Soil Tillage Influences on Soil Mineral Nitrogen and Nitrate Leaching in Swedish Arable Soils

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Abstract

Leaching of nitrogen (N) is an unwanted effect of agriculture practices which contributes to eutrophication of surface waters. This thesis examined how soil tillage practices affect leaching losses of N from arable fields. This was done directly by measuring N in drainage water and indirectly by studying the dynamics of soil mineral N (SMN) within the soil profile and involved long-term and short-term studies of tillage of different timing and intensity. The impact of time of tillage in autumn on soil structure and crop yield was also examined.

It was found that adapting soil management and tillage to crop rotation in order to synchronise SMN with crop demand could substantially decrease leaching losses of N. Tillage effects on SMN were mainly attributable to interruption of N uptake in crops and weeds, rather than stimulation of N mineralisation. Timing of tillage proved to be important in this regard. In clay soils, however, delayed tillage in autumn (previously shown to reduce N leaching losses in coarse-textured soils) resulted in operations being performed when soil water content was higher than optimal, causing a poor tillage outcome and decreased yield. From the results it can be concluded that a reduction in N leaching by delaying autumn tillage may be achieved on lighter clay soils in warmer and moister areas of Sweden whereas the effects may be small on heavier clay soils.

The results indicated potential for further reductions in N leaching, especially in autumn-sown crops, by early sowing, a short time interval between tillage and sowing and undersowing of a catch crop in spring. SMN accumulation in winter wheat during autumn and winter was not influenced by tillage method. Therefore changing from conventional to reduced tillage or direct drilling of winter crops is unlikely to reduce overall N leaching losses. The importance of high biomass production during autumn and winter was identified and should be the main focus in strategies for mitigating N leaching losses from arable fields.

Keywords: Soil tillage, nitrogen leaching, soil mineral nitrogen, SMN dynamics, tillage timing, reduced tillage, catch crops, straw treatment

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Dedication

To my sister Hanna

Contents

List of Publications

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

I Å. Myrbeck, M. Stenberg, J. Arvidsson, T. Rydberg. (2012). Effects of autumn tillage of clay soil on mineral N content, spring cereal yield and soil structure over time. *European Journal of Agronomy* 37, 96-104.

II Å. Myrbeck, M. Stenberg, T. Rydberg. (2012). Establishment of winter wheat – Strategies for reducing the risk of nitrogen leaching in a cool-temperate region. *Soil & Tillage Research* 120, 25-31.

III Å. Myrbeck, J. Arvidsson, T Keller. (2014). Effect of time of primary tillage on soil structure, grain yield and risk of nitrogen leaching in two Swedish clay soils. *Acta Agriculturae Scandinavica, Section B – Soil & Plant Science* 64(1), 33-44.

IV Å. Myrbeck, M. Stenberg. (2014). Changes in N leaching and crop production as a result of measures to reduce N losses to water in a 6-yr crop rotation. *Soil Use and Management 30,* 219-230.

Papers I-IV are reproduced with the permission of the publishers.

The contribution of Åsa Myrbeck to the papers included in this thesis was as follows:

I Main author. Planned the analyses together with co-authors. Performed parts of the soil sampling, field analyses and laboratory analyses. Performed data analysis. Carried out the writing with the assistance of the co-authors.

II Main author. Planned the study together with co-authors. Planned the field experiments and the sampling and analyses. Performed minor parts of the sampling. Performed data analysis. Carried out the writing with the assistance of the co-authors.

III Main author. Performed soil sampling and soil physical analyses with some assistance. Performed data analysis. Carried out the writing with the assistance of the co-authors.

IV Main author. Was responsible for planning the field experiments and for the sampling and analyses. Performed data analysis. Carried out the writing with the assistance of the co-authors.

Abbreviations

CON	Conventional
N	Nitrogen
NH_4-N	Ammonium-N
NO_3-N	Nitrate-N
NTU	Nephelometric turbidity units
NUE	Nutrient use efficiency
OM	Organic material
PL	Lower plastic limit
SBD	Soil bulk density
SMN	Soil mineral nitrogen
SOM	Soil organic material

1 Introduction

Of all the nutrients used within food production, nitrogen (N) has the single largest effect on crop yields and also contributes most to environmental concerns and discussions (Roy *et al*., 2006). Contribution to eutrophication of surface waters is an unwanted effect of agriculture practices. This is following on N, together with phosphorus (P), being transported through the soil profile or over the soil surface to ditches and rivers and further into lakes and seas. The problem is especially troublesome in cold and humid regions, where large amounts of water percolate through the soil (Morecroft *et al*., 2000). In some areas, leaching losses of N also cause high levels of N in groundwater, which can result in unhealthy levels of nitrate (NO_3) in drinking water.

Research to identify measures to reduce agricultural non-point source pollution of N has been underway for some decades. However, in Sweden, as in the rest of Europe, agriculture is still reported to be one of the main contributors to excess N in surface waters (EU, 2006; Brandt *et al*., 2009). In Sweden, more than 40% of estimated anthropogenic loads of N to coastal waters originate from agricultural land (SEPA, 2006). In accordance with targets adopted by the Baltic Sea Action Plan (HELCOM, 2007) and OSPAR (OSPAR, 1992), aiming at improving the environmental status of the Baltic Sea and the north-east Atlantic, respectively, Sweden has reduced its estimated total N inputs to coastal waters (Blombäck *et al*., 2011; Stålnacke *et al*., 2014). However, the latest revision within the Helsinki Commission (HELCOM, 2013) involves a further reduction in Swedish contributions of 9240 ton N to the Baltic Sea from today to 2021, putting the agriculture sector under further pressure to achieve reductions.

Water quality management within the European Union (EU) is regulated by the EU Water Framework Directive (EU, 2006) and for the agriculture sector also by the EU Nitrate Directive (91/676/EEC). According to these regulations, Sweden has classified areas vulnerable to eutrophication. Extensive parts of the coast along southern Sweden, together with three large inland lakes, are classified as polluted or at risk of being polluted (Figure 1). Land areas from which water is transported to these water bodies are identified as ‘nitrate vulnerable zones’, where special actions must be taken to reduce NO_3 losses from agriculture. According to the Nitrate Directive, these zones have to be reviewed every four years and at present they include major areas of Swedish arable land used for commercial crop production (Figure 1).

Soil tillage plays a central role in agriculture, *e.g.* in the control of weeds and pests, especially in cropping systems dominated by monocultures. However, it is also one of the management factors affecting the magnitude of N leaching losses from arable land (*e.g.* Francis et al., 1995; Catt *et al.*, 2000; Mitchell *et al.* 2000; Thomsen, 2005; Askegaard *et al.*, 2011), an effect ascribed to increased amounts of leachable N in soil following tillage operations. Hence there is a need for knowledge on the impact of different tillage methods on N leaching. Such knowledge may be useful in the development of farming systems with limited negative impacts on surrounding waters.

Figure 1. Areas in southern Sweden vulnerable to eutrophication according to the EU Nitrate Directive. Coastal waters and lakes in southern Sweden identified as polluted or at risk of being polluted (blue marks): 1) Coastal waters along the Baltic Sea, 2) coastal waters along Kattegatt, 3) coastal waters along Skagerack, 4) Lake Ringsjön, 5) Lake Mälaren and 6) Lake Hjälmaren); and nitrate vulnerable zones (red marks). Data from the Swedish Board of Agriculture (SJV, 2011; SJV, 2014).

2 Aim

The overall aim of this thesis was to improve our understanding of how soil tillage practices affect leaching losses of N from arable fields, directly by measuring N in drainage water and indirectly by studying the dynamics of soil mineral N (SMN) within the soil profile. The work included long-term and short-term studies of tillage at different timing and intensity. An additional aim was to obtain information about the impact of time of tillage in autumn on soil structure and fertility.

Specific objectives, in the context of N leaching and SMN dynamics, were:

- To study the effects of shallow cultivation and/or direct drilling in relation to deeper mouldboard ploughing (Papers I, II, III and IV).
- To study the effect of timing of tillage for spring-sown and winter-sown crops (Papers I, II, III and IV).
- To quantify the effects of straw incorporation compared with removal (Paper I).
- To quantify the influence of sowing date on N uptake in winter wheat and thereby its capacity for reducing the amounts of SMN during autumn (Papers II and IV).
- To investigate the effects of combining several measures aimed at reducing N leaching within a cropping sequence (Paper IV).
- To study the long-term and short-term consequences of delayed tillage, as a measure for reducing N leaching, on soil structure and crop yield in clay soils (Papers I and III).

The main hypothesis was that leaching of N from arable fields can be reduced by choice of suitable tillage strategies. The results presented are mainly summarised from Papers I-IV, but some novel findings are also presented in the following chapters.

3 Background

3.1 Nitrogen leaching

The magnitude of N leaching losses varies greatly between agricultural systems and locations. According to estimates reported within HELCOM, average N leaching from Swedish arable land (all agricultural land, uncultivated pasture excluded) in 2009 was 18.7 kg ha^{-1}, varying from ~10 kg ha^{-1} in the north to 30-50 kg ha^{-1} in the south (Blombäck *et al.*, 2011). The lowest leaching rates occur in forest regions and in regions with low runoff rates and the highest in intensively cultivated agricultural areas in high precipitation regions of south-western Sweden (SEPA, 2008). Furthermore, more N is generally leached from sandy soils than from more fine-textured soils (Vinten *et al.*, 1994; Hansen & Djurhuus, 1997). Note that the estimated N leaching losses mentioned above and throughout this thesis represent root zone leaching, *i.e.* N that has passed through the root zone and is no longer available for plant uptake.

The main factors regulating N leaching from arable land are the amount and intensity of rainfall (Morecraft *et al.*, 2000), soil texture and the amount of N in easily leachable form, *i.e.* SMN (NO_3-N and ammonium-N, NH_4-N), present within the soil profile during periods when there is net water drainage (Malhi, 2001, 2006; Hooker *et al.*, 2008). N leaching mainly occurs during autumn and winter, when evaporation is low, precipitation is high and crop uptake of N is small. Avoiding SMN accumulation within the soil profile during autumn and winter is therefore crucial for reducing N leaching losses (Francis *et al.*, 1994; Mitchell *et al.*, 2000; Mitchell *et al.*, 2001; Engström *et al.*, 2011). SMN is partly regulated by temperature and moisture. However, in contrast to soil type and precipitation, which are fully dependent on natural prerequisites, SMN is also greatly affected by farming practices such as crops grown, fertilisation regime and tillage strategy.

3.2 Soil tillage – for optimal crop growth

Tillage can be divided into primary and secondary practices, where the former are considered to be deeper and heavier than the latter. The main objective of primary tillage, which in Sweden is often carried out to a depth of approx. 0.10-0.25 m, is to obtain fine soil with varying clod sizes, to kill weeds by burying or cutting and exposure of roots, and to chop and incorporate crop residues, mainly to control diseases. Secondary tillage is undertaken after primary tillage and the main objectives are to reduce clod size for preparation of a seedbed and to control weeds.

For spring crops, primary tillage is carried out either in autumn or in spring. Based on common practice and due to their structure and physical properties, clay soils are tilled in autumn under Nordic conditions. Mouldboard ploughing to a depth of 0.20-0.25 m is the most common primary tillage practice. However, shallower non-inversion tillage and direct drilling, often referred to as reduced tillage, are attracting increased interest in Sweden and internationally, mainly due to the lower workload and fuel costs.

3.3 Soil tillage and SMN

SMN comprises at most a few per cent of total soil N (Tate, 1995), which in Swedish soils is around 5-10 ton. Nevertheless, the mineral N content is the determining factor for processes in soil such as N uptake in plants, N leaching and gaseous losses of N by emissions to the atmosphere. Mineralisation of N from plant residues or soil organic matter (SOM) is a continuous aerobic microbial process at temperatures >0º C and this naturally produced mineral N usually comprises a larger proportion of the N leached from the soil than the N from fertilisers applied to growing crops (Addiscott, 1988; Goss *et al*., 1993). The rate of mineralisation increases with temperature and with soil water content, usually up to either field capacity or just beyond the soil plastic limit (Watts *et al*., 2000).

Many studies have shown increased amounts of SMN after a tillage operation (*e.g.* Hansen & Djurhuus, 1997; Catt *et al*., 2000; Mitchell *et al*. 2000; Thomsen, 2005; Askegaard *et al*., 2011). This has often been ascribed to stimulation of organic matter (OM) mineralisation by incorporation of crop residues and by disruption of aggregates, making previously protected organic material accessible to microorganisms (Adu & Oades, 1978; Six *et al*., 2004), although the mechanisms behind this are not very well known. Tillage may affect mineralisation rate *e.g*. by alteration of soil geometry (Young & Ritz, 2000; Morris *et al*., 2010; Silva *et al*., 2014), soil aeration (Khan, 1996; Morris *et al*., 2010), soil temperature (Malhi et al., 2001), soil moisture content and placement of crop residues (Balesdent *et al*., 2000). However as the influence of soil tillage on OM mineralisation is complex, the net effect may change with time and place, which also makes the results of studies within this area very variable. For example, incorporation of aboveground crop residues may speed up decomposition of these residues, provided the conditions (*e.g*. temperature and moisture content) are more favourable within the soil than on the soil surface (Malhi *et al*., 2001; Coppens *et al*., 2007). In contrast, deep incorporation by mouldboard ploughing might slow down decomposition compared with shallower incorporation due to lower temperatures and water contents with deeper tillage (Kainiemi, 2014). Tillage effects on SMN also include regulation of SMN depletion by uptake in plants.

In addition to influencing N losses from soil by encouraging SMN accumulation, tillage practices may alter the flow pathways through which water carries SMN from the soil. For example, long-term use of reduced tillage has been shown to encourage preferential flow of water by allowing flow-active macropores made by soil fauna or by roots to develop within the soil (Shipitalo *et al*., 2000).

3.4 Incorporation or removal of crop residues?

Residues of arable crops can have large effects on SMN and subsequent N leaching losses. However, crop residues may be either a source or a sink of mineral N depending on their C/N ratio (Jensen *et al*., 1997). Incorporation of cereal straw residues, which often have a high C/N ratio, has been suggested as a measure to control N leaching due to immobilisation of soil N in microbial biomass during the decomposition process in autumn (*e.g*. Bhogal *et al*., 1997; Jensen, 1997). In laboratory incubations with non-limiting inorganic N concentrations and milled cereal straw, net immobilisation is reported to be 12-16 kg N per ton straw (Smith *et al*., 1993; Mary *et al*., 1996; Bhogal *et al*., 1997), which would amount to approximately 50-60 kg N ha^{-1} for barley yielding 6 ton ha^{-1}. Many studies show net immobilisation of N also after incorporation of chopped straw into small field plots (*e.g*. Jensen, 1997; Lindén & Engström, 2006), although at a much lower rate than under incubation, around 2-4 kg N per ton straw (Mary *et al*., 1996). However, there are few full-scale field studies comparing SMN after incorporation of full length straw. Moreover, the reaction to addition of plant residues seems to vary with climate and also soil type (Nyborg & Malhi, 1989).

3.5 Time of tillage for spring crops

It is well known that delaying tillage for spring cereals to late autumn or spring in cold-temperate regions decreases the levels of SMN and N leaching during autumn and winter, especially in sandy and loamy soils, compared with tillage in early autumn (Francis et al., 1995; Känkänen *et al.*, 1998; Stenberg *et al*., 1999; Mitchell *et al*., 2000). This has often been ascribed to less mineralisation of organic material when the soil is left undisturbed at a time during autumn when the soil temperature still allows high microbial activities. In southern Sweden, as much as half of annual mineralisation may take place during the autumn (Wallgren & Lindén, 1994). Delaying tillage in autumn is therefore regarded as a means of limiting N leaching. In the same way, delaying incorporation of ley until late autumn has been found to cause less build-up of mineralised organic N (Wallgren & Lindén, 1994) and lower NO_3-N concentrations in drainage water (Neumann *et al*., 2011). However, the majority of previous studies describing the effects of autumn soil tillage on SMN accumulation have been carried out on sandy soils, while knowledge about reactions in clay soils, which are less prone to leaching, is somewhat more limited.

3.6 Timing effects on soil structure and tillage outcome

A possible drawback from delaying tillage to late autumn in order to decrease N leaching is that tillage is then not performed in optimal soil conditions. In temperate climates, clay soils often have high soil water content during late autumn and traffic at high water contents induces plastic deformation and shearing (Lipiec *et al*., 1991; Horn *et al*., 1995). This may result in soil compaction, characterised by a more dense soil with higher soil bulk density and poorer aeration (McAfee *et al*., 1989), reduced root growth and thereby lower nutrient and water uptake efficiency in the crop.

The soil water content during tillage is also very important for the tillage outcome (Watts & Dexter, 1994; Keller *et al*., 2007). The optimal water content for tillage has been defined as ‘the water content where tillage produces the largest proportion of small aggregates’ (Dexter, 1988), and is generally found at intermediate water contents. One way of defining the optimal water content for tillage is to relate it to the soil lower plastic limit (PL), as defined by Atterberg (1912). The optimum water content for tillage is frequently reported to be equal to the gravimetric water content at ~0.7-0.9 PL (Dexter & Bird, 2001; Keller *et al*., 2007). Moreover, Arvidsson & Håkansson (1996; 2014) found that compaction of clay soils resulted in poorer topsoil structure, with a decrease in the proportion of fine aggregates in the seedbed and decreased yield of all the most common crops in Sweden except for winter wheat. With a predicted future increase in autumn precipitation (Christensen *et al.*, 2007), this issue is likely to become very important.

3.7 Soil tillage to winter crops

The proportion of autumn-sown crops is increasing in many areas of north-west Europe (EuroStat, http://epp.eurostat.ec.europa.eu, data APRO_CP_CROP), with *e.g.* increasing acreage of autumn-sown cereals (mainly winter wheat) in Sweden from 1981 to 2009 (Svensson, 2010). In these crops, where delaying tillage to late autumn is not possible, it is relevant to find alternative ways of reducing N leaching. In Sweden, winter wheat is one of the crops eligible for winter subsidies for covering soil (SJVFS 2011:25), but different establishment strategies may differ in how effectively they close the N cycle.

Since the recommended sowing date for winter wheat in Sweden is in September, tillage has to be performed during August and September. These months normally have high temperatures and often humid conditions, favouring N mineralisation and consequently causing an early increase in SMN (Torstensson & Aronsson, 2000; Engström *et al.*, 2011). Winter wheat N uptake during autumn, from establishment until growth ceases owing to low temperatures, has been reported to amount to about 20 kg N ha^{-1} or less (Lindén *et al.*, 2000). This is generally much lower than reported soil N content (Stenberg *et al.*, 1999; Engström *et al.*, 2011), so excess N is at risk of being lost by leaching.

3.8 Tillage intensity

Different tillage systems disturb the physical framework of the soil to different degrees and place incorporated crop residues in different ways (Gantzer & Blake, 1978). Thus, they can also be expected to have different effects on soil microorganisms and N mineralisation rate (Doran, 1987). Under controlled laboratory conditions, it has been found that increasing levels of mechanical energy applied to soil aggregates increase the rate of respiration (Dexter *et al.*, 2000; Watts *et al.*, 2000; Kainiemi, 2014). However, when comparing different intensities of tillage in the field, the effects seem rather short-lived and the overall results are variable.

Some studies have shown that N mineralisation (Reicosky & Archer, 2007; Chatskikh *et al.*, 2008) and N leaching (Catt *et al.*, 2000; Askegaard *et al.*, 2011) increase with increasing intensity of soil tillage (Nyborg & Malhi, 1989;

Goss *et al*., 1993; Hansen & Djurhuus, 1997; Power & Peterson, 1998; Stenberg *et al*., 1999). Reduced tillage has therefore been suggested as a potential measure to mitigate N leaching losses. For example, Stenberg *et al*. (1999) showed that omitting stubble cultivation after harvest, before mouldboard ploughing, reduced N losses, while Catt *et al*. (2000) reported lower N losses under shallow tine cultivation than with mouldboard ploughing. However, other studies have shown no or inconsistent effects of tillage intensity (Hooker *et al*., 2008; Regina & Alakukku, 2010; Hansen *et al*., 2010).

3.9 Catch crops

Keeping the soil covered by growing a catch crop between two main crops, taking up mineralised N during autumn, helps keep SMN low and is an effective measure to reduce N leaching (Askegaard & Eriksen, 2008; Constantin *et al*., 2010). Time of incorporation can be an important management tool for N (Thorup-Kristensen *et al*., 2003).

The most common practice in Sweden is to establish the catch crop by undersowing in spring barley and to incorporate it into the soil in late autumn or spring. Under Scandinavian conditions, somewhat varying results have been found regarding the influence of incorporation time on N leaching and N availability in the soil for the next crop (Hansen & Djurhuus, 1997; Torstensson & Aronsson, 2000; Thorup-Kristensen & Dresbøll, 2010). However, in general delaying incorporation seems to decrease N leaching, whereas incorporation too late in spring may have negative effects on N availability for the main crop (Thorup-Kristensen *et al*., 2003). The actual dates for incorporation of different catch crop species in Sweden are determined by government regulations and vary between locations. Of interest for the work in this thesis are the dates 10 and 20 October, when a grass catch crop may be incorporated at the earliest in Västergötland and Halland county, respectively (SJVFS, 2011:25).

4 Tillage definitions used

In this thesis, the term ‘soil tillage’ refers to primary tillage practices. Comparisons are made between mouldboard ploughing, shallow tillage (in this work represented by stubble cultivation) and no tillage. However, the nomenclature sometime varies between Papers I-IV. For a description of the tillage definitions and abbreviations used within the respective papers, see Table 1.

Table 1. *Tillage definitions and abbreviations used for the different tillage practises in Paper I-VI*

Tillage practices	***Equipment***	***Working depth***	***Nomenclature***	***Abbrev-iation***
Paper 1				
Mouldboard ploughing	Reversible plough	0.20-0.25 m	Mouldboard ploughing	MB
Stubble cultivation	Tine cultivator	0.10-0.12 m	Stubble cultivation	SC
Paper II				
Mouldboard ploughing	Reversible plough	0.20-0.22 m	Conventional tillage	CT
Stubble cultivation	Disc/tine cultivator	0.8-0.10 m	Reduced tillage	RT
No tillage	Direct drilling	-	No tillage/direct drilling	NT
Paper III				
Mouldboard ploughing	Reversible plough	0.20-0.22 m	Mouldboard ploughing	MP
Stubble cultivation	Tine cultivator	0.11-0.13 m	Stubble cultivation	SC
Paper IV				
Mouldboard ploughing	Reversible plough	0.20-0.25 m	Mouldboard ploughing	MB
Stubble cultivation	Disc/tine cultivator	0.10-0.12 m	Stubble cultivation	SC
No tillage	Direct drilling	-	Direct drilling	DD

5 Materials and methods

The studies presented in Papers I-IV were restricted to mineral soils and to agricultural systems without animal manure.

5.1 Site location and description

Seven Swedish sites, located from Uppland county in central Sweden to Skåne county in southern Sweden, were used for *in situ* field studies (Figure 2). Soil texture ranged from sandy loam to heavy clay soil (5-58% clay) (Table 2) and climate conditions varied in terms of precipitation and temperature (Table 3). Most of the locations were used during several consecutive years (Table 3). At Mellby, Lanna and Ultuna, treatments were repeated on the same plots during all years. At Rydsgård, Lönnstorp and Bjertorp, a suitable field with respect to the crop rotation on the respective farm was chosen each year. In all experiments, experimental plots were distributed in a block design with 3-4 replicates. Individual experimental plots measured 900 m^2 at Mellby and 120-270 m^2 at the other six sites.

All seven sites are located within the Swedish nitrate vulnerable zones depicted in Figure 1.

Table 2. *Location and information on soil texture and organic matter content (OM) in the topsoil at the seven study sites used in Papers I-IV. The range given shows the variation between years*

Farm, county	Coordinates	Clay (%)	Silt (%)	Sand (%)	OM (%)
Ultuna, Uppland	59°49'N, 17°38'E	58	33	9	2
Lanna, Västergötland	58°21'N, 13°8'E	45	45	10	3.5
Bjertorp, Västergötland[1]	58°15'N 13°6'E	17-19	20-56	25-63	3
Mellby, Halland	56°29'N, 13°0'E	6	48	46	5
Alnarp, Skåne	55°39'N, 13°5'E	11	24	65	3
Lönnstorp, Skåne[1]	55°40'N, 13°7'E	17-20	28	52-55	2.5
Rydsgård, Skåne[1]	55°30'N, 13°35'E	28-43	51-60	6-12	2.5

[1] Two different fields at Bjertorp, three at Lönnstorp and three at Rydsgård.

Table 3. *Site-specific precipitation (Prec.) and air temperature (Temp.) during the experimental period and for a 30-year period (1961-1990). All data are from SMHI (Swedish Meteorology and Hydrology Institute) except data from the experimental period for Bjertorp, which are from Lantmet*

Site	Years	Experimental period			Reference normal		
		Temp (°C)	Prec. (mm)	Prec. Sep-Mar	Temp (°C)	Prec. (mm)	Prec. Sep-Mar
Ultuna	99/00-10/11	7.5	597	333	5.6	544	299
Lanna	97/98-06/07	7.1	607	297	6.1	560	314
Bjertorp	07/08, 09/10	6.7	583	311	6.1	560	314
Mellby	99/00-10/11	7.8	804	401	7.2	803	482
Alnarp	09/10	7.9	581	357	7.7	536	311
Lönnstorp	07/08-09/10	8.6	673	368	7.7	536	322
Rydsgård	99/00-01/02	9.6	777	463	7.5	621	482

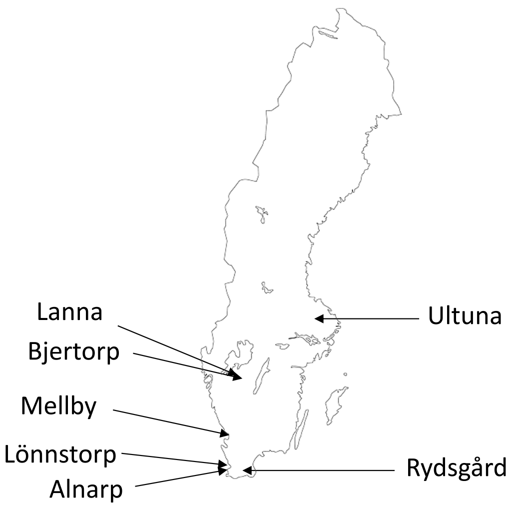

Figure 2. Location of the seven study sites.

5.2 Study design

Treatments included in Papers I-III are shown in Table 4 and treatments included in Paper IV in Table 5.

Table 4. *Treatments included in Papers I–III. Papers I and III studied autumn tillage strategies for spring cereals and Paper II strategies for winter cereals. (-) indicates that the parameter was not a treatment factor in the study*

Abbreviation	Tillage treatment	Tillage time[1]	Sowing[2] time	Catch crop	Straw treatment
Paper I - Lanna					
A	Mouldboard ploughing	Early	-	No	Incorporation
B	Mouldboard ploughing	Early	-	No	Removal
C	Mouldboard ploughing	Late	-	No	Incorporation
D	Mouldboard ploughing	Late	-	No	Removal
E	Mouldboard ploughing	Late	-	Ryegrass	Removal
F	Mouldboard ploughing	Late	-	Chicory	Removal
G	Stubble cultivation/ mouldboard ploughing	Early/late	-	No	Incorporation
H	Stubble cultivation, mouldboard ploughing	Late/late	-	No	Incorporation
I	Stubble cultivation/mouldboard ploughing	Early/early and late	-	No	Incorporation
Paper II – Bjertorp, Lönnstorp, Alnarp					
MP1 S1	Mouldboard ploughing	Early	Early	-	-
MP1 S2	Mouldboard ploughing	Early	Late	-	-
MP2 S2	Mouldboard ploughing	Late	Late	-	-
SC1 S1	Stubble cultivation	Early	Early	-	-
SC1 S2	Stubble cultivation	Early	Late	-	-
SC2 S2	Stubble cultivation	Late	Late	-	-
NT S1	No-till	-	Early	-	-
NT S2	No-till	-	Late	-	-
Paper III – Ultuna, Rydsgård					
MP1	Mouldboard ploughing	Early	-	-	-
MP2	Mouldboard ploughing	Normal	-	-	-
MP3	Mouldboard ploughing	Late	-	-	-
SC1	Stubble cultivation	Early	-	-	-
SC2	Stubble cultivation	Normal	-	-	-
SC3	Stubble cultivation	Late	-	-	-

[1]Average date for early and late tillage was 12/9 and 5/11 in Paper I and 27/8 and 21/9 in Paper III. Average date for early, normal and late tillage in Paper II was 31/8, 7/10 and 14/11.
[2]Average date for early and late sowing in Paper II was 31/8 and 23/9.

Table 5. *Treatments included in Paper IV. Crop rotation and soil management operations in the conventional (CON) and N use efficient (NUE) management systems. SC=stubble cultivation, MB=mouldboard ploughing, DD=direct drilling. Measures were: (a) mouldboard ploughing in spring instead of stubble cultivation and mouldboard ploughing in autumn before sowing of spring barley, (b) earlier sowing of barley in spring (about 3 weeks earlier), (c) sowing of winter wheat immediately after the green manure ley was ploughed under compared with one month later, (d) undersowing of a ryegrass catch crop in winter wheat in spring, (e) mouldboard ploughing of the catch crop undersown in barley in spring instead of autumn, (f) direct drilling of winter wheat instead of mouldboard ploughing and conventional drilling, and (g) earlier sowing of winter wheat (about 3 weeks)*

Crop rotation year	Crop	M.Yr[1]	Measure	Management operations	
				CON	NUE
1	Winter wheat	1999/2000, 2005/2006	d, f, g	MB in late August. Sowing of wheat in late Sept.	DD of winter wheat in early Sept. Undersowing of ryegrass in spring.
2	Spring barley + clover/grass mixture	2000/2001, 2006/2007	a, b	SC early in Sept. MB in Nov. Sowing of barley and clover/grass mixture at normal time in spring.	Catch crop growing during autumn. MB in spring. Early sowing of barley and clover/grass mixture in spring.
3	Green manure[a]	2001/2002, 2007/2008	-	-	-
4	Winter wheat	2002/2003, 2008/2009	c, d	MB of grassland in Aug. Sowing of winter wheat in late Sept.	MB of grassland at the same time as in CON. Sowing of winter wheat after one week, in late Aug. Undersowing of ryegrass in spring.
5	Spring barley + ryegrass	2003/2004, 2009/2010	a	SC in early Sept. MB in Nov. Sowing of barley and ryegrass at normal time in spring.	Catch crop growing during autumn. MB in spring. Sowing of barley and ryegrass as in CON.
6	Spring oilseed rape	2004/2005, 2010/2011	e	MB in late autumn. Sowing of oilseed rape at normal time in spring.	MB in spring. Sowing of oilseed rape as in CON.

1. Management years (M.Yr) ran from after harvest in one year to after harvest in the following year.

5.2.1 Paper I - Timing of tillage on clay soil

Paper I examined different tillage strategies for spring cereals on a clay soil at Lanna. It included mouldboard ploughing and shallow cultivation in different combinations and timing, together with different options for crop residue management and catch crops (Table 4). The main objective was to identify ways of managing the soil in order to minimise the content of SMN during autumn and winter. A further objective was to investigate the long-term impact of the different tillage strategies on yield of spring cereals and clay soil structure over seven consecutive years. The starting hypothesis was that delayed autumn tillage, reduced tillage intensity, use of catch crops and straw incorporation decrease SMN accumulation during autumn and winter.

5.2.2 Paper II - Establishment techniques for winter wheat

This series of field experiments at Bjertorp, Lönnstorp and Alnarp examined different strategies for winter wheat establishment in relation to SMN accumulation during autumn and winter (Paper II). Conventional tillage (CT), reduced tillage (RT) and non-tillage (NT) and early (1) and late (2) time of tillage were tested in combination with early (1) and late (2) sowing (S) times, including different time intervals between tillage and sowing (Table 4). In all treatments the preceding crop was oilseed rape. Glyphosate was applied once in autumn, between harvest of the oilseed rape and sowing of winter wheat, in all treatments except at Lönnstorp 2007/08, where it was only applied in the non-tillage treatments, and at Bjertorp 2007/08, where no glyphosate was applied in any treatment. The starting hypothesis was that decreasing the interval between tillage and sowing would decrease SMN accumulation within soil during autumn.

5.2.3 Paper III – Tillage of clay soils at different soil water contents

This study was conducted on two clay soils (Ultuna and Rydsgård) differing in clay content in order to examine the effects of tillage at different times and at different soil water contents during autumn (Paper III). Soil tillage outcome, yield of spring cereals, short-term and long-term soil structure effects and SMN during autumn and winter were determined after two tillage treatments, (mouldboard ploughing and stubble cultivation) performed on three occasions (early, normal and late), during three years (Table 4). Studies of soil structure parameters and SMN were performed during three years. The experiment at Ultuna is still running and yields during a further nine years are presented in this thesis. In the first year, mouldboard ploughing was the only tillage treatment included at Rydsgård. After primary tillage in autumn, the soil was left bare during the winter in all treatments until harrowing and sowing of spring cereals. The starting hypotheses were that delaying tillage to late autumn on clay soils: i) reduces SMN accumulation and hence the risk of NO_3-leaching; but ii) has a negative impact on soil structure and yield at high soil water contents.

5.2.4 Paper IV – N use efficient management within a crop rotation

Paper IV examined the effects of introducing several measures (relating to soil tillage and crop management) aimed at reducing N losses to water in a crop rotation with respect to SMN accumulation, N leaching and crop production. A conventional farming system, using conventional methods for the region at the time when the project started, (CON), was compared with an N use efficient system (NUE) where measures for reduced N leaching were combined based on achieving good synchrony between mineralisation of crop residues and SMN and crop demand for N (Table 5). The study was conducted in a six-year crop rotation running for two cycles (12 years in total) in a field with separately tile-drained plots at Mellby in south-west Sweden. The same six-year crop rotation was used in the two systems compared, while times and methods of soil tillage, sowing and use of catch crops differed (Table 5).

5.2.5 General information

The crops grown were spring wheat (*Triticum aestivum* L.), oats (*Avena sativa* L.) and barley (*Hordeum vulgare* L.) in Papers I and III, winter wheat (*Triticum aestivum* L.) in Paper II and winter spring barley, oilseed rape and green manure ley in Paper IV. Fertiliser was applied in all experiments based on expected yields and with no differences between treatments. Pesticides were applied according to requirements and local recommendations. No herbicide was used between harvest and the first soil tillage operation in autumn except in Paper II, where glyphosate was used before sowing of winter wheat throughout the study except at Bjertorp 2007/08 and the no-till treatment at Lönnstorp 2007/08. This proved to be of major importance for the results. For exact dates of tillage operations, sowing dates and fertilisation, see Papers I-IV.

5.3 Measurements

5.3.1 An overview of crop and soil sampling and measurements

A number of measurements of the plant material were made. As production is the ultimate objective in managing agricultural soils, yield levels were recorded in all experiments. Total N content in plant material (main crops, catch crops and weeds) was determined in several of the studies to obtain knowledge about the proportion of N moving from the soil and into the plants.

For a given soil, N leaching is related to the amount of SMN accumulated within the soil profile during periods with a precipitation surplus. Measuring the amount of SMN during autumn and winter then gives an indication of the risk of N being leached. Measurements of SMN on several occasions during autumn, winter and spring were therefore made in all studies included in

Papers I-IV. When comparing different treatments, quantifying SMN provides a good relative estimate of the N leaching risk and facilitates studies in many different locations, as it does not require permanent installations in field as do sampling of drainage water and to some extent the use of suction cups. At the sandy loam soil at Mellby, differences in SMN between the treatments were correlated with differences in leaching losses of NO_3-N (R^2=0.87; Figure 3).

A more direct indication of the amount of N lost from a field by leaching can obviously be obtained by measuring the N concentration in drainage water together with quantification of drainage amount. This was done in Paper IV.

In order to quantify any possible effects on clay soil structure from tillage late in autumn at high soil water contents, a number of soil physical measurements were made in the clay soils in Papers I (Lanna) and III (Rydsgård and Ultuna). Properties determined were soil bulk density (SBD), aggregate size distribution after tillage in autumn and in the seedbed in spring, water infiltration rate, water-holding capacity, water content in the seedbed in spring and aggregate strength of wet and dry aggregates.

5.3.2 Crop analyses

Grain yield was determined by plot-wise sampling with a combine harvester at harvest in each year. The grain was analysed for N by near infrared transmission spectroscopy (InfratecTM1241 GrainAnalyzer).

For determination of the *N content in aboveground biomass during autumn*, green material (catch crops, weeds and winter wheat) was sampled once or several times during autumn. The plant material was sampled by cutting at the soil surface in 3-4 randomly located frames, 0.5 m by 0.5 m, in each plot. The

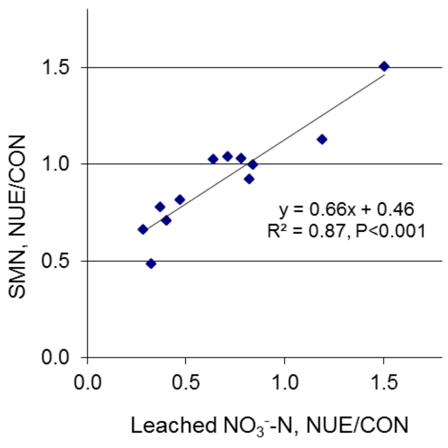

Figure 3. Relative difference between two tillage systems (NUE/CON) in SMN (annual mean from measured values) plotted against relative difference between the same systems in annual amount of leached NO_3-N during the corresponding 12 years.

samples from the frames were pooled and analysed plot-wise. The plant material was dried at 55°C, weighed and milled. Total N content was determined with a LECO® CNS-2000 element analyser. (Papers I and IV)

For determination of the grain/straw ratio in the main crop, grain and straw were sampled and analysed separately for N content at harvest. The ratio was then used together with grain yield measured by combine harvester for calculations of the *N uptake in aboveground parts of the main crop*. Sampling and analysis techniques were as described above (Paper I).

In order to quantify *mineralisation of N from soil organic matter*, non-fertilised (0N) subplots were used. For determination of the plant uptake of N during the growing season in the non-fertilised (0N) subplots, the main crop (grain and straw) together with all green material such as weeds and volunteer plants were sampled in August at late milk/early dough ripening stage, BBCH 80 (Lancashire et al., 1991). Sampling and analysis techniques were as described above (Paper I).

5.3.3 Nitrogen in drainage water

At Mellby in Halland, six experimental plots measuring 30 m x 30 m were separately tile-drained, each plot with five drainage pipes at 6.8 m spacing and 0.9 m depth (Figure 4). To prevent lateral flow of water into and out of the plots, they were surrounded by drainage pipes located 1.5 m from the border and at a depth of 0.9 m. Drainage water collected from the plots through the drains was diverted to a measuring station (Figure 5) and accumulated daily drainage volume from each plot was recorded by dataloggers connected to tipping buckets. Flow-proportional water samples (15 mL) were taken using a peristaltic pump for every 0.2 mm discharge and stored in individual polyethylene bottles for each plot. The bottles were emptied every two weeks when drainage water was available. The NO_3^- concentration in the water was analysed by standard methods as described in Paper IV. The term nitrate (NO_3^-), when used throughout the thesis and in Papers I-VI, refers to NO_3^- plus nitrite (NO_2^-), which is what the analyses measure, but the proportion of NO_2^- is assumed to be close to zero, so the term nitrate is used (Paper IV).

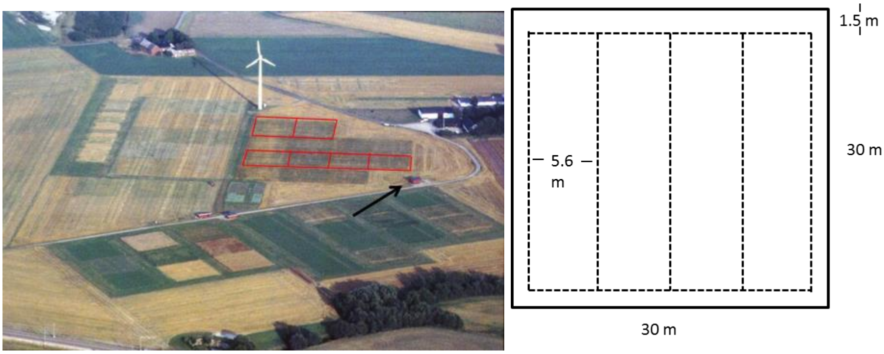

Figure 4. Mellby farm in Halland. Left: The crop sequence field trial (Paper IV) was located within the six experimental plots marked in red. The black arrow indicates the measuring station for drainage water. Photo: Rural Economy and Agricultural Society of Halland. Right: Drainage layout within the experimental plots.

Figure 5. Measuring station for drainage water from the experimental field at Mellby in Halland, with tipping buckets for measurement of draining volumes (middle) and pumps and plastic flasks for collection of flow-proportional water samples (right). Photo: Åsa Myrbeck.

5.3.4 Soil N

Amount of SMN was determined on soil samples collected 3-5 times per year from each plot (depending on crop grown, management practices and weather in different years), from harvesting in autumn to early spring before crop establishment. In each plot, 12 soil probe samples (diameter 0.02 m) were taken from the 0-0.30 m layer and nine each from the 0.30-0.60 and 0.60-0.90 m layers (Figure 6). The individual samples were then pooled for the respective layer and plot and deep-frozen (-20°C) immediately after sampling. The frozen samples were milled, extracted with 2 M KCl and analysed by standard methods as described in Papers I-IV.

Figure 6. Sampling of soil probes for determination of SMN (left and middle). Preparation of soil cylinders for determination of soil bulk density (right). Photos: Liselott Evasdotter, Åsa Myrbeck.

5.3.5 Soil physical properties

Dry bulk density was determined in the 0.09-0.14 m soil layer in spring. Three soil cylinders (diameter 72 mm, height 50 mm) were extracted from each plot (Figure 6). Dry bulk density was calculated after drying the samples at 105°C for 72 h (Papers I, III).

Fractioning of aggregate size classes in the topsoil immediately after primary tillage treatments in autumn was determined to define the workability of the soil at the time of tillage. Approximately 0.020 m^3 of loosened soil were collected from the 0-0.20 m layer in each plot, left to dry at room temperature and then sieved into five aggregate size fractions: <4 mm, 4-8 mm, 8-16 mm, 16-32 mm and >64 mm. The method is further described by Kainiemi (2014) (Paper III).

Soil water-holding capacity was determined at 10, 60 and 1500 kPa in the 0.9-0.14 m soil layer. For this, three soil cylinders (diameter 72 mm, height 50 mm) were extracted from each plot in spring (Paper III).

Water infiltrability, expressed as the saturated vertical hydraulic conductivity coefficient (Ksat), was determined *in situ* by a falling head method with the aim of capturing possible long-term effects of tillage treatment at the bottom of the tilled layer and the upper subsoil. The measurements were performed in spring by inserting a 400 mm diameter steel cylinder to a depth of 0.15 m into a horizontal soil surface prepared at 0.19 m depth in the soil. The soil inside the cylinder was submerged by a water head of 0.1 m, which was kept constant between measurements of falling water head rate (Figure 7). Two measurements were made per plot. The results presented correspond to measurements made 60 minutes after initial wetting of the soil surface. Ksat was calculated by applying Darcy's law to the vertical flow rate of water. The method is further described by Löfkvist (2005) (Paper I).

Figure 7. Water infiltrability measurements at Lanna. Left: Insertion of steel cylinders. Centre: Filling of buckets from a water tank. Right: Measurement of water head. Photos: Maria Stenberg.

Aggregate tensile strength was determined as the mechanical resistance of aggregates from the topsoil dried for one week at room temperature according to Dexter and Kroesbergen (1985). This involved measuring the force needed to crush the aggregate (where high friability is preferred to achieve a good tillage outcome) (Papers 1 and III).

Wet aggregate stability in the topsoil was expressed as the amount of readily dispersible clay according to Czyz *et al*. (2002). Weighed aggregates of 8-16 mm diameter from each plot (5 subsamples with 8 aggregates each) were placed on porous sand blocks with 0.5 kPa suction for one week to equilibrate the moisture content. The aggregates were then placed in plastic flasks with deionised water and shaken moderately (by hand, 10 shakes). After sedimentation for 24 h, the *turbidity* in the aqueous phase was determined in Nephelometric Turbidity Units (NTU) using a Hach 2100N turbidimeter (Figure 8). The amount of suspended material was quantified for 8 samples by drying at 105°C and weighing. The NTU value for all samples was calculated from this calibration and expressed as the amount of dispersed material in relation to aggregate weight (Paper I).

The seedbed properties aggregate size distribution, seedbed depth and water content in the seedbed and seedbed base were characterised according to a method used by Håkansson *et al*. (2002) (Figure 9). Duplicate measurements were made in each plot (Papers I and III).

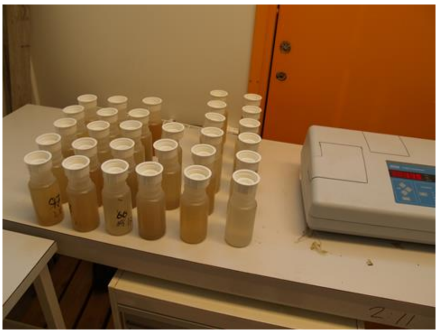

Figure 8. Flasks with the aqueous phase obtained after shaking soil aggregates in deionised water. Beside is the apparatus used for measuring turbidity in the aqueous phase. Photo: Ararso Etana.

Figure 9. Left: Characterisation of the seedbed. Right: Sieve used for quantification of different aggregate fractions within the seedbed. Photos: Maria Stenberg.

5.4 Calculations

5.4.1 Net soil N mineralisation during the growing season

Soil net N mineralised (Nmin) during the growing season was calculated as:

$$\mathrm{Nmin} = \mathrm{Nsoil\ at\ harvest} - \mathrm{Nsoil\ in\ spring} + \mathrm{Ncrop\ at\ harvest} + \mathrm{Nroot\ at\ harvest}$$

where Nsoil is mineral N is the soil in 0N sub-plots, Ncrop is total N in aboveground biomass of the main crop plus weeds and catch crops in 0N sub-plots and Nroot is N in roots, calculated as 50% of N in aboveground biomass (estimated from Hansson *et al*., 1987; Bolinder *et al*., 1996). All were calculated as kg N ha^{-1} (Paper I).

5.4.2 Total crop uptake of N

For estimation of total N uptake in wheat plants in Paper II, N in roots during autumn was calculated as 70% of N in aboveground biomass (estimated from Hansson *et al*., 1987; Bolinder *et al*., 1996).

5.4.3 SMN

The analytical concentrations of SMN were converted into kg ha^{-1} by using average dry bulk density values for the different soil layers. In Papers III and IV, a slightly different approach was used compared with that in Papers I and II (see section 6).

5.5 Statistical analyses

Data were subjected to analysis of variance using the SAS (9.2) procedures GLM and MIXED (SAS Institute, 2008). The T-test was used for separation of means at 5% level by the pdiff statement in SAS. The data involved repeated measurements in time on the same plots. Therefore, mixed linear models were used for the analyses when testing differences between treatments over the whole experimental period, as suggested by Fitzmaurice *et al*. (2004) and Littell *et al*. (2006). The dependence between observations over time was modelled using an AR (1) covariance matrix.

Average values over years were calculated using the SAS procedure MIXED with year as a random effect.

For saturated hydraulic conductivity geometrical mean values were used, since these are usually better normally distributed than arithmetic values.

6 Aspects of soil N sampling

6.1 Concentration and mass per unit area

The concentration of *e.g.* C or N can easily be determined from a soil sample in the laboratory. However, comparing concentrations and transforming concentrations into mass per unit area is a problem in research involving different tillage methods, since tillage loosens the soil, hence altering the SBD (Stockfisch, 1999). In this thesis, soil was sampled before tillage from three layers, 0-0.30 m, 0.30-0.60 m and 0.60-0.90 m. After tillage, the same plots were sampled again to the same depths. As the topsoil was loosened, the surface height was increased and the sampling cone did not reach the same soil layer as before tillage (Figure 10). Hence concentrations were not measured on exactly the same soil layers as before tillage. When estimating mass per unit area, using an uncorrected value for SBD in the sampled layers and not adjusting for changes in depth will in most cases both lead to overestimation of SMN in tilled compared with untilled soil, as SMN concentration usually increases towards the soil surface.

To correctly compensate for this increase in soil height created by tillage and adjust the depth from the soil surface to which sampling is made, knowledge of the average increase is needed. Changes in soil height can be estimated by sampling SBD in the tilled layer before and after tillage. New SBD values then have to be determined for each sampling occasion, as the soil tends to settle with time. The conventional way of determining SBD is by extracting and weighing cylinders of known volume. Due to the generally great spatial variation in SBD, a substantial number of soil samples needs to be collected, which is very time consuming. It is also a destructive method and only a limited amount of cylinders can be sampled within a field experiment. An alternative to sampling of SBD is to use general values on changes in soil height by tillage from the somewhat limited literature on the subject.

Andersson and Håkansson (1996) and Arvidsson and Bölenius (2006) determined the average increase in soil height created by different tillage practices in Swedish soils by burying steel plates below ploughing depth as a depth reference from which average soil height was measured mechanically and by laser, respectively, in the two studies. Measurements showed that part of the initial loosening created by tillage generally remained for only quite a short period. Already about two weeks after tillage, less than half the initial soil height increase remained. Thereafter the soil surface sank slowly for a further couple of weeks, after which it remained more or less unchanged, for autumn tillage throughout winter until seedbed preparation in spring. Values of changes in soil surface height adapted from the abovementioned studies and provided by Håkansson[1] are presented in Table 6.

However, adjusting the sampling depth in the field may be complicated, especially if many different types of tillage equipment are used. One option is to make the adjustments after sampling by calculations, using general values on changes in soil height. This may also be done on old data sampled without corrections.

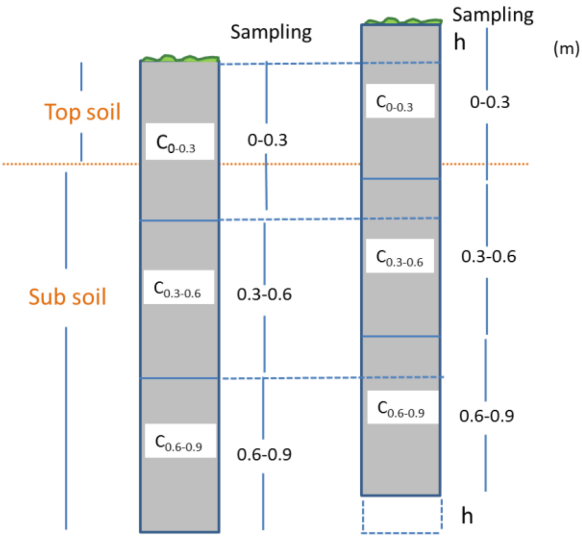

Figure 10. Soil sampling before and after tillage, where h is the increase in soil height (m) created by tillage and C is the N concentration in respective 0.3 m sampled layer.

1. I. Håkansson, personal communication, 2013-03-26.

Table 6. *Average increase in soil height (m) produced by autumn tillage (0 months) and remaining increase at different times in autumn and spring in Swedish soils (estimated from Andersson and Håkansson (1966), Arvidsson and Bölenius (2006) and Håkansson*[1]

Tillage operation	Time after tillage	Change in soil height (m)	
		Clay soil	Sandy soil
Mouldboard ploughing (~0.22 m) in early autumn	0 months	0.06	0.05
	1-2 months	0.04	0.03
	2-3 months	0.04	0.03
	In spring	0.04	0.03
Mouldboard ploughing (~0.22 m) in late autumn	0-1 months	0.05	0.04
	1-2 months	0.03	0.02
	2-3 months	0.03	0.02
	In spring	0.03	0.02
Stubble cultivation (~0.13 m) in early autumn	0-1 months	0.03	0.02
	1-2 months	0.02	0.01
	2-3 months	0.02	0.01
	In spring	0.02	0.01
Stubble cultivation, (~0.13 m) in late autumn	0-1 months	0.03	0.02
	1-2 months	0.02	0.01
	2-3 months	0.02	0.01
	In spring	0.02	0.01

[1] Inge Håkansson, personal communication, 2013-03-26.

6.2 Correction for changes in soil surface height

In Papers I-IV, sampling for SBD determination was not carried out on each sampling occasion for SMN. Furthermore, sampling depth was not adjusted for changes in soil surface height at sampling. Instead, priority was given to obtaining good values of SMN by having close sampling occasions during autumn and winter and by numerous soil probe samples in each plot. In Papers I and II, the analytical values for SMN concentration in the soil profile were converted into kg ha^{-1} simply by using mean dry bulk density values for the different soil layers (*e.g.* Stenberg *et al.*, 1999; Hooker *et al.*, 2008). In Papers III and IV, corrections for changes in soil height due to tillage were made by calculations. These corrections included changes in SBD in the topsoil and changes in depth to which sampling was carried out. Recalculating SMN in Paper I by including corrections for changes in soil height levelled out some of the differences found between early and late tillage. However, this occurred in only few cases and was not very important for the overall conclusions.

To include the same amount of soil in calculations after and before tillage, a layer corresponding to the height rise in the soil surface from tillage was added to the sampled 0-0.90 m layer. The SMN concentration in this layer was assumed to be equal to the concentration in the sampled 0.60-0.90 m layer (which seems reasonable, as N concentrations at that depth are often low and without a sharp gradient) and SBD to be equal to that in the 0.60-0.90 m layer before tillage. The increase in soil height remaining on the different sampling occasions was set according to Table 6.

The amount of SMN in untilled treatments in the different soil layers (depth measured from the untilled, reference, soil surface) was calculated as (N concentration x SBD x thickness of layer):

$$\mathrm{SMN}_{0-30} = \mathrm{C}_{0-30} \times \mathrm{X}_{top1} \times \mathrm{Y}_{top} + \mathrm{C}_{0-30} \times \mathrm{X}_{sub} \times (\mathrm{Y}_{sample} - \mathrm{Y}_{top})$$

$$\mathrm{SMN}_{30-60} = \mathrm{C}_{30-60} \times \mathrm{X}_{sub} \times \mathrm{Y}_{sample}$$

$$\mathrm{SMN}_{60-90} = \mathrm{C}_{60-90} \times \mathrm{X}_{sub} \times \mathrm{Y}_{sample}$$

where C_{0-30}, C_{60-90} and C_{60-90} is the SMN concentration in the 0-0.30, 0.30-0.60 and 0.60-0.90 m soil layer, respectively, $\mathrm{X}_{\mathrm{top1}}$ is the SBD in the topsoil before tillage, $\mathrm{X}_{\mathrm{sub}}$ is the SBD in the subsoil, $\mathrm{Y}_{\mathrm{top}}$ is the thickness of the topsoil layer before tillage and $\mathrm{Y}_{\mathrm{sample}}$ is the length of the soil probe sample (in this thesis 0.30 m).

The amount of SMN in *tilled* treatments in different soil layers (using the soil surface before tillage as a reference) was calculated as:

$$\mathrm{SMN}_{0-30} = \mathrm{C}_{0-30} \times \mathrm{X}_{top2} \times (\mathrm{Y}_{top1} + \mathrm{h}) + \mathrm{C}_{0-30} \times \mathrm{X}_{sub} \times \left(\left(\mathrm{Y}_{sample} - (\mathrm{Y}_{top} + \mathrm{h}\right)\right) + \mathrm{C}_{30-60} \times \mathrm{X}_{sub} \times \mathrm{h}$$

$$\mathrm{SMN}_{30-60} = \mathrm{C}_{30-60} \times \mathrm{X}_{sub} \times (\mathrm{Y}_{sample} - \mathrm{h}) + \mathrm{C}_{60-90} \times \mathrm{X}_{sub} \times \mathrm{h}$$

$$\mathrm{SMN}_{60-90} = \mathrm{C}_{60-90} \times \mathrm{X}_{sub} \times \mathrm{Y}_{sample}$$

where concentrations are for sampling depths from the soil surface after tillage, h is the average increase in the soil surface thickness created by tillage and used in accordance with Table 6 and $\mathrm{X}_{\mathrm{top2}}$ is the SBD in the topsoil after tillage, calculated as:

$$\mathrm{X}_{top2} = (\mathrm{X}_{top1} \times \mathrm{Y}_{top}/(\mathrm{Y}_{top} + \mathrm{h})$$

7 Main results and discussion

7.1 Incorporation or removal of crop residues?

As reported by others (Àlvarez *et al.*; 2008; Hansen *et al.*, 2010), it turned difficult under field conditions at Lanna to recapture the immobilisation effect from incorporation of cereal straw obtained in more controlled small-scale studies (*e.g.* Bhogal *et al.*, 1997; Ambus & Jenssen, 2001; Lindén & Engström, 2006) (Figure 11). Averaged over years, incorporation of 3.3 ton dry matter of cereal straw per hectare did not result in any net N immobilisation. Generally low levels of SMN within the experiment might have contributed to the lack of net immobilisation of N, as extra N is needed for the microbial population during the decomposition process (Moreno-Cornejo & Zornoza, 2014). However, as shown in Figure 11, this finding corresponded to measurements carried out in a similar and longer time series on a sandy loam soil at Mellby in south-western Sweden (Stenberg *et al.*, 1999; Myrbeck & Rydberg, 2012). In that study, immobilisation of N by straw incorporation occurred during the first few years of the experiment, after which net mineralisation increased. This was probably due to the higher input of total OM to the system, since in the control plots straw was removed from the field. This short-lived effect is in agreement with results by Nyborg *et al.* (1995) and Catt *et al.* (1998).

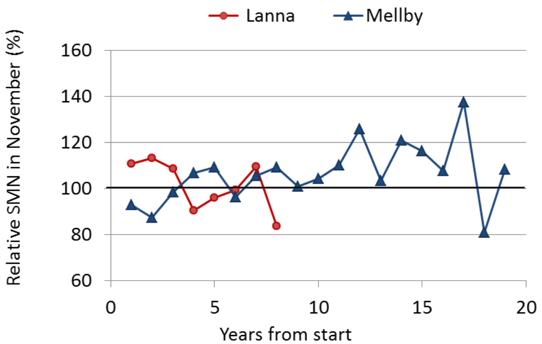

Figure 11. Long-term effects of straw incorporation relative to straw removal on SMN in late autumn (straw removal=100). Results from eight years at Lanna and 19 years on a sandy loam at Mellby (from Myrbeck & Rydberg, 2012).

The inconsistency between results from field and laboratory experiments may be explained by the typically larger straw particles in the field than in laboratory experiments, as crop residue particle size has been shown to be of great importance for the immobilisation process (Ambus & Jensen, 2001). In addition, field conditions provide a less even distribution of the residues and less soil-residue contact (Jin et al., 2008).

The possibility of achieving the desired effect might be better in soils high in SMN and perhaps also in areas with higher temperatures than those in Scandinavia (Wang *et al.,* 2014).

7.2 Timing of tillage for spring crops

Delaying primary tillage operations for spring cereals on the clay soils used in this thesis (Ultuna, Lanna and Rydsgård) did not show the consistent reduction in SMN expected from previous studies of SMN and/or N leaching on coarse-textured soils (Hansen & Djurhuus, 1997; Känkänen *et al.*, 1998; Stenberg *et al*., 1999; Mitchell *et al*., 2000). In general, the soil profile contained somewhat more SMN during autumn when tillage was carried out early rather than late in autumn. However, the results varied between sites and between years at the same site (Figures 12 and 13). The average difference at Lanna in November and December was 14 and 6 kg ha^{-1}, respectively (Figure 12), mainly due to large differences in 2002/2003, with crop failure. At Ultuna the effects on SMN of different times of tillage were even smaller (Figure 13), while results from the lighter clay soil at Rydsgård in one year showed increased levels of SMN from early compared with late mouldboard ploughing (55 and 20 kg ha^{-1} respectively). This increase was of the same magnitude as previously measured in light-textured soils in south-western Sweden (Stenberg *et al*., 1999; Myrbeck & Rydberg, 2012). At Lanna, considering plant N uptake was similar in both treatments during autumn (Paper I), more N seems to have been mineralised with early rather than late tillage.

There are several possible explanations for the generally rather limited effects of time of tillage on the two heavy clay soils Ultuna and Lanna. The rate of SOM decomposition may be lower in clay soils than in more coarse-textured soils, since biomass may adhere to the clay fraction, forming complexes and microaggregates that protect SOM from degradation (Rovira & Greacen, 1957; McInerney & Bolger, 1999). A likely contributing factor is losses of N by anaerobic denitrification, which also explain some of the yearly variations, as the denitrification process is very dynamic and highly dependent on soil moisture content (Beare *et al*., 2009). The extent to which SMN reacted to the different times of tillage at Lanna seemed to vary with precipitation

(Figure 12), with the most pronounced differences occurring during dry autumns, when denitrification losses were probably small. For the Lanna soil, the latter is also supported by a positive N balance in this experiment (as well as in earlier studies in nearby fields at Lanna research station; Lindén *et al*., 2006; Aronsson & Stenberg, 2010). This indicates that gaseous losses of N may be an important pathway for N losses from this soil, and according to van deer Salm *et al*. (2006) they can be greater than losses of N through leaching.

A comparison of SMN within the different soil layers at Lanna (Paper I) showed very limited movement of SMN to deeper soil layers. Furthermore, in the Lanna and Ultuna soils, the increase in SMN from late autumn/winter to spring indicated that SMN accumulated during autumn was retained within the profile during winter and was available for plant uptake during the following growing season. Accordingly, the amounts of SMN reaching the drainage system could be assumed to be relatively small. Several previous studies (*e.g*. Koskiaho, 2002; Aronsson *et al*., 2007; Aronsson & Stenberg, 2010; Neumann *et al*., 2011) have also reported generally low losses of N (2-15 kg N ha^{-1} depending on crop grown) through the drainage system in clay soils under Nordic conditions. In contrast, at Rydsgård, where some of the SMN accumulated throughout autumn was not recovered in spring, N must have been lost by leaching and/or denitrification (Figure 13).

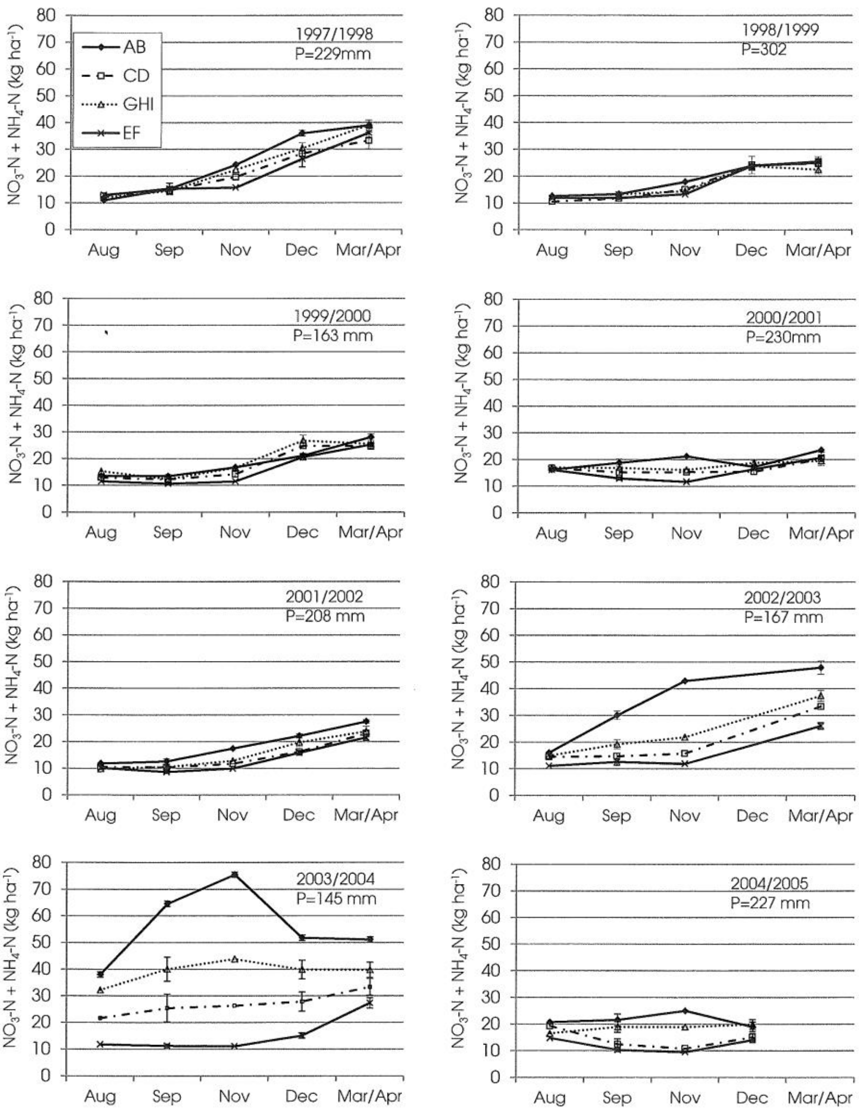

Figure 12. Soil mineral N concentration (kg ha^{-1}) at 0-0.90 m depth in the Lanna soil on five sampling occasions per year from August 1997-December 2004. AB: Mouldboard ploughing in September, CD: Mouldboard ploughing in November, GHI: Mouldboard ploughing in November with preceding stubble cultivation, EF: Mouldboard ploughing in November with a catch crop. P: Precipitation during August-November. Error bars: ± standard error.

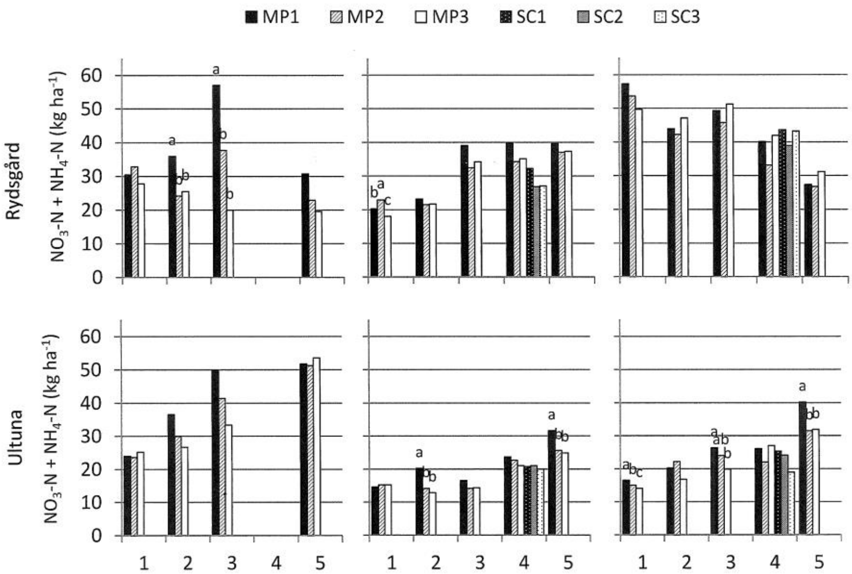

Figure 13. Soil mineral N concentration (kg ha^{-1}) within the 0-0.90 m soil layer for different times of mouldboard ploughing and stubble cultivation on different sampling occasions: 1) at the time of early tillage, 2) at the time of normal tillage, 3) at the time of late tillage, 4) one month after late tillage, 5) in spring. Stubble-cultivated treatments were only sampled on one occasion in years 2 and 3. No sampling was carried out on occasion 4 in year 1. MP=mouldboard ploughing, SC=stubble cultivation, 1=early, 2=normal, 3=late. Bars marked with different letters at each sampling occasion are significantly different for SMN ($p<0.05$).

7.3 Delayed autumn tillage – effects on soil structure and yield

My starting hypothesis was that delaying autumn tillage impairs soil structure in clay soils due to increasing soil water content throughout autumn. According to measurements of soil water content at the time of early, normal and late autumn tillage at Rydsgård and Ultuna (Paper III), the soil water content increased during autumn in all years (Table 7) and the soil was wetter than 0.9 PL at the time of both normal and late tillage.

For stubble-cultivated treatments in particular, there was a negative correlation between soil water content at the time of tillage in relation to PL (w/PL) and the proportion of small aggregates produced by tillage (Figure 14). Consequently, the earlier in autumn tillage was performed, the finer the aggregate structure in the tilled layer. These results are in agreement with Keller *et al*. (2007), who found that for water contents above the optimal (which they found to be ~0.8 PL), the amount of small aggregates decreases and the amount of clods produced increases with increasing water content. However, the differences in aggregate size distribution rarely persisted after spring seedbed preparation according to the measured aggregate size distribution in the seedbed (Papers I and III). This was probably due to the effect of freezing and thawing processes improving soil structure (Hjalmarsdottir Kvæaernø & Øygarden, 2006), since temperatures were below freezing and the soil at the experimental sites was frozen during parts of the winter. However, residual structural effects in the seedbed in spring from compaction of the soil before mouldboard ploughing in the autumn were reported by Arvidsson and Håkansson (1996).

Furthermore, other soil physical properties measured in order to detect negative effects from late tillage were very variable, and no consistent results could be obtained. This can be ascribed to the typical spatial and temporal variation in soil physical properties, the relatively small sample size and the limited number of samples. Despite this, the average values in Table 8 still indicate a structural effect from repeated tillage in late autumn, with higher SBD, higher water content at 1 and 6 m drainage (as a consequence of fewer large pores and more small pores), lower aggregate stability (from a less well developed aggregate structure) and lower infiltration capacity. This supports findings by Arvidsson and Bölenius (2006), who measured changes in soil surface height with high spatial resolution in the Ultuna experiment during year 2 and observed higher soil loosening during primary tillage at the lowest soil water content, *i.e.* after early tillage. These differences between tillage times decreased over time, but were still significant after sowing in the spring. Those authors concluded that measurement of soil surface height, and thus topsoil thickness, was more sensitive in detecting differences between treatments than bulk density measurements determined by core sampling. Arvidsson and Håkansson (1996) also reported changes in clay soil structure visible to the naked eye, although difficult to quantify, still causing a reduction in yield.

Table 7. *Gravimetric soil water content (%) at 0-0.20 m depth for different times of tillage during autumn and at 0.9PL[1] at each site and year.*

Site	Year	Soil water content (%)			
		Early tillage	Normal tillage	Late tillage	0.9 PL
Ultuna	1	20	30	34	28
	2	26	32	35	28
	3	25	30	34	28
Rydsgård	1	25	28	31	24
	2	20	24	24	23
	3	17	22	21	15

[1.] PL= lower plastic limit as defined by Atterberg (1912).

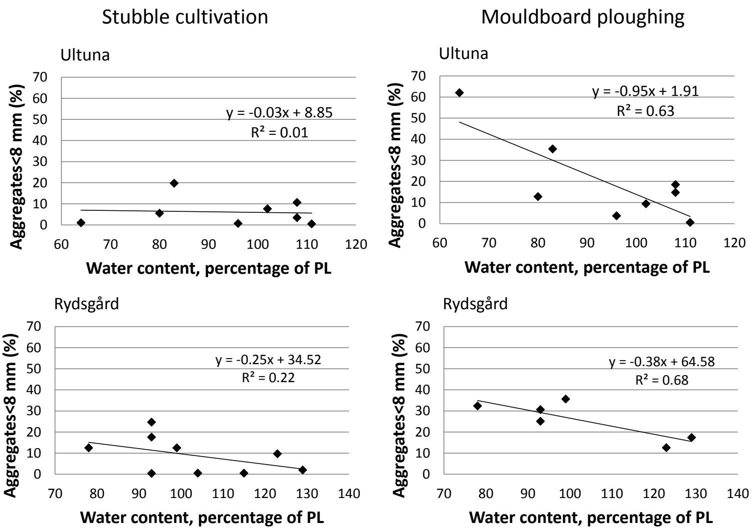

Figure 14. Proportion (% by weight) of aggregates <8 mm in diameter in the tilled layer after tillage (mouldboard ploughing or stubble cultivation) in autumn, plotted against the soil water content (%, w/w) at the time of tillage. The soil water content is expressed as percentage of water content at plastic limit (PL).

In the studies in this thesis at Ultuna and Lanna (Papers I-IV), where the treatments were repeated in the same plots year after year, late tillage resulted in a yield reduction of 11 and 7% averaged over 12 and eight years, respectively. Furthermore, the yield reduction seemed to increase with time (Figure 15). It seems reasonable to assume that this was due to poorer soil structure in late-tilled treatments. This was supported by the fact that the yield effect accumulated over the years. Moreover, it was supported by a significant difference in plant emergence observed at Ultuna, with on average 251 and 230 plants m^{-2} in early and late tilled treatments, respectively. At the same time, yield at Lanna was negatively correlated with SMN in spring (R^2=0.84). Available soil N during crop growth might explain some of the yield differences, as treatments tilled in early autumn had higher SMN when the crop was established (Figure 16) and also N mineralisation during the growing season (Paper I) than treatments tilled in late autumn. This could be of particular importance in organic farming systems, where N is a frequent growth-limiting factor.

Stenberg *et al*. (1999) obtained a similar yield reduction on a sandy loam soil, where delaying mouldboard ploughing from September to November decreased yield by 18%. They attributed the yield decrease following late tillage to couch-grass (*Elymus repens* L.) infestation. However, in the present study the incidence of couch-grass and other weeds competing with the main crop during the growing season was quite low, and hence could not explain yield differences. In summary, the results in Papers I and III showed that late autumn tillage of clay soils reduces yield, carries a risk of reducing plant available N during the cropping season and negatively affects soil structure.

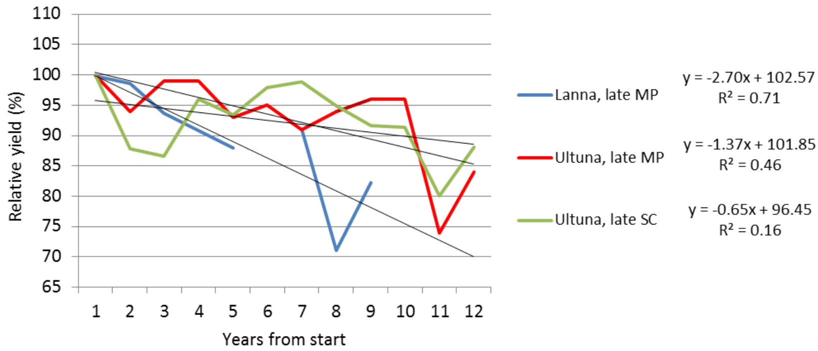

Figure 15. Relative yield (%) after mouldboard ploughing (MP) and stubble cultivation (SC) of clay soils in late compared with early autumn (early autumn=100%) during nine consecutive years at Lanna and 12 at Ultuna. Data for year six at Lanna were excluded due to severe damage by the saddle gall midge. The equation and R^2-value for each trend line are shown in the legend.

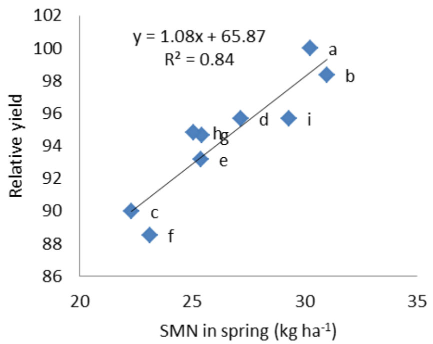

Figure 16. Yield (%, treatment a=100) in relation to soil mineral nitrogen (SMN) in the soil profile (0-90 cm) in spring in treatments a-h at Lanna (for explanation of treatments see Table 4).

Table 8. *Soil physical properties – a comparison between early and late autumn tillage. Moisture content (0.09-0.14 m depth), at -10 (MC_{10}) and -60 (MC_{60}) kPa, dry bulk density (0.09-0.14 m depth), aggregate tensile strength (0.05-0.12 m depth), wet aggregate stability expressed as dispersion (0.05-0.12 m depth), water infiltration capacity expressed as Ksat. MP: mouldboard ploughing; SC: stubble cultivation. (MP and SC do not include the same years, so they should not be compared with each other). The underlined figure within the comparison of early and late tillage indicates the most favourable soil structure*

		Ultuna		Rydgård		Lanna	
		Early	Late	Early	Late	Early	Late
Moisture content, MC_{10}	(%. v/v)	-	-	-	-	<u>38.9</u>	41.4
Moisture content, MC_{60}	(%. v/v)	-	-	-	-	<u>34.2</u>	37.2
Dry bulk density, MP	(g cm^{-3})	<u>1.30</u>	1.33	<u>1.47</u>	1.48	<u>1.33</u>	1.43
Dry bulk density, SC	(g cm^{-3})	1.36	1.36	<u>1.55</u>	1.57	-	-
Tensile strength, MP	(kPa)	<u>763</u>	777	<u>724</u>	783	948	<u>857</u>
Tensile strength, SC	(kPa)	815	<u>775</u>	588	<u>570</u>	-	-
Aggregate dispersion[1]	(NTU g^{-1})	-	-	-	-	<u>78.8</u>	105.9
K_{sat}, MP	(cm h^{-1})	<u>0.54</u>	0.31	0.32	<u>0.41</u>	<u>0.46</u>	0,11
K_{sat}, SC	(cm h^{-1})	0.03	<u>0.4</u>	0.31	<u>0.58</u>	-	-

[1.] Figures refer to turbidity in an aqueous phase determined in Nephelometric Turbidity Units (NTU).

7.4 Time of tillage and date of sowing of winter wheat

The accumulation of SMN in autumn is generally larger after winter oilseed rape than after cereals (Sieling *et al*., 1999; Ryan *et al*., 2006). In the study in Paper II, SMN in late autumn and winter was 21-52 kg ha^{-1}. This is somewhat lower than that measured at the corresponding latitude by Engström *et al*. (2011), who reported 30-86 kg ha^{-1} in November in winter wheat following oilseed rape. Nevertheless there was a large variation in SMN between treatments in Paper II. Changes in SMN during autumn in late-sown treatments varied between the experiments, mainly due to different strategies regarding the use of glyphosate. Therefore in Figure 17, SMN is presented separately for experiments with and without glyphosate. In accordance with our hypothesis, SMN during autumn and early winter was lower when the time interval between tillage and sowing in autumn was shortened, showing that the focus of N reduction strategies should not only be on the timing of tillage in autumn, but also on the time interval between tillage and sowing. However, this effect could not be attributed to a direct effect of tillage on N mineralisation, since killing of weeds and volunteer plants by application of glyphosate generally had the same effect as early tillage. Similarly, Aronsson *et al*. (2008) concluded that time of tillage seemed not to affect SMN (or N leaching) during autumn and winter at all when a cover crop was killed by chemical treatment in early autumn. They observed rapid nutrient release from the chemically killed plant material. This highlights the impact of glyphosate on accumulation of SMN during autumn by interruption of plant uptake of N, together with release of mineralised N from the killed plant material.

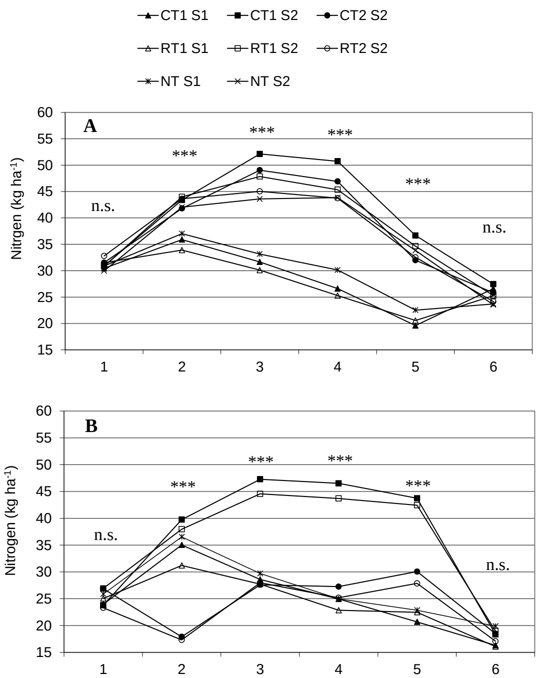

Figure 17. Soil mineral N at 0-0.60 m depth on six sampling occasions (nos. 1-5 during autumn and no. 6 in spring). A) Mean of four experiments where glyphosate was applied in all treatments in August. B) Mean of two experiments where no glyphosate was applied. Conventional tillage (CT), reduced tillage (RT) and non-tillage (NT) and early (1) and late (2) time of tillage in combination with early (S1) and late (S2) sowing. Sampling occasion 1 = Early autumn (immediately before the first tillage occasion), 2 = immediately before the late tillage occasion, 3 = two weeks after the late sowing occasion, 4 = one month after the late sowing occasion, 5 = late November and 6 = spring. n.s. = no significant difference between treatments ($p<0.05$), *** = significant difference, $p<0.001$.

With an early established winter wheat crop, N accumulation in the soil during autumn remained low, irrespective of tillage method. Autumn SMN was reduced by 14-24 kg ha^{-1} when sowing was carried out immediately after early tillage compared with 3-4 weeks later (Figure 17). This is in agreement with Lindén *et al*. (2000), who reported a SMN difference of 16 kg ha^{-1} in November when comparing early and late sowing of winter wheat. Differences in SMN could be fairly well explained by differences in crop and weed uptake of N (Figure 18). Exceptions were where no glyphosate was applied; late stubble-cultivated treatments at Lönnstorp 2007/2008 and all late-sown treatments at Bjertorp 2007/2008 (Paper II). In these treatments SMN was low, almost certainly due to N being bound to incorporated plant tissues of weeds and volunteer plants, taken up during the 3-4 weeks between early and late tillage.

The uptake of N in winter wheat aboveground material during autumn was rather high (11-24 kg ha^{-1}) with sowing in late August/early September, compared with sowing approximately three weeks later (3-7 kg ha^{-1}) (Table 9). Lindén *et al*. (2000) reported somewhat lower average uptake in aboveground parts of winter wheat in two field trials in south-western Sweden (10 kg ha^{-1} when sown on 8 September and 17 kg ha^{-1} when sown on 15 August).

Table 9. *Nitrogen content (kg ha^{-1}) in aboveground parts of winter wheat crop, weeds and volunteer plants sampled in late November after early (average date 31/8) and late (average date 23/9) sowing. Conventional tillage (CT), reduced tillage (RT) and non-tillage (NT) and early (1) and late (2) time of tillage were tested in combination with early (S1) and late (S2) sowing*

	Bjertorp 2009/10	Lonnstorp 2007/08	Lonnstorp 2008/09	Lonnstorp 2009/10	Alnarp 2009/10	Average
CT1 S1	19.9a	21.8ab	22.7a	16.3a	13.2a	18.7a
CT1 S2	4.2c	7.6c	7.4b	5cd	4.2d	5.7b
CT2 S2	3.4c	6.3c	7.3b	5.4c	4d	5.3b
RT1 S1	20.4a	19.3b	21.2a	11.2b	10.7b	16.6a
RT1 S2	4.6c	7.9c	6.5b	3.6cd	3.2de	5.2b
RT2 S2	4.7c	6.6c	6.8b	4.2cd	3.1de	5.1b
NT S1	19.5a	22.4a	23.5a	13.2b	9c	17.5a
NT S2	7b	7.2c	8.2b	3.5d	2.2e	5.6b
S1 (31/8)	19.9a	21.2a	22.4a	13.6a	10.9a	17.6a
S2 (23/9)	4.8b	7.1b	7.2b	4.3b	3.4b	5.4b

Values within years or means followed by different letters are significantly different ($p<0.05$).

However, they too observed a large effect of sowing time, with only 2 kg ha^{-1} N uptake with sowing in the beginning of October. Hence early sowing of winter wheat seems a possible way of reducing the risk of N leaching.

Thomsen *et al.* (2010) pointed out the importance of early sowing of a winter crop in reducing the risk of accumulation of N in soil during autumn in temperate climates, not least in light of predicted future increases in air temperature and N mineralisation during autumn. Also the crop rotation study in Paper IV showed a substantial increase in plant N uptake during autumn (Table 10) and reduced leaching losses of NO_3-N (Figure 19) from earlier sowing of winter wheat after oilseed rape.

In summary, in agreement with Hansen *et al.* (2010), Paper II demonstrated the importance of a well-established crop for minimising N leaching in winter crops. Furthermore it pointed out the importance of combined timing of tillage, sowing date and application of glyphosate or other herbicides in reducing N leaching. In general, different establishment strategies for winter wheat did not affect yield. However, late direct drilling reduced yield in some years, especially where glyphosate was not used prior to sowing (Paper II).

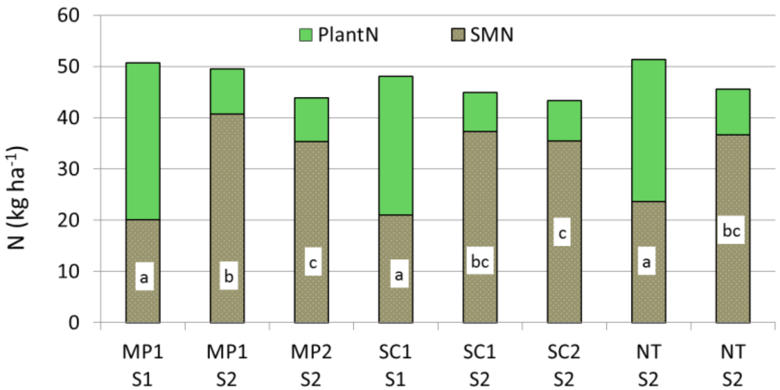

Figure 18. Soil mineral nitrogen (SMN, kg ha^{-1}) in the soil profile and total-N in a winter wheat crop in late November. Late tillage and late direct drilling were preceded by a glyphosate treatment. Mouldboard ploughing (MP), stubble cultivation (SC) and non-tillage (NT) and early (1) and late (2) time of tillage were tested in combination with early (S1) and late (S2) sowing. Bars marked with different letters are significantly different for SMN ($p<0.05$).

7.5 Tillage intensity

Contrasting results have been found when comparing different intensities of tillage on mineral soils. Studies reporting less accumulation of SMN and/or N leaching with reduced tillage practices most often include a comparison between a no tillage (direct drilling) system and a conventional tillage system (e.g. Nyborg & Malhi, 1989; Goss et al., 1993; Hansen & Djurhuus, 1997; Power & Peterson, 1998), while there have been rather few studies on the effect of tillage depth. Stenberg et al. (1999), Catt et al. (2000) and Chatskikh et al. (2008) suggest a lower rate of turnover and/or N leaching after stubble cultivation compared with mouldboard ploughing. However, other studies show the opposite, with no or inconsistent effects of tillage depth (Hooker et al., 2008; Hansen et al., 2010; Regina & Alakukku, 2010). Catt et al. (2000) reported 20% lower mineral N content in soil and 25% lower mean annual NO_3-N losses per 100 mm drain flow during autumn and winter with shallow tine cultivation (0.07 m depth) than with mouldboard ploughing (0.20 m depth) in winter cereals on a heavy clay (55%) soil in the UK. They attributed this to limited mineralisation of OM in the soil compared with after ploughing.

Somewhat contradictory results were also obtained in this thesis. At Lanna, SMN during late autumn (November) was on average 9 kg ha^{-1} lower in stubble-cultivated plots than in plots mouldboard ploughed in early autumn (Paper I). Considering that plant N uptake was similar in both treatments during autumn (Paper I), this appears to be due to lower net N mineralisation after stubble cultivation compared with mouldboard ploughing. For the clay soils at Ultuna and Rydsgård no corresponding difference was detected. Furthermore, results from nine experiments in winter wheat at Bjertorp, Lönnstorp and Alnarp (Paper II) showed that with the same time interval between tillage and sowing, in general there were no differences in SMN between tillage methods (Figure 17).

To winter wheat, the NT treatment generally resulted in high levels of SMN (Figure 17). This confirms previous work under Mediterranean climate by Lotfollahi (2006) and under Scandinavian climate by Hansen *et al.* (2010) and Engström *et al.* (2011). Occasionally higher levels of NO_3 leaching after no-till compared with ploughing were reported by Lotfollahi (2006) and Hansen *et al.* (2010). They attributed this to lower plant uptake of N in no-till caused by poor establishment in too dry soil and reduced root growth compared with in ploughed soil, as shown by Munkholm *et al.* (2008). However, in this thesis crop uptake in winter wheat generally did not differ between establishment methods. Instead, the results obtained were mainly explained by effects on SMN being similar from a glyphosate application prior to direct drilling as from mouldboard ploughing or stubble cultivation, indicating the increase in

SMN was due to interrupted N uptake in weeds and volunteer plants rather than to increased net N mineralisation due to tillage. Any possible effects of tillage on N mineralisation were masked by differences in crop and weed uptake of N. In summary, reduced tillage in autumn for spring cereals might reduce SMN accumulation and N leaching, although in this thesis effects from reduced tillage on SMN were detected at only one of three experimental sites. However, reduced tillage in terms of direct drilling for spring crops might reduce N leaching in clay soils, where delayed autumn tillage and spring tillage are not suitable practices. For winter cereals, there are unlikely to be water quality benefits accruing from a change from conventional to reduced tillage and instead, early sowing and a short time interval between tillage and sowing seem to be important factors.

7.6 Long-term and short-term effects within a crop sequence

Methods for measuring N leaching all have their drawbacks. In the tile-drain study in Paper IV, discharge varied between plots. That experimental field is almost flat, so surface transport of water between experimental plots can be expected to be very limited. Obviously water infiltration occurred in between the drainage pipes. However, average drainage values from the three plots within each treatment were approximately the same for the CON and NUE systems (Paper IV). Total discharge from the drainage systems during the experimental period (1999/00-2010/11) was 3220 mm and 3335 mm for the CON and NUE system, respectively. Several previous studies conducted in nearby fields have used a simulation model (SOILN; Blombäck *et al.*, 2003) which describes water flow and N transformation and transport in soil, in addition to field measurements (mostly separately tile-drained plots but in some cases ceramic cups), to interpret data and to calculate N budgets and N mineralisation in the soil (*e.g.* Blombäck *et al.*, 2003; Torstensson *et al.*, 2006). The results show that there is generally limited interference by groundwater flowing into the drains and affecting N concentrations. The underlying glacifluvial clay at the site can be expected to function as a barrier under the drainage depth, slowing down both upward and downward transport of water. The water sampled in the drains can hence be assumed to be fairly representative and we do believe that sampling of water in tile drains is the most appropriate approach at this site. As previously mentioned, losses of N were also well reflected by measured SMN content in the soil profile during autumn and winter (Figure 3).

In Paper IV, production of winter wheat, spring barley and spring oilseed rape in one conventional (CON) and one N use efficient (NUE) system resulted in a reduction in leaching losses of NO_3-N by in total 37% (Figure 19), and by 35% per kg grain produced. At the same time, as shown in Table 10, biomass production during autumn was significantly greater in the NUE than the CON system (on average 22 and 12 kg ha^{-1}, respectively, in aboveground plant parts). The mean NO_3-N concentration in drainage water was generally higher in the CON than in the NUE system (Figure 20). The mean maximum monthly concentration of NO_3-N in water was 40 mg NO_3-N L^{-1}, which can be compared with the maximum value for drinking water according to the EU Water Framework Directive of 11.3 mg NO_3-N (50 mg NO_3^- L^{-1}) (EU, 2006). Average monthly values exceeded 11.3 mg NO_3-N L^{-1} in 10 out of 12 years in CON, but in only three out of 12 years in NUE. Thus the findings showed that the NUE system better captured the N circulating in the system and that peaks in NO_3-N concentrations can be avoided by altering management practices.

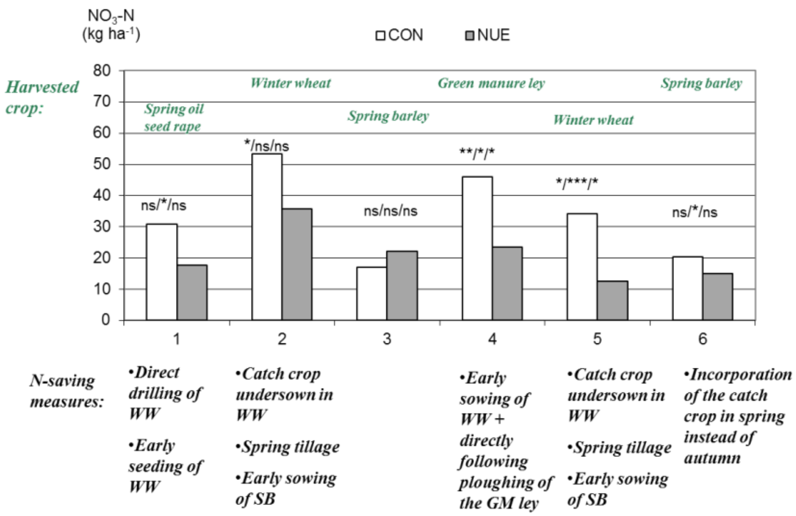

Figure 19. Amount of leached NO_3-N (kg ha^{-1}) in drainage water (average of two cycles of a six-year crop rotation) (agrohydrological years, 1 July to 30 June) in a conventional (CON) and a nitrogen use efficient (NUE) system. The specific N-saving measures associated with each agrohydrological year are shown at the bottom. The crops given are those harvested in the beginning of the respective year. WW=winter wheat, SB=spring barley, GM=green manure. Significant differences between treatments are shown above the bars for the first crop rotation cycle, the second crop rotation cycle and averaged over both crop rotation cycles. *Significant difference between treatments, $p<0.05$; *significant difference between treatments, $p<0.01$; ***significant difference between treatments, $p<0.001$; ns=no significant difference.

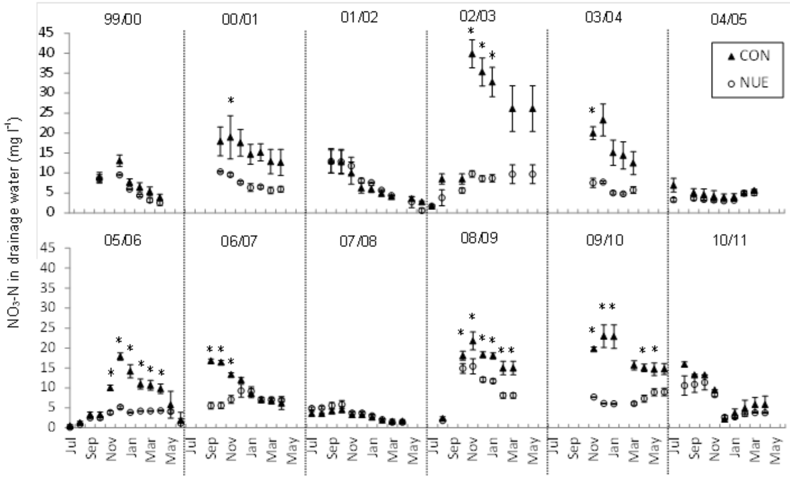

Figure 20. Measured concentrations of NO_3-N (mg/L) in drainage water during two cycles of a six-year crop rotation. CON=conventional system, NUE=nitrogen use efficient system. Months without values had no water running in the drains. *Significant difference between treatments, $p<0.05$. Error bars: ± standard error. n=3.

Measures included in Paper IV were all nested and hence could not be individually evaluated. However, as shown in Figure 19, the most obvious effects were recorded in crop sequence years 4>5>2, including sowing of winter wheat immediately after the green manure ley was ploughed under compared with one month later (yr 4), undersowing of a ryegrass catch crop in winter wheat in spring and mouldboard ploughing in spring instead of stubble cultivation and mouldboard ploughing in autumn before sowing of spring barley (yrs 2 and 5). Previous studies (*e.g.* Neumann *et al.*, 2011; Stenberg *et al.*, 2012) also identified sowing winter cereals after incorporation of clover-grass ley as posing a risk of substantial N leaching. Neuman *et al.* (2011) attributed this to early date of incorporation, as late incorporation followed by bare fallow gave lower leaching of N, and recommended avoiding early incorporation and growing a spring cereal instead of winter wheat in the year following incorporation of ley. Lindén and Wallgren (1993) found that winter wheat sown after early ploughing of ley could not eliminate the increased risks of N leaching during the winter. This was compared with late incorporation followed by spring cereals. However Paper IV, in line with the results presented in Paper II, showed that a reduction in N leaching losses could be obtained by establishing a winter wheat crop soon after incorporation of a ley, as was done in the NUE system – an effect of substantially higher N uptake during autumn (Table 10).

Despite having a well-established catch crop undersown in the barley crop, incorporation in spring instead of autumn was not followed by any substantial reduction in NO_3-N leaching losses (3 kg ha^{-1}). This lack of a pronounced difference between the CON and NUE systems could be due to increased mineralisation in NUE from incorporating the catch crop undersown in winter wheat in the preceding year. Increased net mineralisation from the incorporated catch crop undersown in winter wheat in the NUE system was also observed in 2001/02 and 2007/08, when leaching was higher than in the CON system. Enhanced net mineralisation through growing a catch crop has been reported previously by *e.g.* Constantin *et al*. (2011).

Increased N mineralisation from catch crops should be evaluated in a long time scale (Berntsen *et al*., 2006). This is also true for other measures used in our crop rotation study. A somewhat smaller average difference between the two systems in terms of N leaching during the second crop rotation cycle (33%) compared with the first (46%) could be an indication of increased N delivery of previously recovered N in the NUE system during the second cycle. A residual effect of previous long-term use (24 years) of a ryegrass catch crop facilitated a reduction in N fertilisation to spring wheat by as much as 20-25% at fertilisation rates of 60-120 kg ha^{-1} in a study by Hansen *et al*. (2000). Constantin *et al*. (2011) reported an extra mineralisation rate from incorporation of catch crops, which increased over time at a rate of 2 kg N ha^{-1} yr^{-1}. However, in Paper IV this presumed increase in mineralisation from incorporated catch crop material seemed small in relation to the benefit in terms of reduced N leaching during growth of the catch crop, although this might have changed if the experiment had continued for a longer period. Nevertheless, eight years of continuous use of catch crops at Lanna gave no signs of reduced effectiveness in decreasing leachable N during autumn and winter, where the outcome was reduced SMN accumulation during autumn and winter (Figure 12), increased mineralisation during the growing season and no yield reduction (Paper I).

Nevertheless, probably due to the frequent use of spring ploughing and direct drilling, there was substantial growth of weeds in the NUE system which in some years caused a reduction in yield. Previous studies have shown that when tillage for spring cereals is delayed (Stenberg *et al*., 1999) or reduced (Børressen, 1993) under Scandinavian conditions, there may be substantial autumn growth of weeds, particularly couch-grass. However, average grain yield (12 yr) did not differ between the CON and NUE systems (Paper IV).

In summary, Paper IV, in line with a previous study by Hansen *et al*. (2010), showed that management practices that improve biomass production throughout the year are crucial in order to close the N cycle and thereby reduce N leaching.

Table 10. *Nitrogen content (kg/ha^{-1}) in aboveground parts of green material (weeds, W; volunteer plants, Vp; green manure crop Gm; winter wheat crop, Ww) during autumn. CON=conventional system, NUE=nitrogen use efficient system. (-)=close to zero, too little green material to be sampled.*

Crop rotation yr	Date of sampling	Green material CON	NUE	N (kg ha^{-1}) CON	NUE
1	30 Aug	W, Vp	W, Vp	3.5	7.8
	20 Oct	W, Vp, Ww	W, Vp, Ww	2.4a	12.0b
2	30 Aug	W, Vp	W, Vp, Cc	1.3a	3.5b
	8 Nov	W, Vp	W, Vp, Cc	8.9	18.2
3	20 Aug	W, Vp, Gm	W, Vp, Gm	12.4a	5.6b
	30 Oct	W, Vp, Gm	W, Vp, Gm	44.8	31.7
4	15 Nov	W, Vp, Ww	W, Vp, Ww	3.8a	22.8b
	4 Dec	W, Vp, Ww	W, Vp, Ww	3.6a	31.5b
5	4 Nov	W, Vp	W, Vp, Cc	-	28.9
	3 Dec	W, Vp	W, Vp, Cc	-	23.6
6	2 Sept	W, Vp, Cc	W, Vp, Cc	12.1	12.1

Values within sampling dates followed by different letters are significantly different ($p<0.05$).

7.7 Tillage – Mineralisation – N leaching

Soil tillage has been shown to induce increased biodegradation rates in native soils. Tillage of native soils or old grasslands seems to cause a drop in SOM (Doran *et al*., 1987; Addiscott, 1988; Gupta & Germida, 1988) that cannot fully be explained by changes in *e.g.* C input and outputs or losses of topsoil by erosion (Balesdent *et al*., 2000). The quantity of OM retained in a soil is the result of achieving a balance between inputs and mineralisation, as affected by the physical and chemical properties of the site (Tate, 1995). Thus all disturbance of a soil, for example by cultivation, can be expected to result in the establishment of a new equilibrium. Although tillage is generally said to stimulate mineralisation of SOM, its impact in frequently cropped soils remains somewhat unclear. Frequently cultivated soils may be so close to equilibrium that tillage in general has only limited effects on net mineralisation rates of SOM under cold humid conditions. This is supported by studies of short-term effects showing very inconsistent results for mineralisation rates after tillage (see section 7.5). Furthermore, it is supported by a lack of consistent results on the long-term effects on total C and N in soil in studies comparing conventional tillage and reduced or no tillage. Several studies have reported that reduced tillage appears to have no significant effect on the sequestration of C and N and the global C cycle (*e.g.* Etana *et al*., 1999; Puget *et al*., 2005).

The majority of the experiments reported in this thesis indicated no or very limited influence of tillage on N mineralisation rates, as changes in SMN were mainly explained by plant uptake of N. However, increases in SMN that were not fully explained by differences in plant uptake were detected after early compared with late tillage and after mouldboard ploughing compared with stubble cultivation during mainly two years at Lanna (Figure 12) and one year at Rydsgård (Figure 13). This indicates that mineralisation was enhanced by tillage.

Although a change from mouldboard ploughing to reduced tillage may have limited effects on SMN, long-term use of non-inversion shallow tillage can possibly reduce N leaching by increased macropore flow. Macropore flow can protect NO_3^- within the soil matrix from being washed downwards in the profile compared with when the entire soil volume is involved in the flow process (Shipitalo *et al*., 2000). Goss *et al*. (1993) observed lower NO_3-N concentrations in drainage water after direct drilling than after mouldboard ploughing on a clayey soil in England, which they attributed partly to more bypass flow in direct-drilled plots.

7.8 Results in relation to government regulations

Subsidies have been used by the authorities in Sweden to encourage farmers to grow catch crops and postpone tillage for spring cereals until spring. For spring tillage, no herbicides are allowed during autumn. These actions are highly supported by the results in this thesis.

Furthermore, all farms >5 ha within the main areas classified as nitrate vulnerable zones in Sweden (Figure 1) are affected by regulations on autumn and winter covering of the soil (SJVFS, 2011:25). At a minimum, 50-60% of arable land has to be covered during autumn. Winter wheat is one of the crops eligible, stubble and catch crops are others. The winter wheat crop has to be sown by 5 October at the latest in counties in the very south of Sweden and by 15 October in the remaining counties. According to Paper II, N uptake in winter wheat during autumn is significantly lower when sowing is carried out in late September instead of in late August. The N content in aboveground crop parts in the former was 17 kg ha^{-1}, while in the latter it was only 5 kg ha^{-1}. Hence, the N uptake in a wheat crop established as late as 5 or 15 October can be expected to be very low. It is possible that drainage water quality from winter wheat fields would greatly benefit from these dates being brought forward (to earlier in autumn).

Within the regulations on autumn and winter covering of soil, tillage or chemical treatments are not allowed earlier than 10 or 20 October depending on area. At this time in autumn, the clay soils studied in this thesis (Paper III) already had soil water contents higher than were optimal for tillage. The somewhat heavier clay soils in this thesis, like clay soils in other studies, were not very prone to N leaching, so this regulation runs the risk of having more negative than positive effects, with poor soil structure and yield decreases as consequences.

8 Implications for future research

The results presented in this thesis indicate potential for further reductions in N leaching, especially in autumn-sown crops which, despite a current increase in acreage, are much less discussed in this context in Sweden than spring crops. The most obvious mitigating effect in winter wheat cropping was obtained with early sowing. Despite the absence of negative effects on yield in this thesis, however, too early sowing can be a risk factor for the spread of wheat dwarf virus and snow mould (*Microdochium nivale*). Increased knowledge and quantification of these risks under modern crop varieties and establishment techniques would be valuable in light of predicted future warmer and moister autumns.

Considering that the measures identified as effective in reducing N leaching losses were all related to higher soil coverage by crops, new methods are needed to prevent weeds from increasing in systems with *e.g.* frequent spring ploughing, delayed autumn tillage and the use of catch crops. With current methods, it may be necessary to accept a crop-free autumn every four or five years so that weeds can be controlled either chemically or mechanically.

There was a seemingly fast release of N from chemically killed plant material in this study, as previously shown by Aronsson *et al*. (2008). Thus a more rapid release than from deeply incorporated fresh plant material using mouldboard ploughing is possible. However, this was not investigated and further research is needed. Such knowledge is important in the context of *e.g.* direct drilling and N dynamics, as direct drilling in autumn often requires preceding chemical treatment.

The studies within this work were limited to systems with mineral fertiliser use. On soils high in SOM and with animal manure supplied, tillage may have had a more pronounced effect on N mineralisation. Tillage effects on N leaching in systems with organic fertilisers including various waste products are of interest.

9 Conclusions

- It is possible to substantially reduce leaching losses of N from arable land by choice of soil tillage strategies.

- Tillage effects on SMN can mainly be attributed to interruption of N uptake in crops and weeds rather than stimulated N mineralisation. Therefore, a high degree of soil coverage by living plants during autumn and winter should be the main focus in mitigation of N leaching losses from arable fields. Timing of tillage is an important tool in this aspect.

- SMN accumulation in winter wheat during autumn and winter was not influenced by tillage method and hence there are unlikely to be water quality benefits accruing from a change from conventional to reduced tillage or direct drilling to winter crops.

- There is potential for further reductions in leaching losses of N in winter wheat production by early sowing, a short time interval between tillage and sowing and undersowing of a catch crop in spring.

- The suitability of delayed autumn tillage as a means to reduce loads of N from agriculture to surrounding waters (as earlier shown on sandy soils) varies between Swedish clay soils and sites. A reduction in accumulation of leachable SMN can be achieved on lighter clay soils. However, the effects may be small on heavier clay soils, as repeated late tillage was shown to cause yield reductions, possibly due to poorer soil structure.

- Incorporation of cereal straw with a high C/N-ratio did not reduce SMN during autumn and winter and hence cannot be considered a measure against N leaching.

- The reduction in NO_3^- concentrations in drainage water and 37% reduction in leaching of NO_3^- obtained within a 6-year crop rotation, without severe effects on yield, show the potential of adapting soil management and tillage to the crop rotation in order to synchronise SMN with crop demand.

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