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Cover: Deep placement of straw slurry
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# Subsoil improvement for sustainable intensification. Impact of loosening with straw incorporation or liming on subsoil properties, crop performance and water quality


## Abstract

Subsoil has a high capacity for nutrient and water retention, but arable subsoil is often nutrient poor, carbon-deficient and compacted, affecting both root growth and yield. In field and lysimeter experiments, this thesis investigated the effects of subsoil loosening and loosening with cereal straw incorporation (24-60 Mg ha$^{-1}$) (loosening + straw) on crop yield, soil properties (bulk density, penetration resistance, moisture characteristics) and leaching. A rectangular metal tube welded behind each tine of a deep loosener was used to inject straw as a slurry in the field, while subsoil was loosened and mixed manually with milled straw in lysimeter studies. In laboratory experiments, subsoil was limed with different amounts of $CaCO_3$ and CaO to increase soil pH from 7.0 to 7.5, 8.0 and 8.4 and incubated for 22 months to examine changes in soil structural stability and dissolved reactive phosphorus.

Field subsoil loosening + straw significantly increased soil organic carbon, total nitrogen and water holding capacity. It also decreased bulk density, from around 1.5 Mg m$^{-3}$ in the control to about 1.0 Mg m$^{-3}$. The effects of loosening + straw persisted for at least three years, but loosening alone had weak and short-lived effects. Loosening + straw significantly increased grain yield in the first cropping season (6% higher than the control), but not in the following two years.

Nitrogen balance calculations of lysimeters showed that short-term nitrogen losses were lowest in the subsoil loosening + straw treatment and that nitrogen leaching was reduced by about 62%. In incubations, subsoil liming decreased clay dispersion. Wet aggregate stability and concentration of dissolved reactive phosphorus increased and peaked around pH 7.8 and 7.5, respectively. Combining loosening with straw incorporation into subsoil appeared to improve soil properties and water quality, but not crop yield on the experimental soil. On other soil types, this practice may have more beneficial effects.



Keywords: aggregate stability, grain yield, immobilisation, lysimeter, organic matter, N-balance, N-leaching, soil pH



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# Dedication

This piece of work is dedicated to

- My father, LiekeTebebit Tarekegn Getahun
- My mother, Tiblet Ayele and
- My wife, Meseret Menil.

This note is in memory of my father, who passed away in July 2020. I was shocked and devastated by his death, which has left a painful scar that will take long to heal. My father placed GOD over everything and he taught me to trust in GOD. I will always remember him for providing me with opportunities and for selflessly encouraging me to become the person who I am today. I am grateful to him for shaping my life through his compassion, pain and sacrifice. I believe he is up there listening, watching over me and sending me his blessings. This is indeed for you Dad, as well as for Tiblet and Meseret.

# Contents

# List of publications

This thesis is a synthesis of the work in the following articles, referred to in the text by Roman numerals.

I. Getahun, G.T., Kätterer, T., Munkholm, L.J., Parvage, M.M., Keller, T., Rychel, K. & Kirchmann, H. (2018). Short-term effects of loosening and incorporation of straw slurry into the upper subsoil on soil physical properties and crop yield. *Soil and Tillage Research* 184: 62-67.

II. Getahun, G.T., Bergström, L., Rychel, K., Kätterer, T. & Kirchmann, H. (2021). Impact of loosening and straw addition to the subsoil on crop performance and nitrogen leaching-a lysimeter study. Manuscript accepted for publication in *Journal of Environmental Quality*.

III. Getahun, G.T., Etana, A., Munkholm, L.J. & Kirchmann, H. (202X). Liming with $CaCO_3$ or CaO affects aggregate stability and dissolved reactive phosphorus in a heavy clay subsoil. In revision (moderate), submitted to *Soil and Tillage Research.*

IV. Getahun, G.T., Kätterer, T., Munkholm, L.J., Rychel, K. & Kirchmann, H. (202X). Effects of loosening combined with straw incorporation into the upper subsoil on soil properties and crop yield in a three-year field experiment (manuscript).

Paper I is reproduced with the permission of the publisher.

The contribution of Gizachew Tarekegn Getahun to the papers included in this thesis was as follows:

I. First and corresponding author. Planned the experiment together with the first and sixth co-authors. Performed the fieldwork with assistance from the third, fifth and sixth co-authors. Performed data analysis and interpretation. Wrote the manuscript with assistance from all co-authors

II. First and corresponding author. Planned the experiment together with the co-authors. Performed data analysis and interpretation. The second co-author did the $N_2O$ data collection and analysis. Wrote the manuscript with assistance from all co-authors.

III. First and corresponding author. Planned the experiment with the third co-author. Performed data analysis and interpretation. Wrote the manuscript with assistance from all co-authors

IV. First and corresponding author. Planned the experiment together with the first and the fourth co-authors. Performed data analysis and interpretation. Wrote the manuscript with assistance from all co-authors

# Abbreviations

| | |
|---|---|
| $CaCO_3$ | Calcium carbonate |
| CaO | Calcium oxide |
| C:N | Carbon to nitrogen ratio |
| DC | Degree of compactness |
| DRP | Dissolved reactive phosphorus |
| N | Total nitrogen |
| $N_2O$ | Nitrous oxide |
| PVC | Polyvinyl chloride |
| SOC | Soil organic carbon |
| SPAD | Soil Plant Analysis Development |

# 1. Introduction

The global population is increasing, with an associated increase in demand for food (Ray *et al.* 2013; FAO 2018). However, arable land acreage is limited and there is little option to expand (Alakukku 1999; Rengasamy *et al.* 2003). In addition, in various parts of the world, further increases to crop yield is impeded by climate change (Brisson *et al.* 2010; Ray *et al.* 2012), land degradation (Ladha *et al.* 2003), reduced fertiliser use (Brisson *et al.* 2010; Lin & Huybers 2012) *etc*. Thus, it will be a challenge for future agriculture to sustainably produce more food to meet the needs of the global population (Foley *et al.* 2011; Ray *et al.* 2012).

To avoid further deforestation and exploitation of other ecosystems, crop yield per unit area must increase (Rengasamy *et al.* 2003; Ray *et al.* 2013). In this regard, it could be better to integrate the subsoil fully into crop-soil management decisions (Frelih-Larsen *et al.* 2018). The role of subsoil has been often neglected and subsoil is not valued as it should be (Kautz *et al.* 2013).

In soils where roots have access to a deeper soil layer, the subsoil can contribute water and nutrients such as nitrogen, phosphorus and potassium to crops, even during seasonal drought and nutrient depletion and in low-input farming systems (Kautz *et al.* 2013; Sosa-Hernández *et al.* 2019). Thus, subsoil management may increase crop adaptive capacity to adverse impacts of climate change (*e.g.* use of subsoil water during drought) and mitigate climate change through carbon sequestration (Schneider *et al.* 2017; Frelih-Larsen *et al.* 2018). However, subsoils are often deficient in nutrients, low in soil organic carbon, poor in structure and limited in microbial activity (Håkansson *et al.* 1988; Kautz *et al.* 2013).

Access to subsoil by roots can be limited due to acidity and water-logging (Lynch & Wojciechowski 2015) and by the presence of a plough pan and compaction due to heavy agricultural machinery and dense subsoil matrix (Håkansson & Reeder 1994). Under suboptimal conditions, root growth into deeper layers is restricted and roots grow thicker and shorter and extend laterally (Oussible *et al.* 1992; Lipiec *et al.* 2003). This adversely affects acquisition of resources from the deeper soil layer, weakening the productive capacity of soils.

Mechanical subsoil loosening is a way to loosen up dense soil layers and improve subsoil properties. Specifically, loosening decreases penetration resistance and bulk density (Varsa *et al.* 1997), while it increases infiltration (Raper & Bergtold 2007), rooting depth (Jakobs *et al.* 2019) and crop yield (Khalilian *et al.* 1991; Adcock *et al.* 2007). However, the benefits of subsoil loosening may disappear over time due to recompaction (Larney & Fortune 1986; Johnson *et al.* 1989; Håkansson *et al.* 1996). Subsoil loosening is also expensive and may have adverse effects by destroying the soil structure (Håkansson & Reeder, 1994; Schneider *et al*., 2017).

Combining subsoil loosening with other remedial practices, such as addition of straw, manure, compost or lime, may be a more promising approach to address several subsoil problems at once (compaction, low soil organic carbon content, nutrient deficiency, acidity *etc*.) (Hamza & Anderson 2005; Leskiw *et al.* 2012; Davies *et al.* 2019; Jakobs *et al.* 2019). However, combining subsoil loosening with incorporation of soil amendments is not an easy task in practice, due to lack of technical solutions and high cost. In order to apply amendments to the deeper layer, the soil has to be loosened, which typically entails high costs. Heavy-duty equipment for injecting and incorporating amendments at depth into soil needs to be developed (Hamza & Anderson 2005).

Previous studies that have combined loosening of the subsoil with amendments have demonstrated promising results (Khalilian *et al.* 2002; Clark *et al.* 2007; Gill *et al.* 2008; Leskiw *et al.* 2012). The findings include low physical strength for root channels, increased soil organic carbon content, more plant-available water, better crop performance and higher crop yield. Besides, the presence of organic and/or inorganic amendments is likely to sustain the effects of subsoil loosening. Addition of straw from external sources, alone or in combination with loosening, is also important, as it could increase water-holding capacity (Van Donk *et al.* 2010; Cong *et al.* 2019), yield (Cong *et al.* 2019) and reduce nitrogen leaching (Nicholson *et al.* 1997; Silgram & Chambers 2002). Liming alone could also promote flocculation and improve soil structure and stability (Haynes & Naidu 1998; Blomquist *et al.* 2018). However, the effectiveness of combinations of subsoil loosening and amendments (organic and inorganic materials) or single measures needs to be further investigated.

# 2. Aim and objectives

The overall aim of this thesis was to examine the effect of subsoil improvement on subsoil properties, crop performance and the environmental impact. Specific objectives of the work were to:

- Evaluate the effectiveness of subsoil improvement on subsoil properties (soil organic carbon content, total nitrogen, bulk density, penetration resistance, water holding capacity) and crop yield in a three-year field study (Papers I and IV).
- Quantify the effect of subsoil treatments (subsoil loosening and subsoil loosening combined with straw) on nitrogen leaching and crop yield in a lysimeter study (Paper II).
- Evaluate structural stability (wet aggregate stability, clay dispersion) and dissolved reactive phosphorus in subsoil after applying liming materials at different rates (Paper III).

The following hypotheses were tested:

- Subsoil loosening combined with straw incorporation increases subsoil organic carbon, total nitrogen and water holding capacity, and decreases bulk density and penetration resistance (Papers I and IV).
- Subsoil loosening with straw addition improves crop yield and decreases leaching water and nitrogen losses (Paper II).
- Application of lime improves structural stability in the subsoil (Paper III).

# 3. Background and problem statement

## 3.1 Food demand, trends in crop yield and available arable land

The global population is increasing and is estimated to reach about 10 billion within the next 30 years, leading to high demand for food (Ray *et al.* 2013; FAO 2018). This means that food production needs to increase by more than 70% by 2050 to satisfy human needs (Schmidhuber 2010; Tilman *et al.* 2011). Moreover, the demand for feed and biofuel will increase, putting more pressure on agriculture.

Recent years have witnessed a crop yield plateau in various parts of the world, including Europe and North America (Calderini & Slafer 1998; Cassman *et al.* 2003; Brisson *et al.* 2010; Lin & Huybers 2012; Grassini *et al.* 2013). Meanwhile, arable land is a limited resource and bringing more land into cultivation at the expense of natural ecosystems might result in biodiversity loss, water quality deterioration, degradation of land and increased greenhouse gas emissions (Foley *et al.* 2005; Green *et al.* 2005; Power 2010).

The great challenge for agriculture is therefore to guarantee food supply for humankind in the future using existing arable land with minimal adverse environmental impacts (Foley *et al.* 2011; Ray *et al.* 2012). Increasing the soil volume penetrated by roots, thereby improving crop yield per unit area, could be one solution to address the rising food requirements (Lin & Huybers 2012). In this case, ameliorating subsoil problems would provide the opportunity for crops to utilise additional resources to boost crop production (Jakobs *et al.* 2017; Frelih-Larsen *et al.* 2018).

## 3.2 Subsoil properties

Subsoil in this thesis refers to the soil layer below ploughing depth, which is typically around 25 cm in Sweden. Despite the subsoil comprising a large volume and supporting root growth, studies on this soil resource and published evidence on its properties are limited (Kautz *et al.* 2013; Sosa-Hernández *et al.* 2019).

In most subsoils, organic carbon and nutrient concentrations are generally lower than in topsoil and are not uniformly distributed, and roots are sparse and spatially dispersed (Chabbi *et al.* 2009; Kautz *et al.* 2013). While the bulk subsoil is a less favourable habitat for root growth and microbial activities, there are hotspots with intense microbial activity and nutrient acquisition (Kautz *et al.* 2013). These hotspots, combined with a lack of soil mixing by tillage practices and differences in ploughing depth over time, may result in variations in root, carbon and nutrient distribution in subsoil.

### 3.2.1 Role of subsoils

The subsoil has high potential for nutrient and water retention. According to a comprehensive review of nutrient acquisition by Kautz *et al*. (2013), subsoils can supply crops with nutrients, with the contribution from subsoil varying from less than 10% of annual nutrient uptake in fertile soils to more than 65% when the topsoil is nutrient-depleted or dry. Subsoils also provide water to plants. Being able to take up water from subsoils will become more important under a future warming climate. In a study of amelioration of subsoil constraints via deep placement of organic amendments (Lucerne pellets or dynamic lifter) on a dense sodic subsoil by Gill *et al.* (2008), extraction of approximately 50 mm of extra water below 40 cm by crops was observed. This additional water uptake by plants, together with nutrient supply, led to a yield increase of about 60-70% compared with a control, which received only 70 kg $ha^{-1}$ mono-ammonium phosphate as a starter at the time of sowing.

These results reflect the importance of the subsoil for water and nutrient supply and crop yield. It has been predicted that dry periods will increase and droughts will last longer in the future, affecting agriculture (Heinrich & Gobiet 2012; Spinoni *et al.* 2018). Thus, the use of available water in subsoil can be important for crops when there is water shortage during the growing season (Schneider & Don 2019).

The subsoil is relatively low in soil organic carbon, but some subsoils hold over 50% of total soil carbon stocks (Rumpel & Kögel-Knabner 2011). Furthermore, the potential to store and stabilise additional carbon is higher in the subsoil than in the surface layer (Lorenz & Lal 2005), because of its large volume (Alcántara *et al.* 2017), content of mineral surfaces unsaturated with soil organic carbon (Beare *et al.* 2014) and slower decomposition rates (Rumpel & Kögel-Knabner 2011).

The higher stability of soil organic carbon in subsoils may also be due to inaccessibility (physical protection) and limited supply of fresh organic material, resulting in overall low microbial activity (Fontaine *et al.* 2007). Likewise, the subsoil is less prone to mechanical disturbance and associated acceleration of decomposition. Environmental conditions in the deep soil profile may also limit decomposition in the subsoil (Rumpel & Kögel-Knabner 2011).

Paul *et al*. (1997) found shorter residence time of organic matter and higher decomposability in the surface layer than in deeper soil layers. A long mean residence time of organic carbon in subsoils means a low turnover rate and good potential of subsoil to function as a carbon sink (Rumpel & Kögel-Knabner 2011). The high stability of organic matter in subsoil offers the opportunity for more carbon sequestration. However, due to the normally low carbon input by roots and root exudates and low input of dissolved organic matter from the topsoil, the bulk subsoil is low in organic carbon. Thus, finding ways to add organic matter to the subsoil is necessary. Despite decreasing microbial abundance with depth, the subsoil is host to distinct microbial communities that may prove important in maintaining the system's viability under fluctuating environmental conditions (Turner *et al.* 2017; Sosa-Hernández *et al.* 2019).

### 3.2.2 Constraints of subsoil on root and shoot growth

Root and shoot growth may be constrained by physical and chemical subsoil properties. Poor conditions such as a plough pan, poor soil structure, soil acidity (aluminium toxicity), hypoxia (level of oxygen below the normal range) and suboptimal temperature negatively affect root penetration and elongation, leading to low yields (Rengasamy *et al.* 2003; Lynch & Wojciechowski 2015).

A study by Voorhees *et al*. (1989) showed lower water uptake and lower grain yield from a compacted subsoil than a non-compacted control.

Compaction reduces the amount of air-filled macropores, limiting aeration and affecting root respiration, increasing nitrous oxide production and losses of nitrogen through denitrification (Håkansson 2005).

Soil constraints that restrict root growth affect the supply of water and nutrients to shoots and thereby retard overall crop growth (Masle & Passioura 1987). Shoot growth retardation due to suboptimal growth conditions suggests that shoots are receiving root-derived hormonal signals (Lynch *et al.* 2012). As mechanical impedance increases, leaf area and shoot dry weight decrease. Limited water availability to shoots diminishes the rate of photosynthetic activity, due to a drop in stomatal conductance (Masle & Passioura 1987).

Thus, management strategies to alleviate subsoil constraints are needed to improve root and shoot growth. Improved root growth into the subsoil and efficient extraction of soil water and nutrients could be an option to improve crop production. This can be considered as an alternative to areal expansion of arable land.

## 3.3 Measures to improve subsoil conditions

Under current soil management practices, processes such as freezing-thawing, wetting-drying, roots and soil organism activities are mainly responsible for subsoil structural development (Ball *et al.* 2015). However, the intensity and frequency of these processes diminish with depth, which means that improvement through these mechanisms is a slow process (Håkansson *et al.* 1988; Håkansson 2005). As these processes are often inadequate to alleviate subsoil problems, there is a need to look for management options.

However, established subsoil improvement options are limited (Batey 2009; Kautz *et al.* 2013). This is mainly because subsoil sampling is laborious and time-consuming and there has been a lack of interest (Kautz *et al.* 2013; Schjønning *et al.* 2015). Besides, the role of subsoil in nutrient acquisition has been underestimated (Kautz *et al.* 2013). Thus, information on improving subsoil conditions is relatively scarce (Kautz *et al.* 2013; Kirchmann *et al.* 2013). Some management practices have been implemented to improve subsoils, and a few of these are described below.

### 3.3.1 Mechanical measures

Subsoil loosening, also known as deep loosening, deep ripping or subsoiling, is a technique commonly used to ameliorate subsoil compaction (Ghadim *et al.* 1991; Davies *et al.* 2019). However, it may not be possible to perform in all soil types or in wet years (Schulte-Karring & Haubold-Rosar 1993; Schneider *et al.* 2017). Subsoil loosening is intended to break up the plough pan, loosen dense soil layers and increase the topsoil depth, using strong tines without inverting and mixing the soil profile. Thus, the surface soil is not expected to be turned down into the subsoil.

For subsoil loosening to be effective, it should be done when the soil is sufficiently dry, but not fully dry. In this condition, the soil is expected to be friable and the bearing capacity is high to moderate (Larson *et al.* 1994). Subsoil loosening should be avoided when the soil is wet, because the soil may smear and become compacted (Schulte-Karring & Haubold-Rosar 1993; Soane & Ouwerkerk 1994). Similarly, subsoil loosening should be avoided when the soil is too dry, since it demands high traction power and creates thick clods (Schulte-Karring & Haubold-Rosar 1993). The need for optimum soil moisture makes the time window for implementation of subsoiling rather narrow.

Positive outcomes due to loosening of compacted subsoils have been reported, such as reduced penetration resistance (Larney & Fortune 1986) and improved yield (Adcock *et al.* 2007). However, the effect is not long lasting and subsoil loosening has been found to be ineffective in most cases. Inconsistent results have been attributed to site, weather conditions, soil type, and recompaction by subsequent field operations and adverse impacts, and mechanical loosening may make bad subsoil conditions worse (Raper 2005; Raper & Bergtold 2007; Kautz *et al.* 2013; Schneider *et al.* 2017).

The major drawbacks of subsoil loosening are that it is expensive (the average cost of subsoiling in the United Kingdom according to (Chamen *et al.* 2015) is £50-56 $ha^{-1}$, demands more time to implement at a large scale, is energy-demanding and its effect can be short-lived as there is a risk of recompaction (Larney & Fortune 1986; Raper *et al.* 2005). In summary, subsoil loosening alone is not considered the best alternative for improving subsoil conditions.

It might be beneficial to combine subsoil loosening with addition of organic or inorganic soil amendments (Hamza & Anderson 2005), relevant field practices, *e.g.* controlled traffic (Duval *et al.* 1989) or on-land ploughing (Håkansson & Reeder 1994; Munkholm *et al.* 2005). The positive effects of subsoiling have been found to last for years when followed by reduced traffic (Duval *et al.* 1989; Raper 2005), when performed together with organic amendments (Sale & Malcolm 2015; Sale *et al.* 2019) or when rotated with no-till (subsoiling once every two years) (Zhang *et al.* 2017).

### 3.3.2 Combined mechanical subsoil loosening and organic amendments

One management option for ameliorating subsoil problems is deep placement of organic material, which could resolve physical and biological constraints (Davies *et al.* 2019). Subsoil loosening can be expected to break up the plough pan, fracture dense soils and open up a space for incorporation, while organic matter addition can be expected to improve aggregation, increase water-holding capacity and maintain the effect of subsoil loosening (Zhang *et al.* 2020).

Deep placement of organic amendments has been tested in different parts of the world and has been found to result in increased water-holding capacity and grain yield (Khalilian *et al.* 2002; Gill *et al.* 2008; Leskiw *et al.* 2012; Jakobs *et al.* 2017). For instance, in a study by Peries (2013), subsoil manuring increased plant-available water and resulted in a yield increase of 27-96% in different soil types and rainfall conditions. The soils studied were low in available water, constrained root growth and were prone to dispersion.

Despite promising results, implementation of this measure is technically difficult and expensive, and success depends on other factors. For example subsoil loosening combined with incorporating an organic amendment may not significantly affect yield if the topsoil supplies enough moisture and nutrients to the crop, or if a drought-induced moisture deficit develops in the subsoil or no water moves into the subsoil (Gill *et al.* 2008; Celestina *et al.* 2018). Machines that can simultaneously perform subsoil loosening and incorporation of amendments are scarce. Table 1 shows how organic materials have been added to the subsoil in previous studies and the outcome.

Table 1. *Literature review of type and quantity of organic materials tested as subsoil amendments, application method and outcome.*

| Depth of operation, cm | Type of organic material and amount added | Method used to reach the subsoil | Outcome | Reference |
|---|---|---|---|---|
| 15-45 | Composted municipal solid waste, 9 to 27 Mg $ha^{-1}$ | A rectangular guide tube welded to the rear end of each shank of the subsoiler was used to place the compost at the bottom of the slot. | Increased crop yield, plant nutrient content, soil organic matter content, and improved physical properties, with the best results obtained at the highest rates. | Khalilian *et al.*(2002) |
| 30-40 | Pelleted organic material (dynamic lifter and Lucerne pellets) 20 Mg $ha^{-1}$ | Applied manually, through a 15 cm diameter pipe attached to a deep ripper | Increased plant-available water and use, deep root growth, improved nutrient supply and yield. | Gill *et al.* (2008) |
| 20-40 | Organic manure pellets, 20 Mg $ha^{-1}$ | A subsoiler with specially designed pellet delivery and injector system was used to inject pellets while ripping the subsoil | Improved soil structure, higher deep root density, nutrient availability and yield | Leskiw *et al.* (2012) |
| 35 | Corn stover, 9 Mg $ha^{-1}$ | Corn stover (2-5 cm pieces) was spread over the soil surface and incorporated to 35 cm depth using a subsoiler | Increased soil organic carbon, available plant nutrients and crop yield | Bai *et al.* (2016) |
| 30-60 | Bio-decomposed organic waste and decomposed green cutting compost and cattle manure | A compact excavator (Kubota K008-3) was used to prepare slots, followed by mixing of organic materials by hand with the B-horizon soil | Promoted short term improvement of crop yield | Jakobs *et al.* (2017) |
| 30-40 | Poultry litter 20 Mg $ha^{-1}$ | A purpose-built prototype machine (Peries-Wightman subsoiler) loosened the soil and incorporated the amendment | Increased nutrient availability and yield | Celestina *et al.* (2018) |
| 30-40 | Straw at 6-18 Mg $ha^{-1}$ | Straw was laid on the ground and buried in the subsoil using a high-horsepower straw burying machine | Increased soil water content, organic carbon and yield, while decreasing penetration resistance. | Cong *et al.* (2019) |

### 3.3.3 Addition of straw: nitrogen immobilisation and physical benefits

Returning straw to the topsoil has become standard practice on farms without animal husbandry, due to restrictions on straw burning, awareness of soil quality and benefits for crop production (Allison *et al.* 1992; Nicholson *et al.* 2014). The amount of straw available determines the degree to which soil organic matter content can be increased (Cong *et al.* 2019). Adding small amounts has little effect on organic carbon level and soil physical properties (Mulumba & Lal 2008). Bhogal *et al*. (2009) suggest that repeated and large amounts of organic inputs are needed to give a considerable change in soil properties (soil strength, nitrogen supply, water-holding capacity and porosity).

Organic matter added through straw increases porosity, water-holding capacity and biological activity (Van Donk *et al.* 2010; Cong *et al.* 2019). Through microbial activity, soil particles are glued together, often forming a more stable soil structure (Bhogal *et al.* 2009; Powlson *et al.* 2011). Soil aggregate formation over time decreases bulk density and facilitates root growth, enabling access to more resources. Enhanced root growth in subsoil layers in turn means more organic matter input and improved soil structure (Kautz *et al.* 2013).

The direct effect of straw incorporation on yield is not consistent. Some studies have shown an increase in grain yield, whereas other field studies have not found any impact or have found a decrease due to straw addition (Nicholson *et al.* 2014). A yield decrease, especially in the first year of straw addition, is often due to nitrogen immobilisation (Jenkyn *et al.* 2001). Decomposition of energy-rich straw with a high carbon to nitrogen (C:N) ratio requires extra nitrogen to compensate for soil microbes taking up inorganic nitrogen from the soil solution, which can have an adverse impact on yield (Elliott *et al.* 1981; Jenkyn *et al.* 2001). Over time, nitrogen immobilised by microbes will be mineralised again, becoming available to the next crop (Powlson *et al.* 1985). Shortage of nitrogen during crop growth due to immobilisation through straw incorporation could be corrected by adding extra nitrogen fertiliser (Jenkyn *et al.* 2001) or adding the straw some time before drilling the crop to speed up decomposition (Harper & Lynch 1981; Singh *et al.* 2005). On the other hand, immobilisation can decrease nitrogen losses via leaching (Powlson *et al.* 1985; Allison *et al.* 1992;

Powlson *et al.* 2011). Data obtained by Powlson *et al*. (1985) show that incorporating 3 Mg $ha^{-1}$ of straw into a silty clay loam reduces nitrate losses.

Addition of straw to the subsoil may cause a priming effect, *i.e*. decomposition of native organic matter due to incorporating readily decomposable organic inputs (Löhnis 1926; Kuzyakov *et al.* 2000). Among the few studies on priming in the subsoil, Fontaine *et al*. (2007) observed degradation of old, pre-existing organic matter upon adding fresh plant material. However, other study did not find increased turnover of old organic matter on adding labile material to the subsoil (Salome *et al.* 2010). It should be kept in mind that subsoils have the potential to store additional carbon, as they are far from carbon saturation (Lorenz & Lal 2005; Rumpel 2014). The possibility to supply organic materials into the subsoil would be a useful farming practice.

### 3.3.4 Structure liming

Improved aggregate stability has been observed upon liming (Ulén & Etana 2014; Blomquist *et al*. 2018). A surplus of calcium ($Ca^{2+}$) ions in the soil leads to adsorption on surfaces of soil particles, displacing other ions and causing an attraction between particles, which then floc together. Flocculation occurs rapidly and improves soil workability (Mallela *et al*. 2004). Lime contributes to soil structural stability by aggregating particles through ion exchange, flocculation and a long-term pozzolanic reaction (Mallela *et al.* 2004). In the pozzolanic reaction, dissolving/dissolved silicic acid ($Si(OH)_4$), water and calcium oxide (CaO) or calcium hydroxide ($Ca(OH)_2$) combine to form cementation products, resulting in a fundamental rearrangement of alumino-silicate mineral structures (Cherian & Arnepalli 2015). The strong cementitious matrix that develops is irreversible.

It has been suggested that development of cation bridges between organic matter and clay due to presence of calcium results in greater stability of soil structure (Muneer & Oades 1989; Baldock *et al.* 1994).

When there is a positive impact on aggregate stability and a decrease in clay dispersion, liming affects the soil structure and thus root growth and development, with indirect positive impacts on crop growth and yield (Holland *et al.* 2018). Structure liming of agricultural soils can reduce phosphorus losses (Ulén & Etana 2014; Blomquist *et al.* 2018) and often increases crop yield (Blomquist *et al.* 2018). Liming affects pH in the soil and phosphate solubility is in turn influenced by pH, but the effect of liming on phosphate solubility is not consistent (Haynes 1982). Lower phosphate solubility at near-neutral pH was found by Gustafsson *et al.* (2012), contradicting claims that optimum phosphate solubility is reached at near-neutral pH (Troeh & Thompson 1993; Ashman & Puri 2002).

## 3.4 Compaction and plough pan: cause and extent

Soil compaction refers to a reduction in the pore space. It involves an increase in bulk density and an associated decrease in porosity due to the influence of pressure compelling soil particles closer together (Hamza & Anderson 2005). A major cause of soil compaction is the use of heavy machinery during wet soil conditions (Alakukku *et al.* 2003; Hamza & Anderson 2005). Based on axle load and soil moisture status (moist to wet) during field operations, Keller and Arvidsson (2006) rated the vulnerability of Swedish subsoils to compaction as high to very high.

Repeated actions of wheels of a tractor and/or soil tillage implements to the same soil depth for years lead to the formation of a discrete layer with dense or platy structure called a plough pan (Alakukku *et al.* 2003; Raper & Bergtold 2007; Peigné *et al.* 2013). Peigné (2013) referred to this as a "transition layer" between the topsoil and subsoil horizons. The plough pan, usually between 2 and 3 cm thick, acts as a physical barrier, posing a challenge for roots to grow downwards and water to penetrate (Bowden & Jarvis 1985).

Compaction is a widespread problem globally (Soane & Ouwerkerk 1994; Hamza & Anderson 2005). For instance, studies in Europe based on risk assessment mapping of subsoils indicate that there is severe subsoil compaction in around 39% of agricultural soils in Denmark (Schjønning *et al.* 2015) and in 50% of the most productive agricultural soils in the Netherlands (Van den Akker & Hoogland 2011). A recent study that collected data on 128 sites in the Netherlands found that 43% of agricultural soils had compacted subsoil (Brus & Van Den Akker 2018). A similar survey covering 3078 sites at a national scale in Germany showed that compaction was the leading cause of restricted root growth (to depths of <100 cm) in 51% of arable soils (Schneider & Don 2019). These data illustrate that compaction of subsoils is a serious problem requiring the development of appropriate remedial measures.

# 4. Materials and methods

## 4.1 Experimental sites (Papers I-IV)

The field investigations described in Papers I and IV were carried out in Säby near Uppsala (59°83′N, 17°71′E), Sweden. Soil columns for the lysimeter experiment reported in Paper II were also collected from Säby, at a site near the field experiment area. For the incubation experiment (Paper III), soil from Kungsängen (59º83′N, 17º68′ E), one of the sites in the long-term Swedish soil fertility experiments, was sampled.

According to the FAO classification, the soil at Säby is a Eutric Cambisol and the Kungsängen soil is a Gleyic Cambisol. The soil in Säby and Kungsängen has been under cultivation for more than a century. Characteristics of the Kungsängen soil are shown in Table 2 and characteristics of the Säby soil in Table 3.

Table 2. *Selected attributes of the bulk subsoil (34-44 cm) sample from Kungsängen used in the incubation experiment (Paper III).*

| Soil properties | Value |
|---|---|
| Sand % | 3.2 |
| Silt % | 47.0 |
| Clay % | 49.8 |
| Soil organic carbon (g $kg^{-1}$) | 7.3 |
| Nitrogen (g $kg^{-1}$) | 0.9 |
| pH ($H_2O$) | 7.0 |

Table 3. *Physical and chemical properties of the Säby soil at the site where the soil columns were extracted.*

| Soil layer, cm | Bulk density $Mg\ m^{-3}$ | Porosity (%) | Soil organic carbon | | Total nitrogen | | Carbonate $g\ kg^{-1}$ | pH ($H_2O$) | Clay (%) | Silt (%) | Sand (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | $g\ kg^{-1}$ | $Mg\ C\ ha^{-1}$* | $g\ kg^{-1}$ | $Mg\ N\ ha^{-1}$* | | | | | |
| 0-10 | 1.30 | 50.9 | 28.2 | 36.7 | 2.40 | 3.1 | 0.10 | 6.1 | 21.9 | 54.5 | 23.6 |
| 10-20 | 1.37 | 48.3 | 26.4 | 36.2 | 2.20 | 3.0 | 0.20 | 6.1 | 20.5 | 56.9 | 22.6 |
| 20-30 | 1.41 | 46.8 | 14.2 | 20.0 | 1.20 | 1.7 | 0.09 | 6.3 | 21.3 | 56.2 | 22.5 |
| 30-40 | 1.55 | 41.5 | 7.9 | 12.2 | 0.68 | 1.1 | 0.07 | 6.5 | 18.9 | 54.1 | 27.0 |
| 40-50 | 1.51 | 43.0 | 3.8 | 5.7 | 0.39 | 0.6 | 0.07 | 6.7 | 23.5 | 59.7 | 16.8 |
| 50-60 | 1.42 | 46.4 | 3.4 | 4.8 | 0.39 | 0.6 | 0.10 | 6.8 | 25.3 | 62.6 | 12.1 |
| 60-70 | 1.36 | 48.7 | 3.7 | 5.0 | 0.47 | 0.6 | 0.09 | 6.9 | 31.1 | 61.1 | 7.8 |
| 70-80 | 1.36 | 48.7 | 3.2 | 4.4 | 0.42 | 0.6 | 0.07 | 6.7 | 27.4 | 56.7 | 15.9 |
| 80-90 | 1.34 | 49.4 | 6.3 | 8.4 | 0.85 | 1.1 | 0.11 | 6.1 | 39.6 | 57.7 | 2.7 |
| 90-100 | 1.22 | 54.0 | 6.4 | 7.8 | 0.88 | 1.1 | 0.12 | 5.4 | 34.2 | 63.1 | 2.7 |
| 100-110 | | | 9.8 | 12.0 | 1.30 | 1.6 | 0.16 | 4.9 | 40.6 | 57.4 | 2.0 |
| Total | | | | 153.2 | | 15.1 | | | | | |

*The proportion of soil organic carbon and total N in the subsoil >25 cm compared with the whole profile amounted to about 46% and 54%, respectively.

## 4.2 Weather conditions

Over the years during the experiment, the area experienced lower annual precipitation and higher mean annual temperature than the long-term average (1961-1990). The summer of 2018 was dry, with average monthly temperatures considerably higher than normal (*e.g.* 21.6 °C in July, compared with 16.3 °C as the long-term average). Precipitation was low in 2018 and not evenly distributed. Only about 5 mm of rain fell from June 22 to July 28, but a heavy rain event of 79 mm was recorded on July 29. Total annual precipitation was 472 mm in 2016, 507 mm in 2017 and 429 mm in 2018, while the long-term average is 528 mm. Mean annual temperature over the three years ranged from 6.9 to 7.6 ºC and was higher than the long-term average of 5.5 ºC. Mean temperature between May and September (crop growing period) over the three years was higher than the long-term average (13.5 ºC). It was 15.1 ºC, 14 ºC and 16.8 ºC in 2016, 2017 and 2018, respectively. In the same period, the precipitation deficit was up to 65 mm smaller than the long-term average (Papers I and IV). The columns were therefore irrigated with a total amount of about 157 mm water during the 21 months of the lysimeter experiment (Paper II).

## 4.3 Experimental design and treatments

The field experiment in Säby had a randomised complete block design with four replicates and five treatments, and ran for three years. Treatments were control, subsoil loosening only in the first year ($L_{1y}$), subsoil loosening combined with straw addition only in the first year ($LS_{1y}$), subsoil loosening performed annually for three years ($L_{3y}$), and subsoil loosening combined with straw addition once every year for three years ($LS_{3y}$). In the remainder of this thesis, treatments $L_{1y}$ and $L_{3y}$ are sometimes referred to more generally as 'treatment L' and treatments $LS_{1y}$ and $LS_{3y}$ as 'treatment LS'. In the first year of the field experiment (2016), repeated loosening and straw additions had not yet occurred, so only three treatments were considered. Thus, the first-year results are presented in this thesis for the control, subsoil loosening as $L_{1y}$ and subsoil loosening + straw addition as $L_{1y}$ (Paper I). The lysimeter experiment was randomised into four blocks and included three treatments:

a control, subsoil loosening (L) and subsoil loosening combined with straw addition (LS) (Paper II).

Seven treatments were considered and replicated three times in a randomised complete block design in the incubation experiment. These treatments were: a control at pH 7.0, addition of quicklime (CaO, Alfa Aesar by Thermo Fisher (Kandel) GmbH, Germany, p.a.) to attain a pH of 7.5, 8.0 and 8.4, and addition of $CaCO_3$ to achieve a pH of 7.5, 8.0 and 8.4 (Merck KGaA, Darmstadt Germany, p.a.) (Paper III).

## 4.4 Soil and crop management, sampling and measurements in field and lysimeter experiments

### 4.4.1 Subsoil loosening and loosening with addition of straw in the field experiment (Papers I and IV)

For the subsoil treatments in the field, a modified subsoil loosener with four tines spaced 74 cm apart (Combiplow Gold, AGRISEM International France) was used. The tines had 32 cm wide winged tips. The loosener also had a roller packer, to shatter and level the clods generated during work. A rectangular metal tube welded behind each tine and connected by tubing to a tanker was used to inject straw (as a slurry) into the subsoil during loosening (Figure 1a and b). The subsoil loosener was mounted behind the tanker containing the straw slurry.

Combined subsoil loosening and addition of straw slurry to about 25-34 cm depth (loosening + straw) was performed after harvest in autumn. The straw slurry was made from cereal straw pellets with a C:N ratio of around 85. The straw pellets were mixed with water until a slurry suitable for pumping was obtained.

The amount of straw added in the first, second and third year of the experiment was around 30, 24 and 29 Mg $ha^{-1}$, respectively, which was about 4 to 5 fold the annual amount commonly produced from a hectare of land in the region.

In the second and third year, the subsoil loosening and subsoil loosening combined with straw addition treatments were applied 10 cm away to the right and left side of the first year lane, to allow space for straw addition. The aim with subsequent straw incorporation on previously untreated soil in the same plot was to increase the area affected by straw in each treatment plot.

The subsoil loosening treatment affected around 43% of the plot area in the first year, with around 11% of the plot enriched with straw slurry (Paper I) (Figure 1c and d). In the second and third year, subsoil loosening affected 56% and 64% of the plot area, respectively, while 21% and 32% of the plot area, respectively, was enriched with straw slurry (Paper IV).

Due to pressure and limited space in the subsoil, around 15-20% of the straw suspension ended up on the surface (Figure 1d). Straw slurry did not run entirely sideways in the loosened subsoil and was mainly located in a limited area.


*Figure 1.* a) Subsoil loosener being drawn behind the tanker containing straw slurry, b) close-up view of the modified subsoiler with metal channels, c) soil after subsoil loosening, and d) soil after subsoil loosening with straw slurry addition.

### 4.4.2 Soil management, fertilisation and sampling (Papers I, II and IV)

The field at the Säby site was cultivated to a depth of 15 cm in autumn and harrowed to a depth of 4 cm in spring each year. Seed drilling and fertilisation were performed in spring each year. All plots were ploughed with mould board (~22 to 24 cm) in autumn of 2017.

Fertiliser (NPKS) was added according to standard agricultural practices for the area in all treatments considered in the field study. However, in the second year, 156 kg N ha$^{-1}$, which was about 36 N kg ha$^{-1}$ more than the first and third year, was applied. In the lysimeter study, 100 kg N ha$^{-1}$ were applied and cultivation and sowing were done by hand (Paper II).

Lines of 8 and 32 cm width (4 lines in each treated plot) (Figure 2) for the subsoil loosening combined with straw addition treatment and loosening treatment, respectively along which the subsoil was treated were marked and sampling to assess soil properties, crop growth and yield was made along these marked lines (Papers I and IV). Measured and observed soil and crop properties are listed in Figure 3.

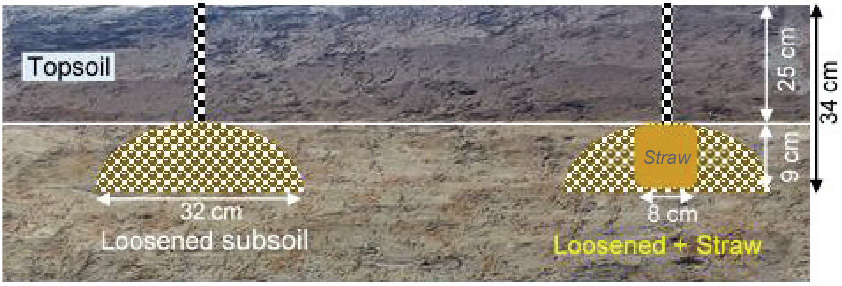


*Figure 2.* Schematic illustration of the dimensions of the subsoil area affected by subsoil loosening and loosening combined with straw addition.

Soil sampling in 2017 and 2018 in the repeated subsoil loosening ($L_{3y}$) treatment was performed following repeated loosening lines, to evaluate repeated effects of treatment, as lines loosened once, twice and three times were available in 2016, 2017 and 2018 production seasons, respectively (Paper IV). However, sampling did not follow the same trend in the subsoil loosening combined with straw treatment. Since treatments were applied once every year for three years in three separate lines in the $LS_{3y}$ plot, *i.e.* subsequent straw incorporation was done on previously untreated soil in the same plot (which means that there were lines only affected once in each production season of 2016, 2017 and 2018), soil property measurements were performed only in the latest straw addition line. Therefore, crop yield was the only measured variable that was able to capture the response for the repeated subsoil loosening combined with straw addition treatment ($LS_{3y}$).

Soil samples for determination of soil organic carbon (SOC) concentration and total nitrogen (total-N) concentration were sampled using an auger at 0-10 and 29-34 cm soil depth. Samples from four sampling points in each plot were pooled for analysis. The concentrations of SOC and total-N were determined by dry combustion with a LECO CNS 2000 analyser.

At the field site, four undisturbed soil cores were extracted from the 29-34 cm subsoil layer in each plot, using open-ended cylinders (7.2 cm inner diameter, 5 cm height), in spring and autumn 2016, 2017 and 2018. The cylinder containing the soil cores was weighed, oven-dried for 72 hours at 105 $^{o}$C and re-weighed to quantify soil bulk density at sampling. Bulk density at 0-10 cm soil depth was measured in the control treatment using cylinders (7.2 cm inner diameter, 10 cm height). Measured bulk density was used as input to determine porosity, assuming a particle density of 2.65 g cm$^{-3}$. The particle density of straw was corrected using literature values (Guerif 1979 cited in Soane 1990).

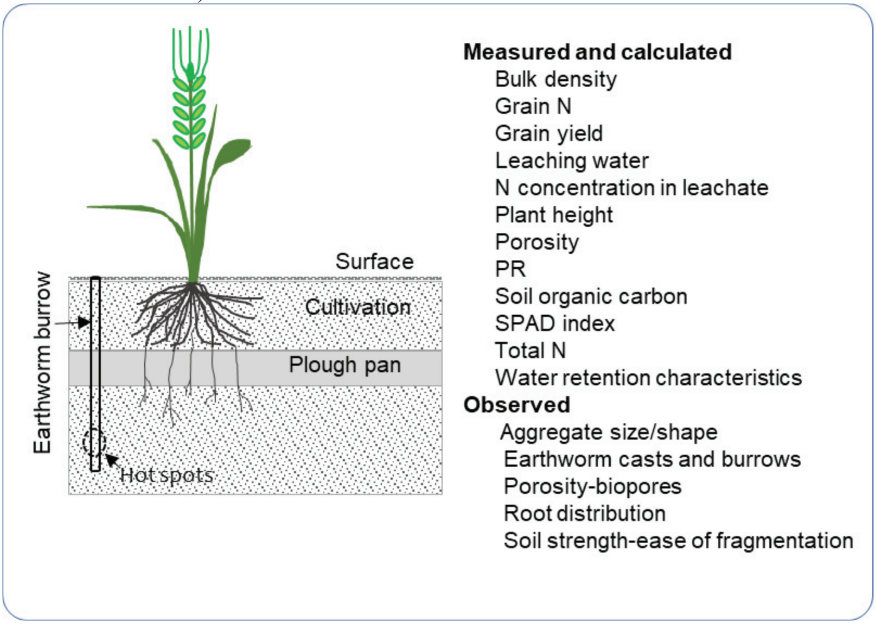


*Figure 3.* Schematic illustration showing soil and crop properties measured and observed in the thesis. (N: nitrogen, PR: penetration resistance, SPAD: Soil Plant Analysis Development index).

Penetrometer measurements to determine soil penetration resistance were made using a hand-held cone penetrometer (Royal Eijkelkamp Company, Netherlands) fitted with a cone of 11 mm diameter, 60$^{o}$ apex angle and 1 cm$^{2}$ base area, in autumn 2016 (after harvest) and spring 2017 (in the growing crop). Measurements were taken at 10 points in each plot, in treated subsoils following lines of treatment (Papers I and IV). Measurements of gravimetric water content were made on the same occasions.

Degree of compactness (DC) of the field soil was determined by dividing the measured bulk density by the reference bulk density in the control treatment. Reference (maximum) bulk density was obtained using four pedotransfer functions developed by Keller and Håkansson (2010) and Naderi-Boldaji *et al.* (2016) (Paper IV). To obtain a single DC value for the field, the DC value was averaged over three years and seasons, and then across four pedotransfer functions.

Water retention characteristics of soil were determined in the laboratory at -0.5, -10, -30 and -60 kPa, using cylinders (7.2 cm inner diameter, 5 cm height) taken in autumn 2018. The water content at -1500 kPa (wilting point) was determined on disturbed soil samples.

### 4.4.3 Crop management and sampling (Papers I, II and IV)

The crop rotation of spring-sown cereals in the Säby field was: spring wheat (*Triticum aestivum* L. var. 'Quarna') (year 1), spring barley (*Hordeum vulgare* L. var. 'Makof') (year 2) and oats (*Avena sativa* L. cv. Symfoni (year 3) (Papers I and IV). The lysimeters in 2017 were sown with spring barley (*Hordeum vulgare* L. var. 'Makof') (Paper II). The lysimeters in 2018 and 2019 were sown with oats and spring wheat, respectively, and the yield data are presented in this thesis (previously unpublished data). Measurements of leaf relative chlorophyll content were carried out at different crop growth stages (Zadoks *et al.* 1974) in both the field and lysimeters, using a hand-held Soil Plant Analysis Development (SPAD-502) meter (Minolta Camera Co., Osaka, Japan). Crop height was measured on the same occasions, using a meter stick (Papers I, II and IV).

The aboveground crop was harvested in lysimeters by cutting close to the soil surface with scissors. Samples were taken for straw and grain yield analysis. Nitrogen harvest index was calculated as the ratio of grain N to total aboveground biomass N (Fageria 2014). Biomass harvest index was assessed based on grain yield as a fraction of aboveground dry matter production (Hay 1995). Grain nitrogen concentration was analysed using a LECO CNS 2000 analyser (Paper II).

In the field, plot-wise measurements of yield, including the straw, were made using a combine harvester. The protein content of cereal grains was also determined, using an Infratec™ NOVA grain analyser (Papers I and IV). Crop samples were threshed, milled and weighed for yield, and data were transformed to a per hectare basis (Papers I, II and IV). Weed infestation was observed in the field during the 2016 cropping season (Paper I) and crop damage due to bird foraging, crop disease and placement of gas measurement chambers was observed in the lysimeter study in the 2017 cropping season (Paper II).

### 4.4.4 Soil column collection and management (Paper II)

At the Säby site, undisturbed soil columns were sampled in May 2016 in polyvinyl chloride (PVC) pipes (0.295 m inner diameter, 1.18 m height) using the drilling method described by Persson and Bergström (1991) and a tractor-mounted hydraulic soil auger. Each soil column was carved out by placing the PVC pipe in a rotating drill cylinder and the soil column was gently slid into the pipe. The soil column was then dug out at the bottom, lifted, covered at both ends and transported to the lysimeter station for preparation and installation. Before installation, a 5 cm soil layer at the bottom of the PVC pipes was detached and replaced with washed gravel (2-5 mm), with a stainless steel mesh placed between the soil and gravel (Paper II).

In the lysimeter station, the topsoil and upper layers of the subsoil were manually excavated from the column in sequence and placed in separate containers. Topsoil from all columns was mixed to produce a homogeneous material. The subsoil was treated with loosening and loosening combined with straw addition (loosening + straw), milled cereal straw with C:N ratio of around 90 was added to the subsoil container at a rate of about 60 Mg $ha^{-1}$. The subsoil was loosened and straw was manually mixed into it in this case.

All lysimeters were then sequentially refilled with treated subsoil and topsoil. After preparation, the lysimeters were installed in an outdoor lysimeter station and exposed to natural weather conditions (Paper II).

In the lysimeter station, pipes were attached to a funnel outlet at the bottom of each lysimeter and connected to glass bottles in the basement of the station, where the amounts of leached water were monitored and water samples for analysis were taken. Installation of the lysimeters was completed in August 2016 and they were left uncropped until spring barley (*Hordeum vulgare* L. var. 'Makof') was sown in June 2017. During the 21-month experiment, a total of about 157 mm of water was added to the lysimeters by irrigation. The barley was harvested in September 2017 (Paper II).

### 4.4.5 Leachate sampling and nitrogen concentrations in water (Paper II)

The leachate collected in glass bottles in the lysimeter station was weighed, subsamples of leachate were analysed for nitrate ($NO_3^-$), nitrite ($NO_2^-$) and ammonium ($NH_4^+$) concentrations, and the concentrations of these were combined to give total mineral N. Nitrate and nitrite plus ammonium were determined colorimetrically, by the vanadium chloride-reduction method and the salicylate method, respectively (ISO 2013) (Paper II).

### 4.4.6 Nitrogen balance of the soil-crop system (Paper II)

The nitrogen balance of the soil-crop system (kg ha$^{-1}$) in the lysimeter experiment was determined similar to a procedure by Sainju (2017) , *i.e.* nitrogen outputs were subtracted from nitrogen inputs. Outputs comprised nitrogen removal in crop fractions (grain and straw), nitrogen losses through leaching and gaseous nitrous oxide emissions ($N_2O$). Inputs comprised nitrogen supplied in chemical fertiliser plus nitrogen in crop seed (Paper II). An Infratec™ NOVA grain analyser was used to determine nitrogen concentration in seeds and an element analyser (CNS Analyzer; LECO Corporation, St. Joseph, MI, USA) was used to determine nitrogen concentration in harvested straw plus grain.

Nitrous oxide emissions were measured using PVC chambers (0.02 m$^3$) equipped with a pressure ventilator and a small axial fan for air mixing within the chamber. During measurements, chambers were placed on top of the lysimeters for approximately 45 minutes, with five air collections taken every 10 minutes beginning at chamber closure. During chamber air sampling, an air pump moved chamber air in a loop between the chamber, pump and a 20 mL glass collection vial for one minute. Measurements took place on 19 occasions during the cropping season and started within 24 h of the day of sowing. Ten measurements were taken in the first two weeks, and then the frequency of measurements was reduced during the rest of the growing period, when measurements were timed to follow periods of rainfall or irrigation as much as possible. A gas chromatograph (Clarus 500, Perkin Elmer, USA) was used to analyse gas samples for $N_2O$. Individual $N_2O$ fluxes were determined by the method "*robust linear*" within the R software *gasfluxes* (FussR, 2019). Before calculation, data were corrected for ambient air pressure and chamber temperature. The *aggflux* function from the R *gasfluxes* package was used to determine cumulative $N_2O$ emissions (Paper II).

### 4.4.7 Visual observations of roots, earthworm burrows and casts and soil structure in the subsoil (Papers I and IV).

The distribution of roots, occurrence of earthworm burrows and casts and soil structure were visually examined in the field. In short, soil pits in each treatment were dug before harvest (2016 to 2018), and root distribution was assessed at 10, 25 and 34 cm depth at a horizontal line of 12 cm width, using a simple and modified profile wall method (Böhm 1979).

A qualitative visual assessment of soil aggregate size and shape (determined by observing the profile face and by breaking fragments), strength (ease of fragmentation by hand or knife) and porosity (for example biopore and root channels) in the subsoil was made in autumn 2018 using a method similar to Ball *et al*. (2015). Soil profile pits, about 60 cm deep and wide enough to work inside, were dug in each replicate treatment for the subsoil visual assessment of soil structure. A rapid visual observation was also made in 2019.

### 4.4.8 Structural stability and dissolved reactive phosphorus measurements (Paper III)

Subsoil taken from the Kungsängen site used for incubation was dried, mixed and crushed to pass a 2-mm sieve and then mixed with CaO and $CaCO_3$ to achieve soil pH levels of 7.5, 8 and 8.4. The samples were then incubated in 500 mL screw-cap polypropylene containers at about 56% of water-holding capacity and 20 °C for 22 months. Regular opening for aeration and monitoring of moisture was undertaken throughout the experiment (Paper III). Structural stability (clay dispersion and wet aggregate stability) and dissolved reactive phosphorus (DRP) were measured after 22 months. Clay dispersion was analysed as outlined by Pojasok and Kay (1990) and wet aggregate stability was determined using a Yoder-type wet sieving apparatus (Yoder 1936). Determination of DRP was performed colorimetrically on aliquots of suspension, using the ammonium molybdate blue method (ECS 1996) (Paper III).

## 4.5 Statistical analysis

Statistical analysis was performed using the R software (RCoreTeam 2020). Treatment effects on soil properties, crop variables and crop yield were determined using analysis of variance followed by multiple comparisons using Tukey's test ($p<0.05$) (Papers I-IV). Relationships between soil variables were evaluated using linear regression (Papers I, III, and IV). The associations of DRP and wet aggregate stability with soil pH were fitted to piece-wise, two-segmented linear equations using SigmaPlot 14 (Systat software) (Paper III).

Time series data on leachate, nitrogen load and volume-weighted concentrations were transformed logarithmically to normalise the distribution (Paper II). A mixed model considering time as a repeated factor in ANOVA was used for data that were broken down into three-month meteorological seasons over 21 months, to compare treatment differences in amounts of leachate (mm), volume-weighted nitrogen concentration (mg N $L^{-1}$) and nitrogen load (kg N $ha^{-1}$). An autoregressive (AR (1)) model was used for the error term (Paper II). The total amount of leachate (mm), volume-weighted nitrogen concentration (mg N $L^{-1}$) and total-N load (kg N $ha^{-1}$) over 21 months in the lysimeter study were analysed using one-way ANOVA followed by Tukey's multiple comparison tests (Paper II).

# 5. Results and Discussion

## 5.1 Changes in subsoil properties in the field experiment (Papers I and IV)

### 5.1.1 Soil organic carbon and total nitrogen (Papers I and IV)

Straw is an essential source of SOC. In this thesis, incorporation of straw into the loosened subsoil (29-34 cm) (treatment LS) resulted in higher concentrations of SOC and total-N (Papers I and IV). For example, in autumn 2018, in the sampled lines where straw had been incorporated three years previously ($LS_{1y}$), the concentration of SOC was 33.3 g $kg^{-1}$ and the concentration of total-N was 2.3 g $kg^{-1}$, compared with 8.6 g SOC $kg^{-1}$ and 0.8 g total-N $kg^{-1}$ in the control (Table 4). These marked changes in SOC and total-N concentration were due to the large amount of straw added in the field experiments compared with the usual relatively smaller annual inputs. The SOC included straw at different stages of decomposition (Papers I and IV).

The observed increase in SOC and total-N concentration was consistent with previous findings for straw addition alone (Jun *et al.* 2007; Malhi *et al.* 2011) or straw incorporation with subsoil loosening (Bai *et al.* 2016). Continuous straw supply to the soil can be expected to increase SOC and total-N levels over time. Morachan *et al.* (1972) reported a considerable increase in SOC in the topsoil after adding chopped crop residues at rates of up to 16 Mg $ha^{-1}$ $yr^{-1}$ for 13 years. Similarly, in an experiment conducted between 2013 and 2016, Cong *et al*. (2019) noted a marked increase in SOC and total-N in the subsoil after incorporating 6 to 18 Mg $ha^{-1}$ straw into a loosened area. The greatest increase was observed at the highest application rate of straw.

The subsoil SOC concentration over the three years in the control treatment in this thesis ranged between 5 and 20 g kg$^{-1}$, while the total-N concentration ranged between 0.5 and 1.5 g kg$^{-1}$ (Papers I and IV) reflecting the variation that existed in the subsoil. The SOC concentration in the topsoil (0-10 cm), which was continuously mixed by tillage, ranged between 28 and 31 g kg$^{-1}$ over the three years and seemed to be relatively uniform. Total N concentration in the topsoil (0-10 cm) ranged between 2.2 and 2.6 g kg$^{-1}$.

Table 4. *Mean soil organic carbon (SOC) and total nitrogen (N) concentration (g kg$^{-1}$) and soil bulk density (kg dm$^{-3}$) at 29-34 cm depth at the Säby site in spring and autumn 2016, 2017 and 2018. Different letters within columns indicate significant differences. $L_{1y}$: loosening in one year, $LS_{1y}$: loosening + straw addition in one year, $L_{3y}$: annual loosening for three years, $LS_{3y}$: annual loosening + straw addition for three years. The first-year (2016) results were represented as control, $L_{1y}$ and $LS_{1y}$ plots.*

| Year | Treatment | Spring | | | Autumn | | |
|---|---|---|---|---|---|---|---|
| | | SOC | Total N | Bulk density | SOC | Total N | Bulk density |
| 2016 | $L_{1y}$ | $27.5^{ab}$ | $2.1^{a}$ | $1.29^{ab}$ | $24.1^{a}$ | $2.1^{ab}$ | $1.39^{a}$ |
| | $LS_{1y}$ | $40.1^{b}$ | $2.1^{a}$ | $1.05^{b}$ | $55.9^{b}$ | $2.5^{b}$ | $1.02^{b}$ |
| | Control | $19.7^{a}$ | $1.4^{a}$ | $1.46^{a}$ | $16.7^{a}$ | $1.5^{a}$ | $1.42^{a}$ |
| 2017 | $L_{1y}$ | $19.3^{a}$ | $1.6^{a}$ | $1.34^{a}$ | $17.7^{ab}$ | $1.5^{b}$ | $1.42^{a}$ |
| | $LS_{1y}$ | $46.4^{b}$ | $2.6^{b}$ | $1.04^{b}$ | $37.0^{c}$ | $2.6^{c}$ | $1.10^{c}$ |
| | $L_{3y}$ | $17.2^{a}$ | $1.5^{a}$ | $1.36^{a}$ | $21.0^{b}$ | $1.8^{b}$ | $1.27^{b}$ |
| | $LS_{3y}$ | $47.0^{b}$ | $2.3^{b}$ | $0.97^{b}$ | $52.7^{d}$ | $2.7^{c}$ | $0.95^{d}$ |
| | Control | $13.0^{a}$ | $1.1^{a}$ | $1.49^{a}$ | $8.9^{a}$ | $0.8^{a}$ | $1.51^{a}$ |
| 2018 | $L_{1y}$ | $19.5^{a}$ | $1.6^{b}$ | $1.36^{a}$ | $10.0^{ab}$ | $0.8^{ab}$ | $1.53^{a}$ |
| | $LS_{1y}$ | $34.1^{b}$ | $2.5^{c}$ | $1.10^{b}$ | $33.3^{c}$ | $2.3^{c}$ | $1.20^{b}$ |
| | $L_{3y}$ | $12.5^{a}$ | $1.0^{ab}$ | $1.46^{a}$ | $14.0^{b}$ | $1.2^{b}$ | $1.51^{a}$ |
| | $LS_{3y}$ | $53.6^{c}$ | $2.8^{c}$ | $0.87^{c}$ | $45.3^{d}$ | $2.5^{c}$ | $1.03^{c}$ |
| | Control | $10.5^{a}$ | $0.8^{a}$ | $1.51^{a}$ | $8.6^{a}$ | $0.75^{a}$ | $1.51^{a}$ |

During the studies, there were occasions (autumn 2017 and 2018) when measurements in the three-year loosening ($L_{3y}$) treatment revealed significantly higher SOC and total-N concentrations than in the control, despite no straw input (Paper IV) (Table 4). This might reflect subsoil variation, based on findings for the control plots, or was possibly due to inversion of topsoil into the subsoil during loosening. Subsoil variation in SOC may also be due to vertical cracks that allow soil organic matter to move preferentially, thereby promoting earthworms and root activities and creating hotspots (Kautz *et al*. 2013), or to variation in ploughing depth over time.

The degradation rate of straw depends on C:N ratio, the composition of the straw and abiotic factors such as moisture and temperature (Hiel *et al*. 2016). In the field, remnants of straw were observed during the last subsoil sampling, where it had been incorporated three years previously (Paper IV). This could be due to lignin and other recalcitrant structures present in straw, which decompose slowly (Hiel *et al*. 2016).

The increase in SOC after loosening combined with straw addition had important implications for soil properties. It decreased bulk density and penetration resistance and increased water retention (Papers I and IV).

### 5.1.2 Bulk density and penetration resistance (Papers I and IV)

Subsoil loosening when combined with straw addition effectively lowered soil bulk density to significantly lower levels than in other treatments. In spring and autumn, bulk density values over the three years in treatment LS, following lines where straw was incorporated, varied between 0.9 and 1.2 Mg $m^{-3}$. In the control, bulk density was 1.42-1.51 Mg $m^{-3}$ (Table 4). Bulk density in the topsoil (0-10 cm) in 2016-2018 was between 1.08 and 1.29 Mg $m^{-3}$.

The lower bulk density values in treatment LS were due to a combined effect of light organic matter particles dominating in samples and soil dilution (Soane (1990) and loosening (Varsa *et al.* 1997). Loosening in treatment LS was an added benefit to decrease the bulk density of the treated soil. Enhanced activity of soil organisms facilitates decomposition and soil aggregation over time, leading to increased porosity and lower bulk density (Cogger 2005; Nicholson *et al.* 2014). These results are in agreement with earlier findings of a decrease in bulk density on adding organic materials (straw, organic pellets, manure) during loosening (Leskiw *et al.* 2012; Zhang *et al.* 2020) or following loosening alone (Varsa *et al.* 1997).

The effect of loosening alone (treatment L) on bulk density was relatively weak. Soil bulk density in these treatments, following lines of loosening, ranged from 1.27 Mg $m^{-3}$ in autumn 2017 to about 1.53 Mg $m^{-3}$ in autumn 2018 (Table 4). The last measurement was marginally higher than that in the control (1.42-1.51 Mg $m^{-3}$) (Papers I and IV). A gradual increase in bulk density in loosened soil may be due to recompaction triggered by field operations and over burden pressure. The increase in bulk density over time supported previous findings that the effect of loosening alone is often of short duration (Larney & Fortune 1986; Twomlow *et al.* 1994; Carter *et al.* 1996). Bulk density differences were not observed between the two different loosening alone treatments ($L_{1y}$ and $L_{3y}$) except in autumn 2017, when the $L_{3y}$ treatment had lower bulk density than the $L_{1y}$ treatment $p<0.05$). However, at the last measurement, the values were almost equal (1.53 and 1.51 Mg $m^{-3}$, respectively), confirming that subsoil loosening is not a sustainable measure to alleviate subsoil constraints.

Calculations indicated that porosity at 29 to 34 cm soil depth was considerably higher in treatment LS (54-66%) than treatment L (42-52%) and the control (43-46%) between 2016 and 2018. In the same period, porosity in the 0-10 cm topsoil layer ranged between 51 and 59%.

The SOC in the 29-34 cm soil layer and control top soil (0-10 cm) were negatively correlated with bulk density. When the data for spring and autumn were treated separately, strong linear relationships were found ($R^2$=0.45-0.95, p<0.05). When data for all seasons and years were combined, SOC and bulk density were significantly negatively correlated ($R^2=0.84$, $p<0.01$) (Figure 4). Other studies have also found an inverse relationship between SOC and bulk density (Schjønning *et al.* 1994; Kätterer *et al.* 2011).

In autumn 2016, the mean penetrometer readings at 29-34 cm depth were high (3.7 MPa in $LS_{1y}$, 4.4 MPa in $L_{1y}$, 5 MPa in the control) compared with the threshold penetration resistance reading of about 3 MPa inhibiting root growth. Statistical analysis of the data indicated that penetration resistance was significantly lower in $LS_{1y}$ than in $L_{1y}$ and the control, and also significantly lower in $L_{1y}$ than in the control ($p<0.05$). Mean gravimetric water content in the 30-35 cm soil layer was 14% in the control, 14.4% in $L_{1y}$ and 17.8% in the $LS_{1y}$ treatment (Paper I).

In spring 2017, mean penetrometer readings at 29-34 cm soil depth were 2.4 MPa in $LS_{3y}$ that was significantly lower than in the control (3.9 MPa) and $L_{1y}$ (3.5 MPa). However, penetration resistance readings in treatment L did not differ from those in the control. During the 2017 season, the gravimetric water content in the 29-34 cm soil layer ranged between 17 and 20% and was significantly higher in the $LS_{3y}$ treatment than in the control (Paper IV).

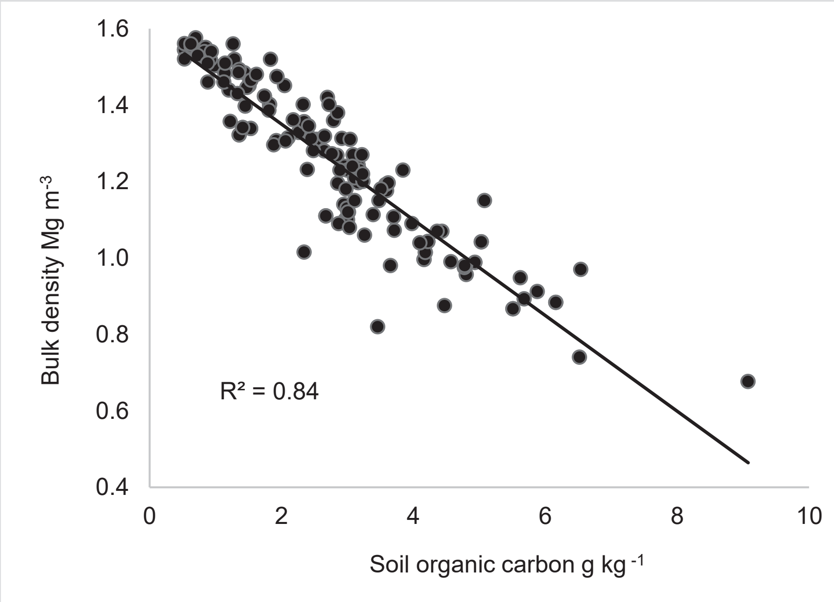


*Figure 4.* Bulk density as a function of soil organic carbon (SOC) based on measured data combined across seasons and years (spring and autumn 2016, 2017 and 2018) at 29-34 cm depth and control top soil (0-10 cm). The first-year (2016) results represent treatments of control, $L_{1y}$, $LS_{1y}$ and the 2017 and 2018 results of treatments $L_{1y}$: loosening in one year, $LS_{1y}$: loosening + straw addition in one year, $L_{3y}$: annual loosening for three years, $LS_{3y}$: annual loosening + straw addition for three years.

Penetration resistance in 2016 was positively related to soil bulk density ($R^2$=0.48) and inversely related to soil water content ($R^2$=0.56) (Paper I). The penetration resistance measurements in spring 2017 revealed similar relationships, although the correlation was weaker than 2016 (Paper IV), indicating that the difference in moisture and bulk density drove penetration resistance. These correlations are in agreement with findings in a study by Khan *et al*. (2001).

As penetration resistance measurements are sensitive to soil moisture, penetration speed and shaft friction (Bengough *et al.* 2000), it is difficult to generalise or identify absolute values. However, the values obtained from penetrometer readings are occasionally used to diagnose compaction levels in soil (Kuhwald *et al.* 2020). Thus, the available data were used to indicate the compaction level of the site used for field studies in this thesis. Except in the $LS_{3y}$ treatment in 2017, the penetration resistance values in 2016 and

2017 increased steadily below 25 cm, and most of the observed values were greater than 3 MPa, which is higher than the threshold inhibiting root growth (Håkansson & Lipiec 2000).

Relative bulk density values, expressed as degree of compaction (DC), are commonly used to characterise compactness of soil layers loosened regularly by tillage. However, DC may also be used for the subsoil or no-till surface layer (Håkansson & Lipiec 2000). The average DC value of the four-pedotransfer functions over the three years and seasons in the experimental plots in this thesis was around 89%, slightly higher than the optimum DC value for the barley crop, defined as 87% in the topsoil (loosened annually).

However, the penetration resistance value limiting root growth and the optimum DC value for root growth in the subsoil may be higher than literature values, because roots can still grow in macropores in a dense subsoil. Håkansson and Lipiec (2000) hypothesised that DC values higher than 87% in undisturbed fine-textured soil could be optimal, due to better macropore continuity. There is also evidence showing that higher DC values of about 95% to 102% were less detrimental in fine-textured soils after 8 to 15 years of reduced tillage (Comia *et al.* 1994; Etana *et al.* 1999). Håkansson (2005) indicated that soil could be classed as very intensively compacted when the DC value is 100 or above. As with the optimum DC, continuous vertical macropores in the subsoil drive the penetration resistance limit to a higher level than 3 MPa (Ehlers *et al.* 1983). Against this background, it can be suggested that the subsoil (29-34 cm) at the field site was moderately compacted, rather than severely compacted.

### 5.1.3 Water retention characteristics (Paper IV)

Subsoil loosening combined with straw addition (treatment LS) significantly increased plant-available water and water retention at 29-34 cm soil depth compared with the control at all soil water potential values tested ($p<0.05$) except at the highest suction corresponding to permanent wilting point (-1500 kPa).The net increase in plant-available water at 29-34 cm depth due to treatment LS was 3-4 mm compared with the control (9.2 mm) (Paper IV). The water content in the control somewhat indicate the inherently high capacity of the untreated soil to retain water. Plant-available water in treatment L was 10-11 mm (Table 5).

The significant increase in plant-available water in treatment LS was probably a combined effect of loosening and organic matter from the straw.

An increase in SOC and a decrease in bulk density are associated with increased porosity, creating an opportunity to retain more water in soil (Bhogal *et al*. 2009). Changes in soil aggregation and structure accompanying increased organic matter and the large surface area of organic material may also contribute to higher plant-available water content, as observed in the study by Franzluebbers (2002). The observed change in water content was an increase at low and moderate suction, but not a change in the wilting-point water content.

Table 5. *Volumetric water content ($m^3m^{-3}$) at different suctions (kPa) and plant-available water (mm) measured in Säby soil sampled at 29-34 cm depth in autumn 2018. Different letters within columns indicate significant differences between treatments ($p<0.05$, Tukey comparison test). $L_{1y}$: loosening in one year, $LS_{1y}$: loosening + straw addition in one year, $L_{3y}$: annual loosening for three years, $LS_{3y}$: annual loosening + straw addition for three years.*

| Treatments | Volumetric water content ($m^3m^{-3}$) at suction: | | | | | Plant-available water (mm) |
|---|---|---|---|---|---|---|
| | -0.5 | -10 | -30 | -60 | -1500 | |
| $L_{1y}$ | $0.386^a$ | $0.325^a$ | $0.207^a$ | $0.190^{ab}$ | $0.135^a$ | $9.5^a$ |
| $LS_{1y}$ | $0.473^b$ | $0.373^{bc}$ | $0.271^b$ | $0.238^{bc}$ | $0.126^a$ | $12.3^{bc}$ |
| $L_{3y}$ | $0.401^a$ | $0.347^b$ | $0.270^b$ | $0.235^{bc}$ | $0.136^a$ | $10.6^{ab}$ |
| $LS_{3y}$ | $0.498^b$ | $0.380^c$ | $0.303^b$ | $0.257^c$ | $0.117^a$ | $13.2^c$ |
| Control | $0.392^a$ | $0.318^a$ | $0.215^a$ | $0.185^a$ | $0.135^a$ | $9.2^a$ |

Based on correlation coefficients, the association between SOC and volumetric water content was stronger at low or moderate suction than at higher suction ($R^2$ = 0.85 to 0.32). The highest suction tested, representing permanent wilting point, was influenced less by SOC than other suction levels (Paper IV).

In summary, the positive change in soil properties (increased concentration of SOC and water holding capacity, decreased bulk density and penetration resistance) observed in this thesis supports the hypothesis that subsoil conditions can be improved by loosening combined with straw addition. Such changes in soil properties may have practical implications, but a corresponding positive effect on grain yield was not seen in this thesis work.

## 5.2 Subsoil improvement and crop production in lysimeter and field experiments (Papers I, II and IV)

### 5.2.1 Seed germination and crop growth

Subsoil improvement measures in the lysimeter and field experiments had no noticeable influence on crop emergence and establishment. However, a difference in plant height was observed. In the lysimeter experiment, the control plots had taller crops than the LS treatment at heading stage (Paper II) (Table 6). However, the $LS_{1y}$ treatment in the field experiment in 2016, and the $L_{1y}$ treatment in 2017, had taller plants than the control at anthesis (Papers I and IV). Significant changes in plant height due to subsoil treatments were not observed at each measurement.

### 5.2.2 SPAD readings and their association with yield

In the lysimeter experiment, SPAD readings was significantly lower in the LS treatment than in the control and loosening alone (L) treatments (Table 6). However, there was no difference in SPAD readings in the field study except in 2018, when there was an indication that the nitrogen content was significantly lower in $LS_{3y}$ (freshly incorporated straw) than in the other treatments (Paper IV). The lower SPAD readings in these soil columns in the lysimeters and in plots in the field (2018) may be attributable to temporary nitrogen immobilisation caused by the high C:N ratio of straw hindering nitrogen supply (Christian & Bacon 1991). However, the effect appeared to be temporary and grain yield was not significantly affected, although mean values in the lysimeter experiments were lower in LS than in treatment L and the control (Paper II). In the field experiment, yield in 2018 was similar to all treatments (Table 7). A transient effect of straw addition on nitrogen uptake has also been reported in studies by Christian and Bacon (1991) and Allison *et al*. (1992).

The results from the lysimeter and field experiments indicated that adding a large amount of straw to the subsoil did not significantly affect the final grain yield in treatments where SPAD readings were lower in the mid-growing season. This could be explained partly by the addition of milled straw and its incorporation 6-11 months before crop sowing. Decomposition rate is higher for finely ground than intact straw (Summerell & Burgess 1989; Angers & Recous 1997), enabling a larger contact area to be exposed to decomposition (Angers & Recous 1997). Incorporating straw prior to sowing the next crop allows microbes to degrade the straw over time, minimising the adverse effects of immobilisation (Harper & Lynch 1981; Singh *et al.* 2005).

Table 6. *Treatment effects on relative leaf chlorophyll content (SPAD-index), plant height at different growth stages and yield (Mg ha$^{-1}$) and nitrogen (N) content (%) of barley straw and grain in the lysimeter experiment. Mean values within rows followed by different letters are significantly different at p<0.05. L: loosening, LS: loosening + straw addition).*

| Crop measurements | L | LS | Control |
|---|---|---|---|
| SPAD-index at booting | 51.1$^{a}$ | 47.1$^{b}$ | 52.0$^{a}$ |
| SPAD-index at heading | 49.4$^{a}$ | 45.1$^{b}$ | 51.0$^{a}$ |
| Plant height (cm) at booting | 54.0$^{a}$ | 52.3$^{a}$ | 51.2$^{a}$ |
| Plant height (cm) at heading | 63.1$^{ab}$ | 60.0$^{b}$ | 65.2$^{a}$ |
| Grain yield (Mg ha$^{-1}$) | 6.3$^{a}$ | 5.8$^{a}$ | 6.2$^{a}$ |
| Straw yield (Mg ha$^{-1}$) | 5.6$^{a}$ | 5.5$^{a}$ | 5.5$^{a}$ |
| Grain N content % | 2.3$^{a}$ | 2.1$^{a}$ | 2.3$^{a}$ |
| Grain protein % | 14.2$^{a}$ | 13.1$^{a}$ | 14.1$^{a}$ |
| Straw N content % | 0.7$^{a}$ | 0.6$^{a}$ | 0.7$^{a}$ |
| Biomass harvest index % | 53.0$^{a}$ | 51.0$^{a}$ | 53.0$^{a}$ |

### 5.2.3 Grain yield

Grain yield in the LS treatment was 5.8 Mg ha$^{-1}$, which corresponded to an average decrease of around 8% compared with the L treatment (6.3 Mg ha$^{-1}$) and the control (6.2 Mg ha$^{-1}$) in the lysimeter experiment (Table 6). In the growing season of 2018, grain yield of oats was similar across treatments, which was around 7 Mg ha$^{-1}$ (unpublished data). However, in the growing season of 2019, unpublished data showed that grain yield of spring wheat crops increased in LS treatment (8.8 Mg ha$^{-1}$), by 11% and 5%, respectively, compared with the control (7.9 Mg ha$^{-1}$) and L treatment (8.4 Mg ha$^{-1}$), although the differences between treatments were not significant.. The grain yield of 7.9-8.8 Mg ha$^{-1}$ in 2019 possibly revealed the high yield potential of Säby soil.

In the field experiment, grain yield increased by a small margin, of about 6% ($p$<0.05) and 4% ($p$=0.06), compared with the control in the $LS_{1y}$ and $L_{1y}$ treatments, respectively, during the initial years of the experiment (Table 7). The marginally higher yield in that year may have been a combined effect of improved plant-available water and increased amount of pores in which roots could grow (Paper I). A major drawback for crop production in that crop-growing season was weed infestation, the magnitude of which was somewhat higher in the $LS_{1y}$ treatment. Weed infestation could be expected to result in yield loss in all treatments.

Another consideration was that biomass sampling during the mid-crop growing season was not restricted to the borders. Mid-crop growing biomass was sampled in the area where the final combine-harvested yields were measured, which could have affected the absolute yield value. The grain yield of spring barley in 2017 varied between 6.5 and 6.8 Mg ha$^{-1}$ and that of oats in 2018 varied between 3.8 and 4.0 Mg ha$^{-1}$ in the different treatments (Table 7). The lower yield of oats resulted from the low moisture and high temperature observed during 2018 could be due to the susceptibility of oat crops to drought stress (Zhao *et al.* 2020).

Table 7. *Grain yield (standard water content) and grain protein content at harvest in the 2016 (spring wheat) 2017 (spring barley) and 2018 (oats) growing seasons. $L_{1y}$: loosening in one year, $LS_{1y}$: loosening + straw addition in one year, $L_{3y}$: annual loosening for three years, $LS_{3y}$: annual loosening + straw addition for three years. The first-year (2016) results were represented as control, $L_{1y}$ and $LS_{1y}$ plots.*

| Year | Treatment | Grain yield (Mg ha$^{-1}$) | Grain protein % |
|---|---|---|---|
| 2016 | $L_{1y}$ | 4.84$^{ab}$ | 16.2$^{a}$ |
| | $LS_{1y}$ | 4.91$^{b}$ | 15.7$^{b}$ |
| | Control | 4.65$^{a}$ | 16.1$^{a}$ |
| 2017 | $L_{1y}$ | 6.68 | 14.5$^{a}$ |
| | $LS_{1y}$ | 6.77 | 14.2$^{ab}$ |
| | $L_{3y}$ | 6.63 | 14.7$^{a}$ |
| | $LS_{3y}$ | 6.46 | 13.8$^{b}$ |
| | Control | 6.52 | 14.6$^{a}$ |
| 2018 | $L_{1y}$ | 3.94 | 15.1$^{a}$ |
| | $LS_{1y}$ | 3.88 | 15.1$^{a}$ |
| | $L_{3y}$ | 3.97 | 15.0$^{a}$ |
| | $LS_{3y}$ | 3.96 | 14.6$^{b}$ |
| | Control | 3.83 | 15.0$^{a}$ |

However, in other studies of different settings, an increase in grain yield greater than in the 2016 cropping season has been reported after deep placement of organic materials (organic manure pellets, lucerne pellets, dynamic lifter, maize residue fragments) and subsoil loosening (Adcock *et al.* 2007; Gill *et al.* 2008; Leskiw & Zeleke 2009; Zhang *et al.* 2020).

Although there was a change in soil properties, the small treatment effect on grain yield observed in this work in the first year of the field experiment was not repeated in the second and third years, as there was no difference between treatments. Similarly, there was no difference in yield between treatments in the lysimeter experiment. This is probably due to the involvement of other factors, which may have buffered subsoil treatment effects. The properties of Säby soil, site and weather condition could have masked the impact of subsoil amendments on crop productivity. This agrees with previous scientific studies and review articles (Kautz *et al.* 2013; Schneider *et al.* 2017; Celestina *et al.* 2019). In general, the effects of subsoil improvement on yield may have been attenuated by nutrient immobilisation, fertility status of the surface layer, site conditions and drought stress.

## 5.3 Leaching and nitrogen balance in lysimeters (Paper II)

The amount of leachate collected during the 21 months of the lysimeter study did not differ significantly between treatments (260 mm on average for treatment L, 271 mm for LS and 301 mm for the control). The amount of leachate collected as a fraction of total precipitation and additional irrigation over the 21 months was 26-30% (Paper II). Most leachate was collected during autumn and spring and there was also leachate in winter, indicating mild conditions. However, there was no leachate during the crop-growing season, due to high evapotranspiration and possibly low precipitation in the month before crop sowing.

The mean volume-weighted concentrations of nitrogen were significantly higher in the loosening alone treatment (56 mg N $L^{-1}$) and the control (64 mg N $L^{-1}$) than in the loosening combined with straw (LS) treatment (28 mg N $L^{-1}$). Accordingly, the nitrogen-leaching load from the lysimeters was relatively high, ranging from 74 to 193 kg $ha^{-1}$ during the 21-month period (Figure 5 and Table 8). This could be due to the content of organic matter in the Säby soil being relatively high and thus mineralisation of nitrogen for about 13 months in the lysimeter before cropping (as cropping was not done immediately after soil column installation). The whole soil columns were exposed to ambient air temperature for three months during this period. Previous studies have reported high nitrogen leaching loads due to uncropped periods (Francis *et al.* 1992; Meissner *et al.* 1998).

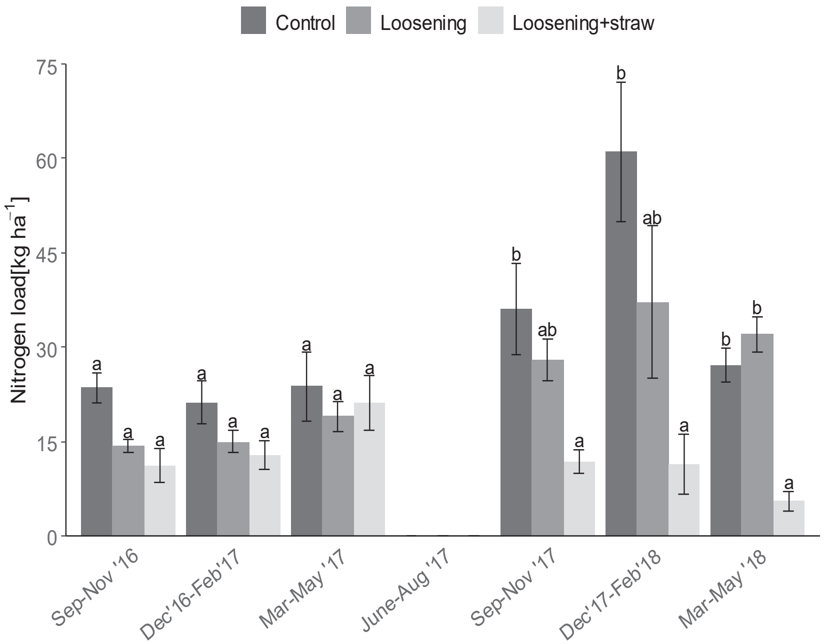


*Figure 5.* Mean (arithmetic) nitrogen load (kg N ha$^{-1}$) from the different treatments during the 21 months of the lysimeter study. Values within three-month periods with different letters are significantly different at $p$<0.05. The $p$-value for the difference between loosening + straw and loosening (December 2017-February 2018) was 0.06. Bars indicate standard error of the mean of four replicates.

The nitrogen leaching load from the LS treatment was 62% and 49% lower than of that from the control and loosening alone treatment, respectively ($p$<0.05), while loosening alone reduced nitrogen leaching load by 25% ($p$=0.07) compared with the control (Paper II). Similarly, the effect of straw addition alone compared with the control (71 kg N ha$^{-1}$) lowered nitrogen leaching by 37% (Figure 5 and Table 8). This outcome is in line with other findings on reduced nitrogen leaching due to straw incorporation (Powlson *et al.* 1985; Machet & Mary 1989; Nicholson *et al.* 1997; Silgram & Chambers 2002). The decrease in nitrogen leaching has been ascribed to immobilisation. Powlson *et al.* (1985) suggested that addition of straw in autumn might decrease nitrogen leaching during the winter and help preserve it within the system. Immobilised nitrogen can be expected to be re-mineralised and delivered to crops in the long term (Powlson *et al.* 2011). The decrease in nitrogen leaching in the short term supported the hypothesis that subsoil loosening with straw addition decreases nitrogen leaching. This result has practical implications for water quality, but should be verified in long-term field experiments.

Table 8. *Nitrogen (N) balance for the soil-crop system in the 21-month lysimeter study period (kg N ha$^{-1}$ 21 month$^{-1}$), calculated as the difference between inputs and outputs, where inputs are N additions (fertiliser and seeds) and outputs are N removal and losses (harvest, leaching and $N_2O$ emissions) L: loosening, LS: loosening + straw.*

| N flux (kg N ha$^{-1}$) | L | LS | Control |
|---|---|---|---|
| Inputs | | | |
| Seeds | 8 | 8 | 8 |
| N fertiliser | 100 | 100 | 100 |
| Straw addition | 0 | 282* | 0 |
| Subtotal | 108 | 108 | 108 |
| Outputs | | | |
| Grain | 144 | 122 | 141 |
| Harvested straw | 38.5 | 32.2 | 38.2 |
| N leaching | 145 | 74 | 193 |
| $N_2O$-N emissions | 0.07 | 0.04 | 0.04 |
| Subtotal | 328 | 228 | 372 |
| Balance | -220 | -120 | -264 |

*Nitrogen input not available in the short-run initially, but during the latter part of the experiment, some straw-derived N may have become available to the crop.

As shown in Table 8, apparent immobilisation corresponded to about 100 kg N (difference between L and LS treatments) over a 21-month period, suggesting that the straw decomposition led to immobilisation of around 1.7 kg N Mg$^{-1}$ of incorporated straw. This is within the range found by Christensen (1985) in a study at Askov Experimental Station in Denmark (1-3 kg N Mg$^{-1}$ of incorporated straw). Immobilised amount for the 11 months after crop sowing was 97 kg N (Figure 6), which was in the same order as for the full 21-month period.

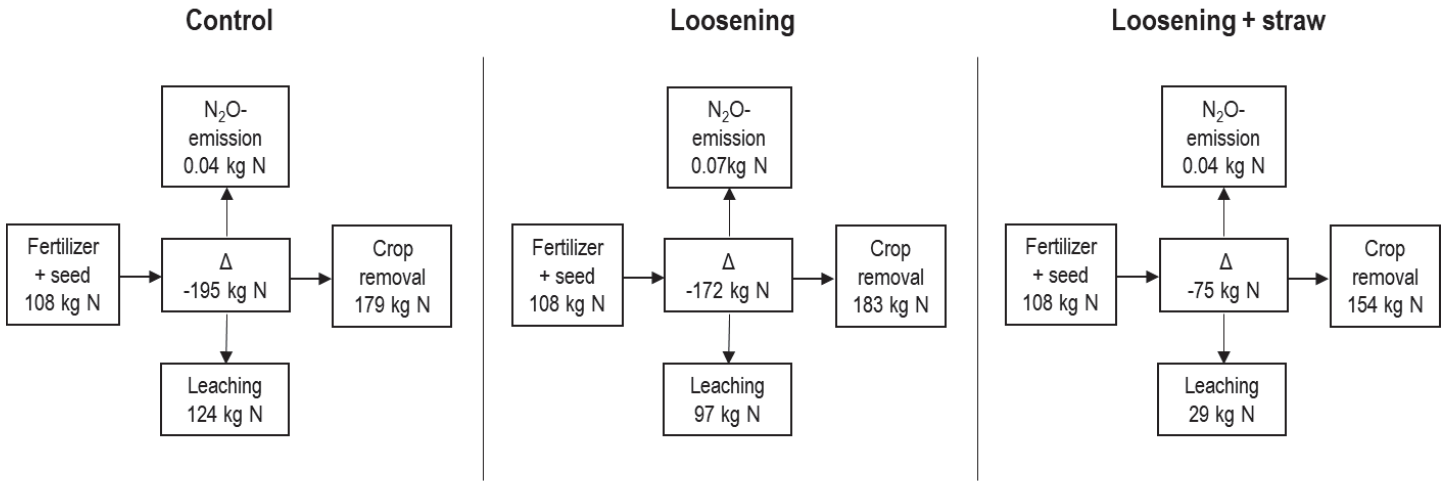


*Figure 6.* Nitrogen (N) balance (kg N $ha^{-1}$) for the soil-crop system for the 11 months after crop sowing, calculated as the difference between inputs and outputs. Inputs are N additions (fertiliser and seeds), outputs are N removal, and losses (harvest, leaching and $N_2O$ emissions) in the different treatments in the lysimeter experiment.

Emissions of $N_2O$ during the crop growing period were low (0.04-0.07 kg $N_2O$-N ha$^{-1}$). These low emissions were probably due to relatively dry subsoil conditions in the lysimeters, as they were detached from the groundwater.

Considering all the above components, the nitrogen balance (amount in inorganic nitrogen fertiliser and crop seed, minus amount in the grain and straw plus leaching loss) over the 21 months was negative in the lysimeter experiment, ranging from 120 kg N ha$^{-1}$ in the LS treatment to 264 kg N ha$^{-1}$ in the control, showing the potential to reduce nitrogen leaching through addition of straw. The nitrogen balance in the loosening alone treatment was 220 kg N ha$^{-1}$. Similarly, the nitrogen balance for the 11 months after crop sowing was -195 kg N ha$^{-1}$ in the control, -172 kg N ha$^{-1}$ in the loosening alone treatment and -75 kg N ha$^{-1}$ in the loosening combined with straw treatment (Figure 6).

## 5.4 Visual observations in the field study (Papers I and IV)

Subsoil loosening combined with straw-treated soil resulted in higher abundance of earthworms and many bio-channels and earthworm casts were detected (Figure 7). Adding organic materials to soil increase earthworm abundance and activities , as found by Bertrand *et al.* (2015). When the straw is milled, this favours earthworms even more (Sizmur *et al.* 2017). A combination of coarse and fine aggregates, which were almost friable, was detected in the treatment LS soil. Roots were seen growing towards the subsoil area where loosened and straw had been incorporated (Figure 7). Root abundance decreased from the topsoil to the subsoil in all treatments. In treatment L and the control, aggregates were often coarser and there were fewer biological pores and sometimes clods with angular and platy structure compared with treatment LS.


*Figure 7*. Visual observations of subsoil treated with loosening+straw over the years of the field study including 2019. The red arrows in (a) and (b) indicate earthworm (c) Insect eggs (d) moisture around the area where straw was incorporated, (e) to (h) roots growing towards the incorporation area and friable aggregates, (i) biopores, (j) roots growing towards the straw area, (k) occasional earthworms and biopores, (l) friable aggregates (m) and (n) biopores and roots growing through biopores, and (o) and (p) friable aggregates.

## 5.5 Structure liming of subsoil (Paper III)

Tests on the use of lime to improve subsoil structural stability showed that clay dispersion decreased linearly with an increase in soil pH achieved using $CaCO_3$ and CaO (Figure 8). Addition of lime ($CaCO_3$ and CaO) reduced clay dispersion on average by 3, 10 and 17 % at low, intermediate and higher rates respectively, compared with the control. When compared to the control, these reductions showed a trend for a difference at the highest $CaCO_3$ and CaO addition rates (*p*=0.07 and *p*=0.1, respectively).

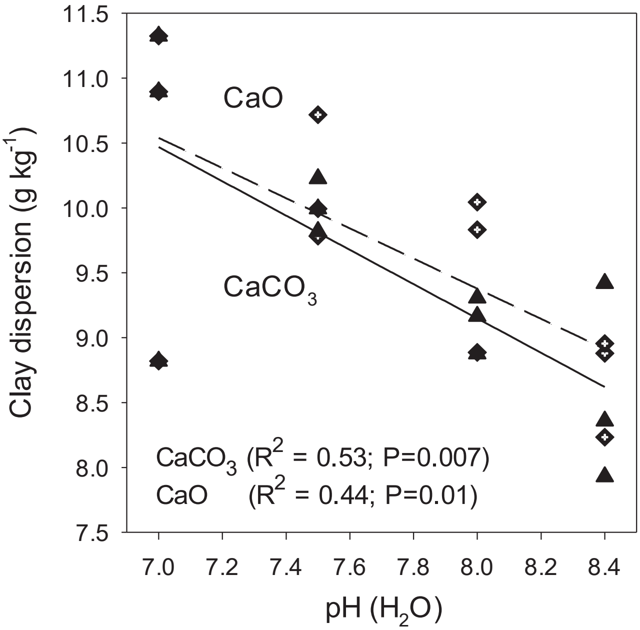


*Figure 8.* Linear regression between clay dispersion (g $kg^{-1}$) and pH after 22 months of incubation with different rates of $CaCO_3$ (triangles and solid line) and CaO (diamonds and dashed line).

The linear decrease with an increase in pH (due to an increase in lime amount) (Figure 8) was possibly due to relatively strong bonds being formed by calcium ions between clay colloids and negatively charged organic materials (Amezketa 1999; Six *et al.* 2004).

In response to lower and intermediate rates of lime addition, wet aggregate stability increased by 10-13%, but the values were not significantly different from the control. However, in the step-wise regression, the amount of water-stable aggregates increased and peaked at pH 7.8, but decreased again at higher pH ($R^2$=0.73 for CaO, $R^2$=0.68 for CaCO3, P<0.001).

A lime-induced soil pH increase and the subsequent effect on organic carbon solubility (You *et al.* 1999) may account for the reduced aggregate stability at higher pH. This is because soil aggregates >250 µm are held together by temporary binding agents that are affected by soil organisms and chemical conditions (Tisdall & Oades 1982). Chan and Heenan (1998) also reported a decrease in structural stability due to lime-induced decomposition of organic matter.

A reduction in wet aggregate stability (breakdown of macroaggregates) may occur without dispersion of smaller aggregates into clay sized particles (Oades & Waters 1991). No differences between the lime types tested were found in terms of effect on clay dispersion and wet aggregate stability.

Phosphate solubility was lowest at neutral pH, while at higher soil pH, it followed the same pattern as wet aggregate stability. The concentration of DRP increased as the pH (corresponding to lime amount increase) was increased to 7.5, by 25 and 37 % compared with the control for CaO and $CaCO_3$, respectively (Figure 9). At pH 8 the concentration of DRP was lower than pH 7.5, however, it was still 15-17% higher than in the control. At pH 8.4, it was almost similar to that in the control for both lime types.

The increase in DRP up to pH 7.5 and 7.6 could be attributed to a less positively charged surface (Murphy 2007) and site competition with negatively charged organic matter (Guppy *et al.* 2005). The subsequent decrease after pH 7.5 was probably attributed to calcium precipitation with soluble phosphate, thus lowering DRP (Haynes 1982) (Figure 9). In general, the reduction in clay dispersion and increase in wet aggregate stability (maximum at pH 7.8) supports the hypothesis that lime application improves soil structural stability in heavy clay subsoil. This has practical implications for crop production and the environment, as clay dispersion is related to soil friability (Czyz & Dexter 2015) and nutrient transport.

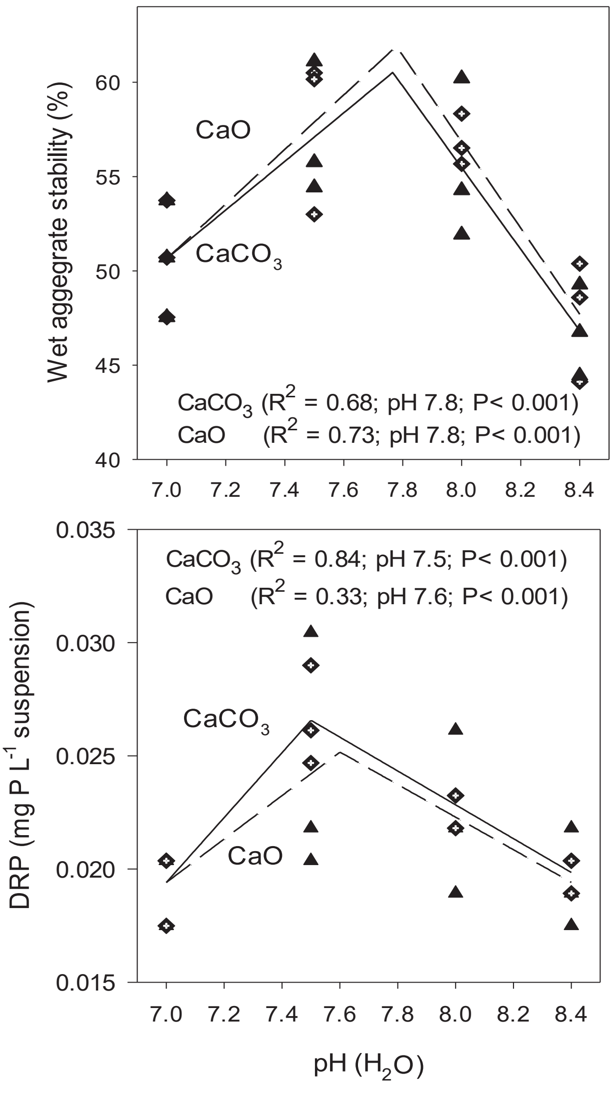


*Figure 9*. (Upper diagram) Wet aggregate stability (%) and (lower diagram) concentration of dissolved reactive phosphorus (DRP, mg $L^{-1}$) as a function of soil pH after 22 months of incubation with different rates of $CaCO_3$ (triangles and solid line) and CaO (diamonds and dashed line). The data were fitted to piece-wise linear functions.

## 5.6 Practical implications of the results

Addition of lime is one of the management options for improving subsoil structural stability. The results presented in this thesis demonstrated that liming could improve structural stability (wet aggregate stability increased and peaked at pH 7.8 and clay dispersion decreased) in the subsoil, which may have important implications for soil structure and crop production. These promising results should be further tested, possibly in combination with subsoil loosening in field experiments.

At the same time, combining subsoil loosening with straw addition generated the benefit of increasing soil organic matter, total nitrogen, porosity and water-holding capacity while decreasing bulk density, physical resistance to root growth and nutrient concentrations in leachate. This suggests that in the short term, this management option has the potential to improve soil properties and water quality. Low physical resistance is likely to favour root growth and crop yield. However, it appears that crop yield are not markedly improved. Although not systematically tested, the following suggestions may be offered for why a substantial yield increase was not observed in field and lysimeter experiments following subsoil improvement treatments:

a) One aim of subsoil management is to make more soil water available for crops. However, precipitation and temperature during the experiment were below and above the long-term average, respectively, possibly affecting the amount of water that could move to the subsoil, particularly during the dry crop growing season .Thus, moisture stress in the subsoil may have prevented achievement of the maximum possible benefits from improving the subsoil conditions in the field experiment. Lack of considerable yield differences after deep placement of organic materials due to drought stress has been reported previously (Celestina *et al.* 2018).
b) The field and lysimeter site (Säby) has been under arable use for more than a century, with standard agricultural practices that could have enhanced surface soil fertility. In all treatments in both the lysimeter and field experiments, grain protein level ranged between 13 and 16 %, indicating that nitrogen was probably not limiting in these years (Papers I, II and IV). Holford *et al*. (1992) found that yield of a wheat crop may be only slightly responsive or unresponsive to additional nitrogen fertiliser if grain protein content exceeds 12%. Therefore,

the potential benefits of subsoil treatments could have been masked by fertilisation effects coupled with relatively high fertility status in the surface layer. A recent comprehensive review suggested that deep tillage can positively impact yield by enhancing access to nutrients in the subsoil when nutrients are limiting in the topsoil (Schneider *et al.* 2017).

c) According to Schneider *et al*. (2017), soils with vertical root growth restriction by compacted layers can be expected to react with up to 20% yield increases due to subsoil improvements. However, the field and lysimeter treatments in this thesis did not enhance yield to that level, perhaps partly because the Säby soil in the 29-34 cm layer seems to be only rather moderately compacted (according to the evaluation of DC results and penetrometer readings), as a result root growth in that layer (29-34 cm) may not be adversely affected.

On the one hand, improvements such as an increase in soil organic matter, water-holding capacity and a decrease in bulk density and nutrient concentrations in leachate, while on the other hand a lack of considerable increase in grain yield complicates generalizing the overall effect. However, this management option may be appropriate for soils that are more severely compacted and have low nutrient availability, or under weather conditions other than those described here. Therefore, it might be useful to undertake further investigations to reconsider the treatments and procedures tested in this thesis or look for alternatives to improve subsoil conditions for Säby type soil in a Swedish climate to affect crop productivity and the environment significantly. In addition, this type of application could benefit from long-term observation. In this regard, cost-benefit analysis including a comprehensive life cycle assessment would be useful for further evaluation of the management options considering both productivity, economic and environmental criteria.

# 6. Conclusions

In this work, management options to improve subsoil properties, and thereby crop performance, were tested. Large amounts of straw (24 to 60 Mg $ha^{-1}$) were placed into subsoil in field and lysimeter experiments during loosening, with the aim of achieving long-lasting improvements in soil properties and crop yield. In a laboratory incubation with subsoil, the impact of liming on structural stability and dissolved reactive phosphorus (DRP) was investigated. Based on the work in this thesis, the following conclusions were drawn:

- Subsoil loosening combined with straw incorporation positively affected soil properties and the effect persisted for at least three years.
- Incorporation of straw into loosened subsoil increased soil water-holding capacity and plant-available water
- A comparison of repeated or one-time subsoil treatments (subsoil loosening or subsoil loosening combined with straw) gave no difference in grain yield
- Subsoil improvement gave small or no yield benefit
- Subsoil loosening as a management option was not an effective measure in the experimental soil
- Subsoil loosening combined with straw incorporation reduced nitrogen leaching by 62% in the short term, indicating potential to improve water quality
- In general, liming a clay subsoil improved structural stability

# 7. Future perspectives

Subsoils have the potential to provide nutrients and water to plants. Limited access by roots to subsoils can constrain crop production. The aim of future agriculture must be to produce more food on existing arable land. The results in this thesis indicate that subsoil loosening combined with straw incorporation could be a useful practice to improve subsoil properties (increased porosity and low physical resistance) and reduce nitrogen leaching in the short run. However, high treatment costs, limited access to organic amendments, lack of technical equipment and small effects on crop yield are likely to constrain adoption of the practice.

Nutrients contained in the amendment, improvements in soil properties due to the amendment (non-nutrient) or a combination of both may result in yield increase following subsoil amendment. Understanding the processes and mechanisms involved in subsoil improvement practices is useful to determine the underlying reasons for crop yield increase. In this regard, appropriately designed controlled experiments and modelling may be used to complement field studies, in order to elucidate the mechanisms responsible for crop yield increases and address confounding variables.

Subsoil constraints are numerous, variable and so far difficult to resolve. Improving subsoil conditions may be achievable through the development of new management approaches. Therefore, technical solutions and combinations of measures that can principally re-shape subsoil properties and reinforce each other to deliver multiple corrections are needed.

Understanding the extent of improvement achievable and how a single measure and combinations of management options affect subsoil properties is important. Deep placement of organic material in soils that are severely compacted and have low productivity may be useful. The type of organic material, optimum depth for placement, frequency needed, optimum amount and timing of addition are still open questions. Lime as a means to improve subsoil structure by aggregating particles could be a further option. Providing answers to these questions, preferably in long-term field experiments, will be valuable for crop production.

The effect of subsoil improvement practices probably depends on the soil type, weather and specific site conditions. Thus, measures to alleviate problems in the subsoil should be tailored to account for variability in soil type, weather and site conditions, as these differences may contribute to differences in soil and crop response.

It appears that not all soils respond positively to deep placement of amendments, and soils with severely constrained root growth should be studied in future work. To this end, constraints that limit crop yield should be identified before employing subsoil improvement practices. This could be done by measuring soil physical, chemical and biological properties and by determining root depth and distribution.

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# Popular science summary

## Can improving subsoil conditions enhance crop yield or water quality?

The subsoil, *i.e.* the layer below ploughing depth (often at about 25 cm in Sweden), can store large amounts of water and plant nutrients. For example, the subsoil can supply 10 to 65% of the nutrients used by crops. Enabling crop roots to access these subsoil resources, especially water, will be important under future climate change when droughts are predicted to become more frequent. However, subsoil compaction or development of a dense plough pan following years of tillage can prevent crop roots from accessing water and nutrients stored in the subsoil.

Topsoil structure is easy to manage by tillage, but there are no easy technical solutions to improve the subsoil. Machines with long mechanical tines can be used to improve the subsoil, but the effects often do not last long. Mechanical loosening is also expensive and the high costs are not covered by benefits in terms of higher crop yield. Combining mechanical subsoil loosening with addition of straw, lucerne pellet, compost, or lime could give longer-lasting improvements in subsoil structure, thereby increasing plant-available water content and crop nutrient supply, which would result in higher crop yield.

This thesis evaluated the effects of subsoil management options on crop yield, soil properties and the environment in field and lysimeter experiments at Säby, Uppsala. Laboratory incubations of soil from Kungsängen, Uppsala, were also performed, to evaluate the effect of adding lime on dissolved reactive phosphorus and in stabilising the soil structure.

The results showed that subsoil loosening combined with straw injection at 25-34 cm depth increased the amount of organic carbon in the soil and reduced the density of soil, with the effects lasting for at least three years in the field. Visual observations in the field showed that there were more earthworms and biopores in the soil along the straw injection lines. Soil clods in treated plots were more easily fragmented by hand and earthworm casts were common. However, there was no great increase in crop yield.

Experiments on extracted soil columns (lysimeters) showed that subsoil loosening combined with straw addition at 25-40 cm depth reduced short-term nitrogen losses via drainage water by about 62%, thus lowering the environmental impact in terms of water quality. Addition of lime materials to the subsoil improved soil structural stability. These promising results should be further tested and evaluated in long-term field experiments.

Subsoil constraints are numerous and variable and so far not easy to resolve. Future research may focus on developing technical solutions and management options that can complement each other in a holistic approach to address multiple subsoil problems at once.

# Populärvetenskaplig sammanfattning

## Kan förbättrade förhållanden i alven öka avkastningen eller förbättra vattenkvaliteten?

Alven, som i en åkerjord är skiktet under plöjningsdjupet (ofta cirka 25 cm i Sverige), lagrar stora mängder vatten och växtnäringsämnen. Alven kan till exempel bidra med 10 till 65% av grödans näringsbehov. Att möjliggöra för grödans rötter att få tillgång till alvens resurser, i synnerhet till vatten, kommer att bli än viktigare i framtida klimatförändringar när torrperioder förväntas bli mer frekventa. Packning av alven, eller utvecklandet av en kompakt plogsula efter långvarig plöjning, kan förhindra rötterna att få tillgång till vatten- och näringsförråden i alven.

God struktur i matjorden är relativt enkelt att åstadkomma med hjälp av jordbearbetning, men det finns inte någon enkel teknisk lösning för att förbättra alvens struktur. Redskap med långa bearbetande pinnar (mekanisk alvluckring) kan användas för att förbättra alven, men effekten av denna typ av åtgärd är ofta kortvarig. Mekanisk alvluckring är dessutom förknippad med höga kostnader som oftast inte kompenseras av en högre skörd. En kombination av mekanisk alvluckring och tillsats av halm, lusern, pellets, kompost eller kalk kan däremot antas förbättra förhållandena i alven mer långsiktigt. Genom att förbättra jordens aggregering och struktur och därigenom öka innehållet av växttillgängligt vatten och förbättra näringsförsörjningen för grödorna har denna åtgärd potential att bidra till en högre skörd.

Denna avhandling utvärderade effekterna av olika åtgärder i alven med avseende på skörd, markegenskaper och miljöpåverkan i fältförsök på Säby utanför Uppsala samt i lysimeterförsök. Inkubationsexperiment i laboratorium med jord från Kungsängen, Uppsala utfördes för att utvärdera effekten av kalktillförsel på halter av vattenlösligt reaktivt fosfor och stabilisering av markstrukturen.

Resultaten visade att mekanisk alvluckring i kombination med tillförsel av halm på 25 till 34 cm djup ökade markens innehåll av organiskt kol och minskade markens densitet, med effekter som blev bestående i minst tre år under fältmässiga förhållanden. Observationer i fält visade att det fanns fler daggmaskar och maskgångar i jorden längs med sträckningen där halminblandning utförts. Jordaggregaten var också lättare att sönderdela efter behandling med halm och spår av daggmaskar var vanligt förekommande. Tillförsel av halm ledde emellertid inte till någon stor skördeökning.

Experiment genomförda på prover från jordkolonner (lysimetrar) visade att mekanisk alvluckring kombinerat med halmtillförsel vid 25-40 cm djup reducerade kväveförlusterna via dräneringsvatten med ungefär 62% på kort sikt och bidrog därmed till en minskning av miljöpåverkan med avseende på vattenkvalitet. Tillförsel av kalk till alven resulterade i en stabilare markstruktur. Dessa lovande resultat behöver utvärderas vidare i långliggande fältförsök.

Begränsningarna i alven kan vara många och varierande och är än så länge utmanande att lösa. Framtida forskning bör fokusera på utvecklandet av tekniska lösningar och åtgärdsalternativ som kan komplettera varandra och som därmed kan ta ett helhetsgrepp för att adressera flera problem med alven samtidigt.

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Acta Universitatis Agriculturae Sueciae

Doctoral Thesis No. 2021:43

This thesis evaluates the effect of subsoil improvement on soil properties, crop performance and environmental impact. Combining loosening with straw incorporation into subsoil affects soil properties and water quality positively, but crop yield was not significantly affected and remains a barrier to treatment adoption, requiring further testing. Addition of lime into the subsoil could be seen as an option for managing subsoil in which results could be further tested in field experimentation for future use.

**Gizachew Tarekegn Getahun** received his graduate education at the Department of Soil Environment, SLU, Uppsala. He holds a degree of MSc in Agro-Environmental Management from Aarhus University and MSc in Sustainable Forest Management from SLU, Alnarp and Copenhagen University.

Acta Universitatis Agriculturae Sueciae presents doctoral theses from the Swedish University of Agricultural Sciences (SLU).

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