, the effect of residual N should first be adjusted for the N use efficiency of the mineral fertiliser used and then, recalculated as corresponding fertiliser N.

The prediction of yield level and soil N mineralisation after previous crops is important for precise estimation of Opt-N, as indicated in the regression analysis (equations (i) and (ii) in Table 1; Paper I). To estimate the yield level of a field, the farmer has to rely on previous experiences of the field with different preceding crops. If a yield increase of 700 kg ha^{-1} at Opt-N (the average in Paper I) can be expected after break crops such as oilseed rape and peas, this would require about 10 kg N ha^{-1} more fertiliser N, according to equations (i) and (ii). In this study, the residual N effect on wheat after winter oilseed rape was 26 kg ha^{-1} and 20 kg N ha^{-1} after peas, compared with after oats (Figure 9). This corresponds to 40 kg ha^{-1} and 27 kg N ha^{-1} of fertiliser N, assuming an efficiency of 65% N use, as calculated from results published by Delin et al. (2008). The N fertilisation rate (including yield increase) to wheat should then be reduced by 30 kg N ha^{-1} after oilseed rape (40 minus 10 kg) and 17 kg N ha^{-1} after peas (27 minus 10 kg). This was similar to the reduction in the average Opt-N (25 kg N ha^{-1} after oilseed rape and 15 kg N ha^{-1} after peas.

However, from equations (i) and (ii), fertiliser N was equal to 1.14 times total N uptake at maturity or 1.24 times net N mineralisation during growing season, corresponding to smaller N amounts than required for the 65% N efficiency used in the previous calculation. The N use efficiency in the nine trials (Paper I) was high, and probably due to good cultivation practices and normal rainfall during the growing season, indicating no large N losses. In the calculation above, we included conditions with higher spring and summer precipitation according to present climate trends in central Sweden, and soils with higher clay contents (30-50%) typical for the region, with risk of larger denitrification and thus greater N losses and less efficient N use. Moreover, we included a higher incidence of plant diseases due to crop rotations in central Sweden being dominated by cereal crops, which also decreases N use efficiency.

In addition, the grain protein content could be considered together with the yield. However, in the trials presented in Paper I, the wheat grain protein content was not affected by oilseed rape and peas, compared with oats. This could be due to comparatively large yield increases at all N fertilisation levels, which depleted the increased soil N. In other investigations (Engström & Gruvaeus, 1998; Angus *et al.*, 1991; Paper IV), the protein content of winter wheat was inconsistently influenced by preceding oilseed rape and peas, with both reduced and increased concentrations.

Temporal distribution of N fertilisation in winter wheat

Increased N uptake in wheat during the growing season after oilseed rape and peas in conjunction with increased yield indicated improved soil N availability after these break crops (Paper I). The increased uptake of plant-available soil N was evenly distributed during the growing season (Figure 9), which should have promoted the development of most yield components. Increased N uptake in wheat from early stages to maturity has a positive effect on several yield components (shoots/m^2, ears/m^2, grains/spike, spikes/ear), therefore increasing the yield potential of wheat (Darwinkel, 1983; Siddique *et al.*, 1988). This agreed with the finding by Kirkegaard *et al.* (1997) that differences in grain yield cannot be accounted for in terms of any single yield component, as all yield components of wheat after wheat had lower values than those of wheat after rapeseed or peas. Similar results were obtained by Angus *et al.* (1991), who demonstrated that plant density at GS15 and growth and N uptake at GS30 were larger in wheat after winter oilseed rape. Moreover, increased yield positively related to increased spike density and grains per spike, but negatively related to weight per kernel. However, the effect of early improvements in growth and yield components on grain yield may be influenced by water availability after anthesis (Kirkegaard et al. 1997). No yield benefits were observed at sites where little rain fell after anthesis, despite more N in above-ground biomass being available at anthesis.

Shoot density of winter wheat was generally higher after oilseed rape and peas than after oats, probably due to the higher soil mineral N supply during autumn and early spring (Paper I). Therefore, application of fertiliser N in spring during tillering stages (before GS30) should not be required (Paper II). N applications in spring, with the intention to make fertiliser N available for the crop 2 to 3 weeks before GS30 or at or just after GS30, had the same impact on yield of winter wheat, with shoot densities of 720-770 shoots m^{-2} in early spring (Paper II). The effect of N applications at or just after GS30 on shoot survival probably balanced the positive effect of earlier applications on shoot number, as the number of ears per m^2 was the same in all treatments. However, there were more ears, lower thousand grain weight and greater shoot density in treatments with the earliest application of N. Excessive N availability early in the season can reduce thousand grain weight, due to larger amounts of tillers competing for moisture and nutrients, thus, leading to inadequate grain filling (Gooding & Davies, 1997).

Conclusions and future work

N fertilisation strategies for winter wheat after winter oilseed rape and peas

Break crop effects of winter oilseed rape and peas on winter wheat included increased yield, increased plant-available soil N, and reduced Opt-N compared with growing wheat after oats (Paper I). Considering the reduced Opt-N for winter wheat after winter oilseed rape and peas (Table 1) and using the N fertilisation model presented should help counteract the increased risks of N leaching after winter wheat arising from excessive N fertilisation.

The variation between sites in terms of yield increase, residual N effects, and Opt-N illustrate the uncertainty of using average values for these when deciding the N rate to winter wheat. The variations in either the net N mineralisation during the main growing season or in the crop uptake of plant-available soil N, combined with the variation in yield levels at optimum, explained 70% of the variation in Opt-N rates (Paper I). Predicting grain yields and net N mineralisation or the sum of the plant-available soil N during the growing season is a challenge because methods for predicting net N mineralisation is not readily available.

However, plant-available soil N at different growth stages during the main growing season of winter wheat, at least at maturity, can be estimated by the farmer through determining crop uptake of soil N in small test plots without N fertilisation. These plots should be distributed over the field with the desired previous crop and correspond to the method used in Paper I for determining crop uptake of soil N. The values obtained after several years with such test plots should be more accurate for the site used than general recommendations are. Although actual soil N conditions in the field are influenced by prevailing weather patterns and cannot be predicted with accuracy, such historical data may help to calculate the N rate. Moreover, the application of split N doses and optical sensors can help to adjust N fertilisation rates to the temporal and spatial changes in soil N supply and crop growth during the growing season, which are otherwise difficult to estimate.

Utilisable soil mineral N in early spring constitutes only a small proportion of the total supply of plant-available soil N due to N losses during autumn and winter. The increased net N mineralisation during the main growing season was the main reason for greater soil N uptake of winter wheat after oilseed rape and peas (Paper I). This increase in soil N supply during the main growing season of winter wheat after oilseed rape and peas was evenly distributed over time, indicating N applications before GS30 are not needed, at least not in high-density crops (Paper II). The avoidance of early N applications should reduce cost and the associated risk for N losses for the farmer.

Future research should focus on estimations of Opt-N based on residual N-effects and expected yield at individual sites, including within-field variations, rather than the current use of general recommendations based on mean values.

Reducing N leaching after winter oilseed rape and peas

The results demonstrated the high N uptake potential of winter oilseed rape in autumn and that it exceeds its requirements for optimum yield (Paper IV). The high N uptake reduced mineral N levels in the soil and thus the risk for leaching. Increasing the N fertilisation rate from 30 to 60 kg N ha^{-1} at sowing of winter oilseed rape did not increase N leaching nor did the yield increase. This implies that the risk for increased N leaching after a moderate excess of fertiliser N applied at establishment of winter oilseed rape can be controlled, but only if the oilseed rape crop develops well in the autumn. Since there is a risk that crop growth and N uptake during autumn can be reduced during autumn by *e.g.* late sowing, dry periods or low temperatures, excessive rates of fertiliser N at sowing can still not be recommended, especially since the effect on the yield is limited. Although, early N fertilisation (at establishment) to give time for a large N uptake and promotion of N uptake during autumn through early sowing is recommended.

The increased risk of N leaching after harvest of winter oilseed rape and peas (Paper IV) demonstrates the need for measures to be taken.

Optimisation of the spring rate of fertiliser N to winter oilseed rape was the most effective measure for reducing leaching after winter oilseed rape in both mild and cold winters. Perennial ryegrass as a catch crop undersown in spring had good potential for reducing leaching after winter oilseed rape and peas in a mild winter, despite only growing until mid-September, when winter wheat was sown. Direct drilling of winter wheat after winter oilseed rape only had a small effect if any on N leaching, and therefore it can only be recommended for reducing the cost of establishing the subsequent crop.

The results showed that long frost periods with frozen soils impede N leaching, but also that there was a risk of large N leaching from a sandy soil in early spring after a cold winter, regardless of crop (Paper IV). One contributing factor is that often soil only freezes superficially under a long-lasting snow cover. Subsequent snowmelt can give rise to abundant spring drainage, resulting in amounts of N leaching as in mild winters. However, regardless of the prevailing conditions (mild or cold winter), temporal drainage and leaching patterns, measures for reducing the risk for N leaching are important (Paper IV).

The incorporated above-ground crop residues of winter oilseed rape and peas may immobilise 7-14 kg N ha^{-1} during the main drainage period and does not contribute to an increased risk of N losses during winter (Paper III). However, incorporated crop residues only reduced the risk of N leaching in the small part of the topsoil where they are incorporated, whereas mineralised N accumulated in the rest of the soil. Therefore other supplementary measures, such as undersown catch crops and postponing tillage until spring, are necessary.

As the decline in net N immobilisation in soil with above-ground pea residues was faster than for the other residues, especially from late March to late April, an increase in soil N supply for the subsequent crop should be expected in spring (Paper III). This indicates a higher risk of N losses after peas in connection with heavy spring drainage (Paper IV). Therefore, winter oilseed rape is a more suitable crop after peas than winter wheat due to the higher N uptake in the autumn and early start of N uptake in spring.

Measures for preventing leaching after crops such as winter oilseed rape and peas should aim to reduce soil mineral N during autumn and winter through, for example, establishing catch crops and changing tillage practices. However, this will influence the residual N effects, such as utilisable soil mineral N in spring and net N mineralisation during the subsequent growing season. In Sweden, this requires further research on soil N transformations following winter oilseed rape and peas, in order to optimise

N fertilisation for a subsequent wheat crop. Current studies mainly focus on cereals preceding cereals.

Future studies should also consider the fate of N lost from frozen winter oilseed rape leaves under north European winter conditions, which in turn affects the spring N rate.

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