Tillage practices and their impact on soil organic carbon and the microbial community

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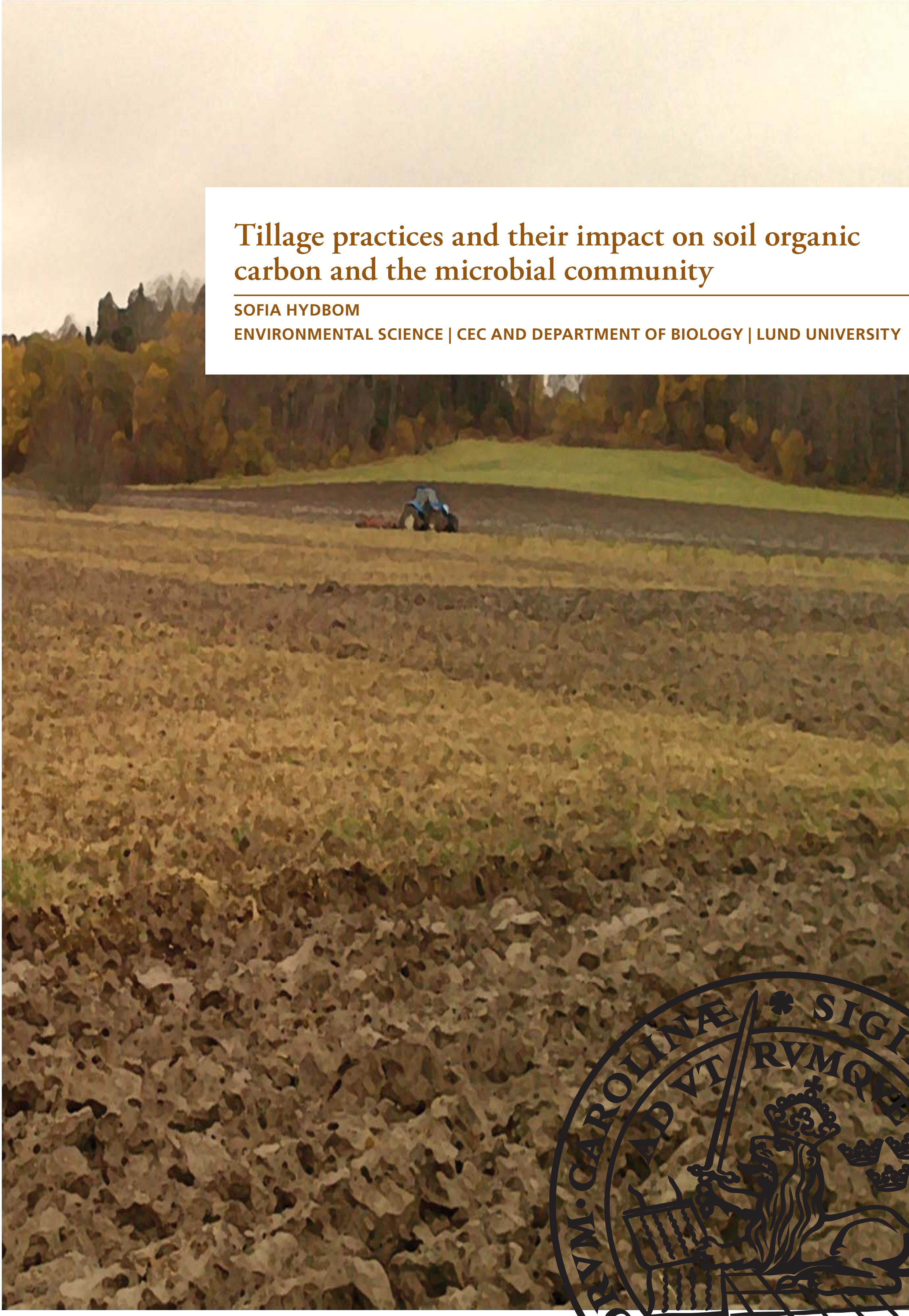

Tillage practices and their impact on soil organic carbon and the microbial community

TILLAGE PRACTICES AND THEIR IMPACT ON SOIL ORGANIC CARBON AND THE MICROBIAL COMMUNITY

SOFIA HYDBOM

LUND UNIVERSITY

DOCTORAL DISSERTATION

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Abstract

Soil microorganisms are important for climate regulation as well as for plant nutrition. In agricultural soils the microorganisms are affected by management choices, like which type of tillage that is used. Moldboard plowing, the most common tillage practice, increases mineralization which leads to soil organic carbon (SOC) loss, and may thus reduce soil quality. Conservation tillage practices infer less soil disturbance and they are considered to reduce mineralization compared to plowing, and favor fungi to greater extent than bacteria, which has been suggested to result in increased SOC content. Conservation tillage has been implemented by farmers worldwide to reduce soil erosion and also to improve farm economy.

The main aims of this thesis were to find out how conservation tillage affect SOC concentrations and the soil microbial community compared to plowing, and which type of farmers that are likely to use conservation tillage and why. The effects of tillage practice on SOC, arbuscular mycorrhizal fungi (AMF), saprotrophic fungi and bacteria, were evaluated using three Swedish long-term tillage experiments, whereas a questionnaire was sent out to Scanian farmers to find out more about conservation tillage use.

I found that long-term conservation tillage do not necessarily lead to an increase in SOC concentrations, and that fungi and particularly AMF benefit from reduced tillage. Although the tillage treatment effect on the microbial activity was not consistent, the respiration rate was often higher under conservation tillage than under plowing, at least when measured near the soil surface. Furthermore, a typical farmer who use conservation tillage is highly educated and work more than halftime with crop production. I also learned that crop rotation, labor savings and soil type are often considered when deciding on which tillage type to use.

To conclude, use of conservation tillage may not increase SOC concentrations in the studied areas, but can still be attractive to farmers as it benefits AMF and can lead to better farm economy, if implemented on suitable soil and with an adapted crop rotation.

Key words
Tillage, agriculture, long-term field experiments, microorganisms, clayey soil, SOC, farmer, Sweden.

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I. **Hydbom, S.**, Ernfors, M., Birgander, J., Hollander, Jensen, E.S., Olsson, P.A. 2017. Reduced tillage stimulated symbiotic fungi and microbial saprotrophs, but did not lead to a shift in the saprotrophic microorganism community structure. Applied Soil Ecology. 119, 104-114.

II. **Hydbom, S.**, Ernfors, M., Olsson, P.A. Biochemical signatures reveal positive effects of conservation tillage on arbuscular mycorrhizal fungi but not on saprotrophic fungi and bacteria. Manuscript.

III. **Hydbom, S.**, Olsson, P.A. Tillage effects on bacterial and fungal saprotrophic activity during the vegetative season in agricultural fields. Manuscript.

IV. **Hydbom, S.**, Alkan Olsson, J., Olsson, P.A. A farmer-based survey on the use of conservation tillage in an agro-intensive region. Submitted.

Paper I is reprinted with permission from the publisher.

Author contributions

I. **Hydbom** and Olsson planned the project together with Ernfors and Steen Jensen. **Hydbom** collected soil samples with help from Ernfors and Birgander. **Hydbom** was responsible for analyses with statistical help from Hollander, and for the writing the first draft of the MS. All authors contributed to the revision of the MS.

II. **Hydbom** and Olsson planned the experiment together. **Hydbom** was responsible for soil sample collection, with help from Olsson. **Hydbom** was responsible for analyses and for writing the first draft of the MS. **Hydbom**, Olsson and Ernfors contributed to revising the MS.

III. **Hydbom** and Olsson planned the experiment together, and **Hydbom** was responsible for soil sample collection, with some help from Olsson. **Hydbom** was responsible for analyses and for writing the first draft of the MS. Both authors contributed to revising the MS.

IV. **Hydbom** planned the project and was responsible for data collection and analysis. The first draft was written by **Hydbom**, and Olsson and Olsson contributed to revision of the MS.

"Essentially all life depends upon the soil…There can be no life without soil and no soil without life" *C.E. Kellogg 1938*

CHAPTER 1

Introduction

Even though we may rarely think about it, the opaque soil layer beneath our feet provides a multitude of benefits that are of great value to us (Altieri, 1999). These benefits are sometimes referred to as ecosystems services, and in the Millennium Ecosystem Assessment (MEA), ecosystems services were described by the concise phrasing "benefits people obtain from an ecosystem" (MEA, 2005). The definition and classification of ecosystem services may however vary (Dominati et al., 2010, Nahlik et al., 2012), but fortunately, the inconclusive nomenclature does not affect the services the soils provide. How well these services function, relates to the health or quality of the soil. Then, what is soil quality? It has been described as "the capacity of soil to function" (Karlen et al., 1997), and is mainly governed by the amount of organic matter present in the soil (Bullock, 2005). Changes in soil quality as a result of agricultural management occur at different time scales. Some changes come about progressively, which make early stage evaluation of soil quality changes due to altered management difficult. Much research has therefore focused on identifying and evaluating possible soil quality indicators, which may facilitate detection of early changes in soil quality (e.g. Schloter et al., 2003; Salome et al., 2014; Gil-Sotres et al., 2005).

Thus, knowing that soil function is important - which are the ecosystem services that a soil can provide? Among the widely accepted services that soils provide are climate regulation (e.g. C-cycling), nutrient cycling (e.g. decomposition of organic matter) and erosion control (Robinson et al., 2013). A shared feature among these services is that they are closely linked to the soil microbial community. Soil microorganisms, like bacteria and fungi, are affected by biotic factors such as predation, and also by abiotic factors like moisture (Brocket et al., 2012), temperature (Frey et al., 2008), and resource quality and availability (Bending et al., 2002). Agricultural management can alter the biological, physical and chemical properties of a soil, and management change is therefore likely to also affect the soil microorganisms. Agricultural management practices can be beneficial for the soil microorganisms, but intensive soil management can have negative unintended effects on the microorganisms. In such cases, management may lead to a disturbance of the soil function, and possibly a downregulation of the soil ecosystem services (Power, 2010).

Tillage is a type of management that is used globally to prepare land for cultivation. Tillage has been carried out by humans for millennia, and for example early art shows the use of simple plows in ancient Egypt (Hughes, 1992). The plow has, however, developed remarkably since, particularly after the industrial revolution, and tillage can now be carried out using heavy machines which have high soil disturbing potential. Moldboard plowing (inversion of the soil layer), followed by tillage without soil inversion to smoothen the soil surface before sowing, is generally referred to as the conventional tillage practice. There are several explanations for why conventional tillage is commonly used for seedbed preparation. For instance, plowing efficiently removes weeds, incorporates crop residues which may otherwise reduce seed-soil contact, it alleviates soil compaction, and redistributes nutrients in the soil profile (Hobbs et al., 2008). Conventional tillage also results in increased soil aeration (Kainiemi et al., 2015), and break up soil aggregates (Quincke et al., 2007). The increased soil aeration enhances evaporation, which can be beneficial if done in cold humid climates, as the lower water content reduces the solar energy needed to warm the soil. Thus, compared to undisturbed soils, seeds in conventional tillage soil may germinate earlier. The disruption of soil aggregates results in a release of nutrients, as previously occluded organic matter get exposed to microbial oxidation (Six et al., 2000). The stimulated mineralization does, however, have disadvantageous consequences as well.

Long-term use of conventional tillage has been shown to lead to soil quality degradation because of the increased decomposition and mineralization of soil organic matter (SOM), which lead to soil organic carbon (SOC) loss (Stockmann et al., 2013). One of the reasons why loss of SOC is problematic, is due to the fact that SOC is negatively associated soil erodibility (Greenland et al., 1975). In America the problem with erodible soils was vividly illustrated during the Dust Bowl in the 1930', and President F.D Roosevelt (1937) spoke the famous words "A nation that destroys its soil, destroys itself". In addition to reducing soil quality, soil erosion also generates economic and environmental costs both on and off-site, and among the consequences are increased maintenance costs for infrastructure, nutrient deficiency, and air and water pollution (Lal, 1998; Pimentel et al., 1995; Uri, 2000).

The need for erosion mitigation was part of the reason why conservation tillage practices, like reduced tillage and no tillage, increased in popularity during the second half of the last century (Doran et al., 1998). Conservation tillage is characterized by low soil disturbance, and often a crop residue cover on the soil surface (Food and Agriculture Organization of the United Nations, FAO, 2017; Gustafsson and Johansson, 2008). In addition to erosion control, conservation tillage has been promoted because of its potential positive effect on the environment as it has been suggested to increase soil C sequestration. Furthermore, the use of conservation tillage reduce the amount of labor and fuel needed, as the number of field operations are lower and less energy-demanding. Conservation tillage can be implemented on its own, or as one of the main principles within the concept conservation agriculture (Palm et al., 2014). In the literature there has been some interchanging use between conservation tillage and conservation agriculture (FAO, 2008), presumably due to terminology confusion (Reicosky, 2015). Therefore, clear definitions of tillage practices are encouraged, as this facilitate both interpretation and comparisons of results. In this thesis, conservation tillage is used to describe three different sets of tillage practices where the tillage is reduced compared to yearly moldboard plowing (Textbox 1).

To secure future food production, increased knowledge of how to protect the soil and maintain its quality is crucial. The human population is growing, and is expected to reach almost 10 billion by 2050 (United Nations, 2015), whereas the area suitable for crop and animal feed production is likely to decrease, if land degradation does not cease. In the making of this thesis, I dug into the world beneath the soil surface to increase my knowledge on how different types of soil management strategies may influence soil services. Long-term experiments were used as they allow analysis of soil quality changes that occur slowly, such as SOC content changes (Saby et al., 2008). In this thesis, I used data from three field experiments in which different tillage practices were combined with fertilization **paper I**, and crop residue management (**paper II** and **III**). Moreover, because farmers are keepers of the soil, I also included a survey where farmers were asked to provide some information regarding tillage (**paper IV**). Using these sources of information, the main aim of this thesis was to determine whether:

Textbox 1. Conservation tillage practices studied in this thesis;

- Shallow (0-10 cm) non-inversion tillage using a harrow (**paper I**)
- Shallow non-inversion tillage (harrowing), and shallow non-inversion tillage with rotational plowing (**paper II** and **III**)
- No tillage, non-inversion tillage (deep and shallow), and shallow plowing (**paper IV**)

1. Long-term reduced tillage increase the SOC concentration compared to plowing?

2. Long-term reduced tillage favors fungi over bacteria?

3. There is a constancy throughout the vegetative season in how soil microorganisms respond to tillage?

4. Addition of organic matter effect the SOC concentration and the microbial community, and if so, whether the effects depend on tillage practice?

5. There are some characteristics that can be used to identify farmers who may use conservation tillage and also which factors influence the choice of tillage, and how the consequences of using different tillage practices perceived?

CHAPTER 2

Materials and methods

Field sites and sampling

The experimental part of the work presented in this thesis was based on soil samples collected from three of the Swedish University of Agricultural Sciences' long-term experiments which are located in the southern half of Sweden (Figure 1). I was fortunate enough to be able to collect soil samples at Lönnstorp in 2013, as the field

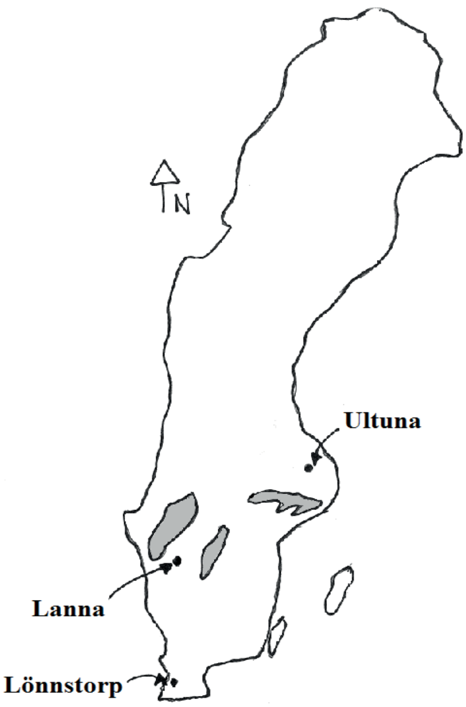

Figure 1. Locations for the three field sites with long-term tillage experiments.

experiment was terminated in 2014 after 20 years. The other two field experiments are still ongoing. The experimental design at Lönnstorp included two tillage treatments (as main plots) combined with three levels of fertilizer applications (as subplots), and was organized following a pairwise design (Figure 2). A more detailed descriptions of the included treatments used in the experiment at Lönnstorp is provided in **paper I**. The results in **paper II** and **III** are based on the two long-term (since 1974) tillage experiments located at Lanna field station and at Ultuna in Uppsala. Both these experiments followed a split-plot design with tillage treatment (n=3) as main plots, and crop residue management (n=2) as subplots. For more details on the experimental design and management strategies see **paper II** or **III.**

Soil samples were collected in 2013 and 2014, using a soil corer (Ø 2 cm). To minimize soil compaction, each core was collected in sections of approximately 10 cm. Samples were mainly collected within the plow profile (0-30 cm), but in the study presented in paper I, soil data from 30-40 cm depth were also included. Subsamples from the same depth within each plot were pooled into a composite sample. The earliest soil sampling occurred in April and the latest in October, and the time and depth of sampling varied between experimental sites (for details see **paper I, II** and **III**). The collected soil samples were placed in plastic zip bags and kept at approximately room temperature during the days it took to return to the laboratory. The analyses for which fresh soil was used were carried out within a week from sampling, and the rest of the soil that I brought back to Lund was frozen and stored at approximately -18 °C until further analyses.

In a survey on tillage use, farmers across the entire Scanian region were approached with an online questionnaire in 2016 (**paper IV**). To encourage participation, the respondents were allowed to be anonymous, and thus the location of the participants was not known. However, information of the geographical coverage of the region was obtained by mapping the contacts that had agreed to distribute a web link to the questionnaire (Figure 3). Data from 118 respondents were collected. The questionnaire was sent out during the summer, which may have led to a bias in which farmers responded. Farmers with an interest in conservation tillage may have been more prone to set aside time to fill in the questionnaire

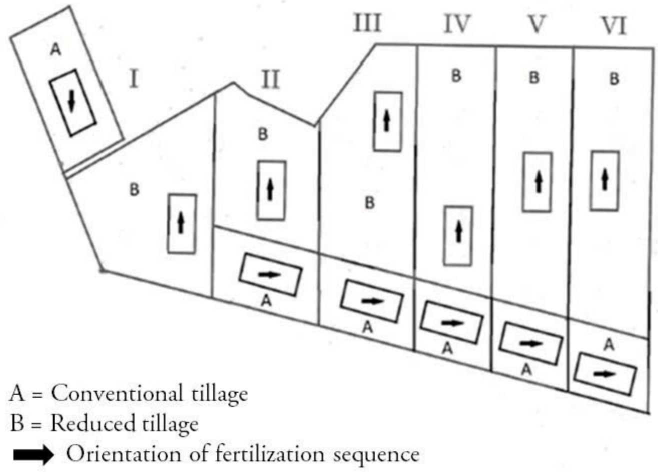

Figure 2. Experimental design of the long-term tillage and fertilizer experiment at Lönnstorp. Soil samples were collected from block I, IV and V in 2013.

than those who are not interested. I do, however, believe that the survey captured the range of different tillage practices used in the region.

The analytical toolbox
Several methods and machines have been developed that can be used to assess soil organic C and microorganism amounts and activities. A likely explanation for the multitude of methods is that none of them are perfect, they all have their advantages and disadvantages. Heterogeneous microbial distribution in the soil, incomplete taxonomic knowledge and difficulties to culture fungi and bacteria in controlled environments, are some of the identified disadvantages that impede soil microbiology research (Kirk et al., 2004). Knowing the limitations may however spur improvements of techniques, and Kirk et al. (2004) also highlighted some of the advantages, like high reproducibility, that were associated with some of the reviewed techniques. Other possible advantages are reduced costs for materials and equipment, increased labor efficiency, and reduced or no risks associated with involved chemicals.

Loss on ignition (LOI) is a fast, inexpensive and commonly used method used to determine SOC and soil inorganic

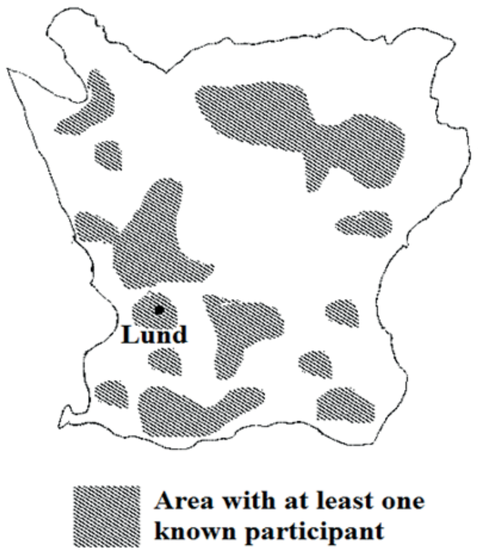

Figure 3. Geographical coverage of known participating farmers in Scania.

C (SIC). However, although there has been attempts (e.g. Hoogsteen et al., 2015), there is no standard protocol for the procedure, which may obstruct comparisons between studies. Moreover, the method has received critique because it may produce erroneous SOC results due to low sensitivity when samples contain little OC, or underestimate SIC content as some IC oxidize at lower temperature than the set ignition level (Santisteban et al., 2004). Typically SOM (including SOC) start to ignite at 200 °C and is completely oxidized at 550 °C, however some of the IC is also oxidized at around 550 °C, although most of it is converted to CO2 between 700 and 850 °C. In the experiments reported in **paper I** and **II**, the SOC concentration was assessed by high temperature ignition (>1000 °C) of dried samples. The CO_2 developed when using such high temperatures can be a result of both OC and IC ignition. However, as we also analyzed the IC content, and found no detectable IC, the measured CO_2 was assumed to represent mainly SOC.

Signature lipid fatty acids can be used to detect changes in the microbial community, and one advantage of analyzing the soil content of signature lipid fatty acids is the simultaneous analysis of several microbial groups. An additional advantage is that the technique does not require the use of fresh soil. In this thesis I used a set of signature lipid fatty acids that represent arbuscular mycorrhizal fungi (AMF), saprotrophic fungi and bacteria (both Gram + and G-). Both the neutral lipid fatty acid (NLFA) 16:1ω5 which is found in AMF storage tissue (Olsson, 1999; Olsson and Johansen, 2000) and the phospholipid fatty acid (PLFA) 16:1ω5 can be used to indicate AMF (van Aarle and Olsson, 2003), and both were used in **paper I**. However, the PLFA 16:1ω5 also occurs to significant amounts in bacteria, and is therefore a less good indicator of AMF (Ngosong et al., 2012; Olsson, 1999). I decided to only use the NLFA 16:1ω5 to indicate AMF when conducting the analysis for **paper II**. One benefit of using phospholipids is that they degrade rapidly upon cell death, and present phospholipids can therefore be assumed to represent living biomass (Calderón et al., 2001). In **paper I** and **II** saprotrophic fungi were indicated by the concentration of the eukaryotic PLFA 18:2ω6,9, and bacteria was represented by the sum of nine selected bacteria-specific PLFAs (i15:0, i16:0, i17:0, a15:0, a17:0, cy17:0, cy19:0, 10Me17:0 and 10Me18:0) (Frostegård and Bååth, 1996; Kaur et al., 2005). The nomenclature of fatty acids follows that of Frostegård et al. (1993). In addition to PLFA 18:2ω6,9, ergosterol was used to indicate saprotrophic fungi (**paper I**), and these two methods are usually well correlated (Joergensen and Wichern, 2008).

Microbial growth rate, respiration rate and microbial biomass C can also be used when evaluating potential soil management effects on the microbial community (**paper I** and **III**). By incorporating radioactive tracers, e.g. ^{3}H-leucine and ^{14}C- acetate, into biomolecules of bacteria (proteins) and fungi (ergosterol) it is possible to assess the *in vitro* microbial growth rate (Bååth et al., 2001; Rousk and Bååth, 2007). In the growth rate analysis it, is important that the microorganisms are only allowed to incorporate the tracers during a discrete time period, thereafter they are killed and the incorporation terminated. The amount of incorporated radioactive tracer can then be measured using a liquid scintillation spectrometer.

Assessment of soil respiration rates (**paper I** and **III**) includes measurement of the amount of evolved CO_2 during a discrete time period. In my project the soil respiration was measured using soil samples that were incubated in vials at room temperature during four days before analysis. On the fourth day, the air in the vials was set to ambient CO_2 levels, and the vials were sealed air tight. The amount of newly evolved CO_2 was measured the next day. The final technique I used was substrate induced respiration, which can be used when quantifying microbial biomass C (Anderson and Domsch, 1978). In short, the mechanisms of this technique is that glucose is added and mixed with the soil samples to stimulate the microbial growth. The microbial growth will increase until reaching a plateau within 2-4 h of the glucose addition. During this time, the microbial biomass is considered to be stable, and amount of evolved CO_2 is considered to represent the biomass. The microbial biomass C can further be calculated as 1 mg CO_2 h^{-1} has been estimated to correspond to 20 mg biomass C. Microbial biomass C was assessed only for samples from Lönnstorp (**paper I**).

CHAPTER 3

Tillage effects on the soil microbial community

The soil microorganisms

When the aim is to determine the effects of a treatment on some feature of the soil microbial community, it is often useful to distinguish between microorganism groups, as they may differ in characteristics, e.g. substrate use. Thus, the microorganisms are often separated into groups in which members are more similar to each other, than to other groups. For instance, bacteria and fungi are commonly separated, but can also be grouped together when representing the saprotrophic microbial community. Saprotrophs decompose organic matter in the soil, and fungi can to degrade and metabolize a wider range of organic compounds than bacteria (from lignin and cellulose to glucose). Fungi have also been suggested to have a higher carbon use efficiency than bacteria, i.e. proportionately more of the consumed carbon is allocated to biomass than respired, which can affect the C dynamics in the soil (Guggenberger et al., 1999; Bailey et al., 2002). That fungi and bacteria dominated communities would differ from each other regarding carbon use efficient was, however, questioned in a recent study (Thiet et al., 2006).

The soil fungi can be divided into saprotrophs and mycorrhizal fungi, e.g. arbuscular mycorrhizal fungi (AMF). Arbuscular mycorrhizal fungi are obligate biotrophs which can form symbiotic relationships with a majority of all vascular plants (Wang and Qui, 2006). Many of the agronomic crops are AMF hosts, although not the members in Brassicaceae (e.g. cabbage and oilseed rape) and Chenopodiaceae (e.g. sugar beet) (Brady and Weil, 1999; Ocampo et al., 1980). The symbiotic relationship evolved around 460 million years ago (Redecker et al., 2000), and results in improved nutrient (mainly phosphorous) acquisition by the plant, on the cost of C-compound (e.g. photosynthates) delivered to the fungi. Because of the symbiosis with plants, AMF do not have to compete with the saprotrophic fungi for carbon sources. When an AM fungus has colonized a host-plant root cell, it forms a branched bundle of hyphae (an arbuscule), and this structure has been suggested as the site where the exchange between the fungus and the plant occur (Bago et al., 2000). The fungus will however have to form several arbuscles during its lifetime as an arbuscule is considered to be short lived (Alexander et al., 1989). In addition, increasing plant phosphorous uptake, there are evidence of additional plant benefits resulting from the AMF symbiosis (Willis et al., 2013), such as increased acquisition of micronutrient (Suzuki et al., 2001), and help to combat soil-borne plant pests and some weed species (Schoteden et al., 2015; Veiga et al., 2011). Furthermore, the involvement of AMF in soil stabilization and C dynamics, has also received attention (Rillig et al., 2001; Wright and Upadhyaya, 1996). Wilson et al. (2009) found that the abundance of AMF hyphae was positively correlated to soil aggregation, and thus soil stability. By taking care of the AMF, it seems possible that farmers may get several valuable benefits associated with crop production. Different AMF species may, however, not be equally useful to the farmers. Inoculation with suitable AMF genotypes may offer a possibility to design parts of the microbial community. To get sufficient inoculum the AMF have to be cultured, and effects of different techniques and organic substrates for AMF cultivation has for instance been studied by Coelho et al. (2014).

Changes in the occurrence of microorganisms

Tillage effects on soil microorganisms are complex, as they can be both direct and indirect. However, compared to conventional tillage, the general effect of shifting to conservation tillage is that the microbial biomass increase (Murugan et al., 2014; Kaurin et al., 2015; Zhang et al., 2014), although there are exceptions (Ahl et al., 1998; Kaurin et al., 2015). Increased microbial biomass C, abundance and diversity have also been found under conservation tillage compared to conventional tillage (Wang et al., 2014). I also found that the microbial biomass C was higher under conservation tillage compared to under conventional tillage (**paper I**).

In continuous conventional tillage systems, the repeated plowing is considered to drive the soil microbial community towards bacterial dominance, as bacteria do not appear to be as harmed by conventional tillage as fungi (Wakelin et al., 2013). It is possible that this is due to the fact that bacteria living inside small soil aggregates are protected against the disturbance, and the minute size of bacteria can also be advantageous as they are less likely to be physically damaged by the tillage. Then what makes the fungi sensitive to tillage? Filamentous fungi and AMF are considered to be sensitive to tillage because their mycelia, and connections to plant-hosts (only relevant for AMF), can be disrupted (Helgason et al., 2010; Wardle 1995). However, despite the generally negative long-term effects on the fungi, short-term increase in saprotrophic fungi may follow plowing, due to increased crop residue incorporation (Murugan et al., 2013). The addition of organic matter would, however, not benefit the AMF as they do not depend on C derived from dead organic matter. Moreover, it has been suggested that AMF are more sensitive to tillage, than saprotrophic fungi (Wortmann et al., 2008). In line with the findings of van Groenigen et al., (2010) and Wang et al. (2010) I also found that conservation tillage favors fungi. In both **paper I** and **II**, I report that the AMF concentrations, indicated by the signature lipid fatty acids NLFA 16:1ω5 and PLFA 16:1ω5, were higher under conservation tillage than under conventional tillage. Saprotrophic fungi were found to benefit significantly from reduced tillage intensity at one of my studied sites (**paper I**), and at the other two sites, there was a trend towards conservation tillage stimulating the saprotrophic fungi (**paper II**). The stronger tillage effect on AMF than on saprotrophic fungi, supports the assumption that AMF are more sensitive to soil disturbance than the saprotrophic fungi. Moreover, the positive effects on the fungi, when the tillage intensity decreases, could potentially lead to a community shift towards fungi. However, the concentration of bacterial indicators were also higher when conservation tillage was used, although only at Lönnstorp. Because I did not detect any change in the F:B ratio under reduced tillage compared to conventional tillage, I concluded that the increase in saprotrophic fungi and bacteria would have had to be proportionately the same. No or inconsistent change in the F:B ratio between conventional and conservation tillage has also been observed by Helgason et al. (2009) and Spedding et al. (2004). It is possible that I would have found a stronger positive effect on the saprotrophic fungi if I had compared no tillage and conventional tillage, as the difference between these treatments are more extreme than between conventional tillage and reduced tillage with harrowing.

Tillage impact on microbial activity

Measurements on how tillage affects the abundance or biomass of microorganisms gives an idea of the potential amount of microorganisms that can perform ecosystem services. However, it does not provide any information about how active the microorganisms are. A more complete picture of the impacts of tillage can be obtained by combining measurements of the abundance or biomass with methods that provides information on activity. Soil respiration reflects the activity of the microorganisms, as it captures the amount of CO_2 produced during mineralization.

Shortly after tillage, there is often a peak in soil respiration, partly because the microorganisms attack the newly exposed organic matter. After some time this surge in CO_2 drops to lower levels, and when tillage is implemented in the fall, the effects are found to be short-lived, and they are usually gone in the spring (Ellert and Janzen, 1999; Glenn et al., 2011). When I measured the respiration rate about two weeks after tillage, I did not detect any surge in CO_2 (**paper III**), and it is possible that if the respiration rate had been triggered by the tilling, the effects had already faded. In the long-term, soil respiration usually decrease with conservation tillage compared to conventional tillage (Ussiri and Lal, 2009; Feiziene et al., 2011), which is assumed to be one of the environmental benefits of conservation tillage. On the other hand, because conservation tillage can lead to an increase of soil microorganisms, and does not necessarily favor fungi over bacteria, more CO_2 loss could be expected. In fact, soil respiration levels equal to, or higher than those in plowed soils have also been observed (Kaineiemi et al., 2015; MacDonald et al., 2010). I found that the respiration rate was higher if the soil was harrowed, than if it was managed with conventional tillage (**paper I**). The most reasonable explanation for this result was that the harrowed soil contained more microorganism than the plowed soil. The depth from which the soil sample was collected also affected the soil respiration. At Lanna and Ultuna, I found that the soil respiration rate tended to be enhanced close to the surface under conservation tillage, and close to the bottom of the plow profile (20 cm depth) under conventional tillage (**paper III**). The high respiration rate under conservation tillage coincided with higher bacterial growth rate (but not abundance) and more fungi (**paper II** and **III**), which could explain the observation. The high respiration in the conventional tillage treatment was, however, not associated with any increased growth rate or microbial abundance (**paper II** and **III**), and I find the result difficult to explain.

During the field season where I visited Lönnstorp (2013), the sampling was carried out in the summer and in the fall. Because the concentration of fungi was affected by tillage I had guessed that this would also be the case for the growth rate. However, I did not find any tillage treatment effects in the fungal or in the bacterial growth rates, at any time point (**paper I**). Thus, the rate by which microbial biomass (fungal ergosterol and bacterial proteins) is built up did not appear to be sensitive to tillage, which is in contrast with the effects on PLFA concentrations (**paper I** and **II**). That microbial growth rates are unaffected by tillage treatment has also been found by van Groenigen et al. (2010). The conclusion of tillage insensitivity was further supported by my observation that neither the fungal nor the bacterial growth rate differed between tillage treatments when measured shortly after tillage (**paper III**). Nevertheless, this conclusion was contradicted by the fact that I found differences in the microbial growth rates between tillage treatments during spring and summer at Lanna and Ultuna (**paper III**). Sampling date has been found to matter when studying soil microorganisms, and Shi et al. (2013) found that the timing of sampling had stronger effect on the microbial community than tillage. Season had effect on soil respiration and the growth rates of both fungi and bacteria in my study (Figure 4). The fungal growth rate was high in spring and fall, and dropped to lower levels in the summer. However, it was in the summer that I found that the fungal growth rate was higher in soil managed by harrowing and occasional plowing than in soil that was only plowed (**paper III**). This suggests that conservation tillage may have a positive effect on fungal growth rate, at least

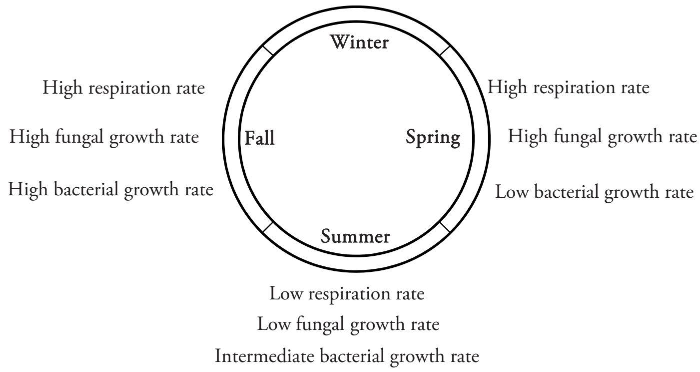

Figure 4. Seasonal variation in microbial activity at Lanna and Ultuna in 2014.

during periods where the overall activity is low. The bacterial growth rate increased throughout the vegetative season, and in spring it tended to be high when plowing was involved to some degree. A similar response was observed from the bacteria in summer soil samples collected at Lanna but not at Ultuna, where conservation tillage appeared to be more favorable for the bacteria (**paper III**). During the spring and summer sampling, six or more months had passed since the soil was tilled. When not measured in association with the actual tillage, it is possible that differences between treatments are due to indirect effects of the tillage, rather than due to the soil disturbance. Long-term tillage can alter soil conditions and lead to structural differences between treatments, and at least soil respiration differences between treatments have been suggested to be due to indirect effects of tillage rather than the actual tillage (Kainiemi et al., 2015). Then again, if changes in the soil conditions was the reason why I observed a difference in growth rates between treatments, why was this not the case at Lönnstorp? The simple answer may be that the different responses are the result of the sites being different.

Other factors affecting soil microorganisms

One structural difference between conventional tillage and no tillage is the vertical placement of crop residues (Arshad et al., 1990). Whether the crop residues are incorporated into the soil, placed on the soil surface, affects how available they are to the attacks from the soil microorganisms (Lynch et al., 2016). The distribution of soil microorganisms often vary vertically (Acosta-Martinez et al., 2007), partly as a result of the amount of available resources. During plowing the crop residues are incorporated in the soil, which increases the soil-residue contact (Kushwaha et al., 2000; Cookson et al., 2008), and enhance the availability for the microorganisms, particularly if the residues are fragmented (Henriksen and Breland, 2002; Kushwaha et al., 2000). In contrast, with no tillage the residues remain on the soil surface, where they become less accessible to the microorganisms. As reduced tillage includes a range of tillage practices, the vertical distribution of crop residues varies between being located on or close to the soil surface to being buried at shallow depth. The extent to which the vertical placement of crop residues can effect decomposition rate was clearly demonstrated by Pascault et al. (2010). They found that incorporated wheat residues were almost completely decomposed after four months, compared to only a third of surface residues. Increased microbial colonization and more favorable moisture conditions were suggested as explanations for the higher decomposition rate of the incorporated residue (Pascault et al., 2010). Addition of organic matter has been shown to increase the total microbial biomass (Guo et al., 2014), including both fungi (Allison and Killham, 1988; Chen et al., 2017; Murphy et al., 2016) and bacteria (Chen et al., 2017) These results are contrasted by the findings of Spedding et al. (2004), who found that residue return does not necessarily result in a change in the microbial community. I found that crop residue management did not affect the saprotrophic community at my study sites (**paper II**). One possible explanation is that the removal of crop residues seldom is complete, even though most of the residues may be removed, some may already have entered the soil through the work of soil fauna. When looking at the AMF data, I was a bit surprised by the results. I found that AMF in plowed plots were stimulated by residue removal (**paper II**). In the conservation tillage treatments there were, however, no effect of crop residue management. Since AMF are not dependent on crop residues for C, addition or removal *per se* should not matter to them and the explanation for this observation remains unclear.

Sampling depth should also be considered, as microorganisms are not evenly distributed in the soil profile. Despite encouragement to extend the sampling depth well below the plow depth as in Fierer et al. (2003), most studies (including mine) has mainly focused on tillage effects within the plow depth (0-40 cm). It is, however, the research question that determines the depth, and my interest was to study effects in soil directly affected by the tillage, and in the layer just below the disturbance. Tillage effects on both AMF and saprotrophic fungi (based on NLFA, PLFA and ergosterol analyses) were restricted to the top 20 cm of the soil layer, whereas I found tillage effects on bacteria also below 20 cm depth. I also found that the microbial activity was generally higher in the upper part of the soil, which is not surprising as microbial activity usually declines with increasing depth (Taylor et al., 2002). This was also the case for the effect of fertilization, which was mainly restricted to the upper 10 cm of the soil layer, and mostly affected the microbial activity (**paper I**). Diverse responses to fertilization by fungi have been observed by e.g. Donnison et al. (2000), who found that, in a controlled experiment, application of inorganic fertilizers stimulated the growth of some fungal species whereas it decreased the growth rates of others.

There are evidently a number of factors which can affect and modify the microbial community in agricultural soils, and the fungi tended to be favored more frequently than bacteria by the use of conservation tillage. One aspect that I did not look into, but which may have implications for soil functioning, is how the composition of soil microorganisms within the large separation of AMF, saprotrophic fungi and bacteria is affected by tillage. It is possible that tillage, in addition to affecting the amount of signature lipid fatty acids, also altered species composition. The methods I used, would not allow for any separation of fungi, (except for into AMF or saprotrophic fungi), but it is possible that the fungal community in the conventionally tilled and conservation tilled soil are different. It would have been possible to separate for instance Gram+ and Gram- bacteria, as they are to some degree indicated by different signature lipid fatty acids, which would have provided additional information on the similarity of the bacterial community under different tillage treatments. Different bacterial communities could potentially explain why the effect of tillage on the bacterial growth rates differed between Lanna and Ultuna in the summer.

CHAPTER 4

Soil organic carbon

The atmospheric C pool is increasing, and it contains roughly 760 Gt (10^{15}g) of C (Lal, 2003), which is approximately a third of the total global soil C pool (both SOC and SIC). Of the soil pool, more than 1500 Gt is SOC (Jobbágy and Jackson, 2000; Lal, 2004a), and around 12 % of the estimated soil C is found in arable soil (Schlesinger, 1991). Conservation tillage has been promoted because of its suggested potential to increase soil C sequestration and storage (Puget and Lal, 2005; Stenberg et al., 2000; West and Post, 2002), and because it can reduce fuel and labor costs (Litourgidis et al., 2005). Both an increased C sequestration, and a reduced fuel consumption would have favorable environmental effects, as it would reduce the agricultural contribution to the atmospheric C pool. However, it has been suggested that soil C sequestration would only be able to compensate for around 15 % of fossil fuel emissions (Lal, 2007). Drastic reductions in current fuel burning and agricultural management which improves the sink capacity of the soil is therefore much desirable. The focus of this thesis is SOC, as no SIC was detected in any of the studied soils, also, although C sequestration is discussed, only data on SOC concentrations are presented. The process of C sequestration may have long term effects on crop productivity (by increasing the amount of soil C), and the potential of different tillage systems to increase C sequestration is often discussed in association with climate change and mitigation of greenhouse gas emission (Abdalla et al., 2013; Lal, 2004b; Zandersen et al., 2016). Measuring the SOC concentration, on the other hand, provides a measure of soil functioning or quality (e.g. in soil aggregate build up) (Tisdall and Oades, 1982).

The amount of C in the soil is determined by the flows in and out of the soil ecosystem, through plants and soil microorganisms (Figure 5). Accumulation of SOC can be achieved by increasing the input (e.g. returning crop residues) or by decreasing the output (e.g. reducing respiration) (Lal, 2004a). So far, studies on the effect on SOC by different tillage systems (conventional and conservation tillage) have been inconclusive regarding the benefits of conservation tillage for SOC increase. One factor that may explain some of the observed divergence in the results, is sampling depth. Most of the studies that report an increased SOC content with conservation tillage analyzed samples from within the plow depth (e.g. Franzluebbers, 2008; Ogle

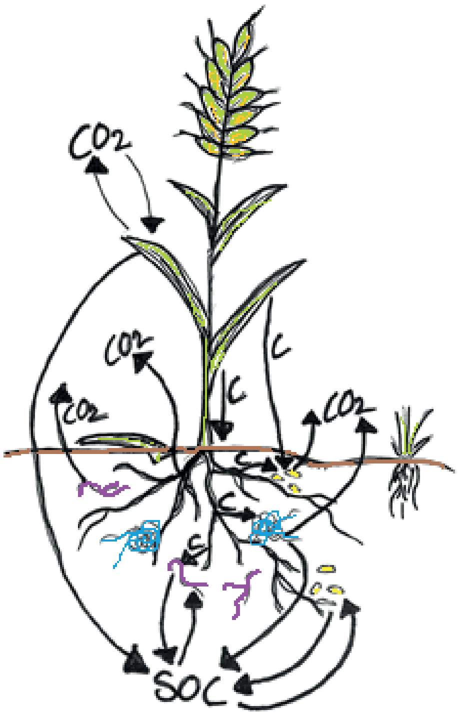

Figure 5. Conceptual model of carbon (C) flow into and out of the soil ecosystem through plants, arbuscular mycorrhizal fungi (blue ball), saprotrophic fungi (purple thread) and bacteria (yellow ovals).

et al., 2005; van Groenigen et al., 2011; Dalal et al., 2011). When SOC in the topsoil has been found to be lower under conservation tillage than conventional tillage, it has sometimes been explained by reduced organic matter input, or by higher turnover rate of the organic matter compared to under conventional tillage (Singh et al., 2015). Kaurin et al. (2015) found that there was no difference in SOC between tillage treatments, and often when SOC levels are reported to be similar or lower in conservation tillage treatments compared to conventional tillage the sampling depth has often been extending below the tillage depth. The reason for this is that SOC mainly accumulates near the soil surface under conservation tillage, and then the amount decreases with increasing depth. In plowed soil on the other hand, the mixing and incorporation of crop residues distributes organic matter throughout a greater soil depth. The benefit of increasing surface C could thereby be counteracted by a reduction in SOC deeper into the soil.

No evidence of conservation tillage leading to increased SOC compared to conventional tillage was found at any of my study sites. However, during part of the year reduced tillage may lead to short-term increase of SOC. I found that the SOC concentration, in the fall at Lönnstorp, was higher in the reduced tillage treatment than in the conventional tillage treatment (**paper I**). As the SOC concentration in the two tillage treatments did not differ statistically from each other in July, the higher SOC in the fall was possibly due to more favorable conditions for SOC buildup in the reduced tillage treatment during late summer. The SOC concentration at Lanna and Ultuna was assessed by analyzing soil samples collected in the spring (April/May), and I found that it did not differ between treatments (**paper II**). The microbial activity was high in the spring, and since I found that the microbial activity was high in the fall 2014, I assume it was similar in the fall in the previous year. Thus, an active microbial community in both fall and spring could potentially consume and respire any SOC accumulated during summer, thereby removing any tillage effect. The absence of any benign effects on SOC from using conservation tillage is in line with the findings of Dimassi et al. (2014). They used a French long-term study (of the same age as the experiments

I used), and compared conventional tillage with reduced and no tillage. They found that tillage treatment had no effect on SOC content within the plowing depth (0-28 cm). However, while we only sampled once after 42 years Dimassi et al. (2014) collected samples every fourth year, which enabled them to track SOC changes over time. They found that SOC increased with reduced tillage during the first four year, but then the SOC level remained constant for 24 years, before declining to levels similar to no tillage and conventional tillage. Thus, the equal SOC concentration between tillage treatments in **paper II** could be due to seasonality, but also be the result of a new equilibrium.

In Europe, where straw burning is banned (Soane et al., 2012), the farmers can choose to leave crop residues in the field or to remove them. As organic matter constitutes the basis for humus formation, decisions on what to do with the crop residues are likely to affect the SOC content. Returning crop residues to the field can generate benefits for the farmer, but it can also have negative impact on the crop production. Protection of the soil from erosion caused by wind (Michels et al., 1995), reduced evaporation (Bescansa et al., 2006), and increased SOC content (Wang et al., 2014), are some of the advantages of returning crop residues to the soil. Among the disadvantages of crop residue returns are reduced seed-soil contact, at least with conservation tillage where much of the residues remain at the surface, and increased risk of plant pathogen carry over from one crop to the next (Gustafsson and Johansson, 2008). Addition of crop residues with high carbon to nitrogen ratio, like wheat straw, can lead to immobilization of nitrogen, as they are used for decomposition (Schoenau and Cambell, 1996). Thus, the need for fertilizers may increase, to make sure that the crop get enough nutrients. However, long-term residue return has been suggested to be beneficial for the nitrogen budget in the soil (Schoenau and Cambell, 1996). There are many factors to consider when deciding on the fate of the residues, and although addition of organic matter is believed to increase SOC, there are studies showing that removal of the crop residues does not negatively affect SOC (Powlson et al., 2011; Singh et al., 2015). The similar SOC concentrations in soil samples from residue return and residue removal treatments that I observed at Lanna and Ultuna (**paper II**), indicate that changing SOC by residue management can be tricky. There is so far, no consensus in the literature regarding the amount and quality of the crop residues required to increase SOC, and general guidelines may be difficult to apply because soil and climate conditions differ between sites.

CHAPTER 5

Farmers, crop yields and environmental implications

Use of conservation tillage

Around 1.5 billion ha (12 %) of the global land area has been estimated to be arable land (Ramakutty et al., 2008), and a proportion of this area is managed with conservation tillage. The proportion of the land under conservation tillage varies among regions, and for instance the use of no tillage is widespread in North and South America, and Australia, whereas the use in Europe, Asia and Africa is much lower (Friedrich et al., 2012). According to recent estimates, conservation tillage is used on 105 to 156 million ha (FAO, 2011). Within the European Union, both reduced and no tillage is used but conventional tillage is the dominating practice, and it is used on roughly 66 % of the arable land area (Eurostat, 2013).

In the dry and warm countries around the Mediterranean Sea, the main reason for adoption of no tillage (through conservation agriculture adoption) is soil erosion control (Soane et al., 2012). In Germany, the UK and Scandinavia on the other hand, the main reason for adopting some form of conservation tillage practice is improved farm economy, as costs for labor, fuel and machines can be reduced with conservation tillage compared to conventional tillage (Soane et al., 2012). Use of conservation tillage because of its potential to reduce farmer expenses for fuel and labor has also been indicated by (Knowler and Bradshaw, 2007; Lithourgidis et al., 2005; Holland, 2004). So far, rather low conservation tillage adoption rate has been noted in Scandinavia (Carter, 2017), with the exception of Finland, where no tillage use is rather high from a European perspective (Friedrich et al., 2012). In Norwegian regions with highly erodible soils, erosion mitigation may nonetheless be a key reason for conservation tillage adoption. Using five experimental sites in Norway, Skøien et al. (2012) found that reductions in fall tillage (using harrowing or no tillage instead of plowing), led to a decrease in soil erosion. I have not found any information on conservation tillage use in Scania to compare my results with, but in my study a majority of the farmers used some form of conservation tillage. Regardless of if they used conservation tillage or not, most of the farmers perceived that reduced tillage led to a reduction in soil erosion compared to conventional tillage. Soil erosion *per se* was not mentioned when the farmers stated which factors influenced their choice of tillage, but soil type (based on dominating particle size) and soil structure were frequently mentioned (**paper IV**). Better soil structure was also among the five most frequently mentioned advantages of using conservation tillage when farmers in central Sweden were participating in a study on conservation tillage use (Stenberg, 2010). However, even more frequently mentioned were labor and fuel reductions, better economy and crop establishment (Stenberg, 2010).

Other factors that were important when deciding on tillage in my study were crop rotation, labor requirement and net income. The crop rotation may be more important when adopting conservation tillage as some crops perform well when planted in the standing stubble of the previous crops whereas other crops may require tillage to develop. According to the farmers who participated in my project, conservation tillage is suitable after crops such as field peas (*Pisum sativum* ssp. (L.) Asch. Graebn), oilseed rape (*Brassica napus* (L.)) and sugar beets (*Beta vulgaris* (L.)). Plowing was, however, often considered necessary after cereals (**paper IV**). This information is in line with the results from Rasmussen (1999), who also stated that one reason why conservation tillage can be successful when implemented after such crops is that they promote a good soil structure. Because crops may differ in their ability to suppress weeds (Liebman and Davies, 2000; McLaughlin and Mineau, 1995), it is possible that crops which are compatible with conservation tillage, manage to outcompete weeds. These crops may also be more intensively treated with herbicides, and thus mechanical weed removal is not required when planting the next crop. Both farmers who used and those who did not use conservation tillage practices thought that the importance of the preceding crop would be higher with reduced tillage than conventional tillage. They also thought that the use of herbicides and fungicides would increase with reduced tillage, which relates to yet another aspect of the why the crop rotation may need extra consideration under conservation tillage. Because crop residues to larger extent remain on the soil surface under conservation tillage than conventional tillage, plant-pathogens which thrive crop residues may carry over infections between crops (Friedrich et al., 2014).

Conservation tillage adoption is generally assumed to be more common on large farms than on small farms (Fykse et al., 2004; Morris et al., 2010), likely because the potential savings in fuel and labor being greater when large areas are cultivated. Large farms are also more likely to have the economic capacity to purchase new equipment and survive if transition yield is initially low (Gould et al., 1989; Lahmar 2010). Among the respondents in my survey it was only conservation tillage users who stated that they had crop production on areas larger than 200 ha. Furthermore, farmers may work full or part time with crop production, and I found that whether farmers used conservation tillage or not was affected by the time spent on crop production. Farmers spending more than half of their work time on crop production were more likely to use some form of conservation tillage than those with a smaller proportion of their time dedicated to crop production (**paper IV**). Crop yields may vary between tillage systems, and conservation tillage has been suggested to result in economic benefits as machinery, fuel and labor is reduced (Riley et al., 1994). Better cost efficiency of conservation tillage has also been suggested by (Sijtsma et al., 1998; Khakbazan and Hamilton, 2012). However, Archer et al. (2002) and Zentner et al. (2002) suggest that the reduced costs under conservation tillage compared to conventional tillage may be balanced out by the increased need to invest in herbicides.

Social implications and prejudice of abandoning the plow in favor of conservation tillage may also make farmers refrain from conservation tillage adoption (Lindwall and Sonntag, 2010). Insufficient "how to" in conservation tillage may also constrain adoption (Cannell and Hawes, 1994). When farmers know of others who have positive experiences of conservation tillage, the likelihood of them trying it increases (D'Emden et al., 2006; Rouchecouste et al., 2015). Furthermore, in contrast to the findings of Townsend et al. (2016) who found that education did not matter, farmers with a higher level of education were associated with conservation tillage use in my survey (**paper IV**). It is possible that the reason why highly educated farmers were associated with conservation tillage is that they are part time farmers, and thus benefit from using tillage practices that save as much time as possible.

Tillage impact on crop yield

The main objective in crop production is getting a good yield, and different soil management can be used to reach this goal. Whether use of conservation tillage is a viable type of soil management to reach this goal depends of factors such as local climate, soil type, and crop species. Conservation tillage has been found to support yields equal to those under conventional tillage (Dam et al., 2005; Dimassi et al., 2014; Su et al., 2007), although sometimes only when the soil is fertilized (Kapusta et al., 1996). Use of conservation tillage can also result in higher yields (Su et al., 2007) compared to conventional tillage, or in lower yields (De Sanctis et al., 2010). Cannell and Hawes (1994) provides a summary of results of tillage effects on crop yield in USA, Canada, New Zeeland and Europe. Van den Putte et al. (2010) showed that crop yields in Europe generally decreased with around 3 % with reduced tillage and with almost 9 % with no tillage. Rasmussen (1999) found that the yields of no tillage and reduced tillage fields, under Scandinavian conditions, did not differ from each other, but they were up to 10 % lower than under conventional tillage. In Norway conservation tillage on poorly drained soil resulted in lower yields compared with plowing (Riley et al., 2005). In regions with wet and cold springs (as in Scandinavia) farmers using no tillage may suffer from reduced yields compared to conventional tillage because the soils do not warm up as fast and thus cause delay in plant emergence (Riley et al., 2005). The water holding capacity is generally higher in fine texture soil than in coarse texture soil, and since most agricultural crop production occurs on clay soil, wet and cold soils may be a problem. However, according to Arvidsson et al. (2014), reduced tillage use under Swedish conditions can be a viable alternative to conventional tillage, as yields tend to be similar when grown on soils with a clay content between 15 % and 25 %. No tillage systems on the other hand was found to be in need of development to compete with reduced and conventional tillage (Arvidsson et al., 2014).

Tillage practices and environmental objectives

Tillage effects the environment, and this section will be focused on how conventional and conservation tillage practices may differ in environmental impact. Tillage can be linked to some of the environmental objectives, such as Reduced climate impact, No Eutrophication, A varied agricultural landscape and A non-toxic environment. In Sweden, these and 11 other objectives were accepted in 1999, and in 2005 the environmental objective regarding biodiversity (A rich diversity of plant and animal life) was added to the list (Swedish Environmental Protection Agency, 2017).

Even though there are still questions regarding whether conservation tillage contributes to a reduction in atmospheric CO_2 by favoring C sequestration, adoption of conservation tillage can still lead to a reduction in agricultural CO_2 emissions, as less fuel is needed when using fewer and lighter field operations. From this perspective, a shift from conventional tillage to conservation tillage could be a step towards reaching the Reduced climate impact objective. However, the positive effects of reduced CO_2 emissions may be balanced out by increased N_2O emissions, particularly as the global warming potential of N_2O is significantly higher than that of CO_2 (United Nations, 2017). After conversion to conservation tillage (mainly no tillage) from conventional tillage, the N_2O emissions may increase during the first couple of years before decreasing after long-term use, at least in temperate humid climates (Six et al., 2004). Other studies do, on the other hand, show that no tillage does not lead to any increase in N_2O emissions (van Kessel et al., 2013), and some suggest that it is only in poorly aerated soil, in which anaerobic conditions occur, that no tillage results in increased N_2O emissions (Linn and Doran, 1984; Rochette, 2008).

In addition to being emitted as nitrous gas, N may also be washed out of the soil system. Conservation tillage effects on water quality has been reviewed by e.g. Holland (2004), and although N and P are important for crop production, they can generate eutrophication related problems when ending up in aquatic environments. Adoption of conservation tillage has been suggested to reduce the runoff of soil, and thereby also of the nutrients attached to the soil particles (Kukal et al., 1991; Zhang et al., 2007). Such a reduction is beneficial from an environmental perspective. However, Ulén et al. (2010) found that although total P transport from the soil is reduced when conservation tillage is used, the amount of dissolved P that leaves the system increase. Thus, there may be some variation in how well conservation tillage manage to reduce the problem of P leaving the soil. Moreover, nutrients may also leave the soil through leaching, and no tillage has been suggested to lead to increased N loss because of the increase in macropores (Uri et al., 1998). In contrast, Hansen et al. (2010) found no evidence that the leakage of N would increase with conservation tillage.

An additional risk associated with increased macropores, is increased transport of pesticides (Uri et al., 1998). However, it has been suggested that the abundant microorganisms under conservation tillage may degrade the pesticides, and thus lessen their impact. The need for pesticides is often considered to be higher under conservation tillage than under conventional tillage, as the mechanical weed control is lower, and the surface crop residues may attract unwanted inhabitants. Increased use of pesticides thus suggests that adoption of conservation tillage is a step away from reaching the environmental objective A non-toxic environment. Many of the farmers who participated in my study perceived that the pesticide-need would increase if not plowing (**paper IV**). There was, however, a difference between conservation tillage users and non-users, in how they perceived that the pesticide-need would change if comparing reduced tillage with plowing. A large proportion of the non-users thought that more pesticides (both herbicides and fungicides) would be needed under reduced tillage. In contrast, most of the conservation tillage users thought that the need of fungicide spraying would not change, and approximately 50 % of the farmers perceived that the need for herbicides would not change (**paper IV**). In a survey on conservation tillage use in central Sweden, Stenberg (2010), found that approximately 34 % of the participating farmers (n=252) perceived that they always had to use more herbicides when using conservation tillage. However, 48 % of the farmers responded that most often, the need of herbicides did not increase. The need of fungicide spraying was not affected by tillage system, but instead depended on the crop rotation (Stenberg, 2010). It seems possible to limit pesticide use by carefully planning the crop rotation, and rotational plowing may be used to suppress weeds when infections are severe. Different experiences with pest control, and higher susceptibility among non-users to the assumption that pesticide use increase with conservation tillage, may explain why users and non-users differed in how the perceived the change in pesticide use.

Herbicide availability may facilitate the shift from conventional tillage to conservation tillage among conventional farmers, but is conservation tillage a viable alternative for organic farmers, who may not control weeds chemically? Peigné et al. (2015) did a survey on conservation tillage use among organic farmers in Europe, and they found that reduced tillage was used by a majority of the respondents. No tillage on the other hand, was only used by approximately a third of the respondents. Furthermore, long-term use of conservation tillage was unusual, as rotational plowing was practiced for some crops and at some stages in the crop rotation to control weeds (Peigné et al., 2015). As in conventional farming, conservation tillage may improve farm economy and soil quality in organic farming (Zikeli and Gruber, 2017). However, for some crop species the yields may be reduced, due to increased weed infestation, which may reduce the attractiveness of the practice. Conservation tillage thus seem to working for organic farmers, at least under some conditions. Improved knowledge transfer among peers on how to handle weed, may facilitate the use of conservation tillage under organic farming.

CHAPTER 6

Conclusions

In my thesis I show that on clay soil, under Swedish climatic conditions, long-term conservation tillage may not lead to an increase in SOC concentration (**paper I**), not even when crop residues are returned (**paper II**). Conservation tillage does, however, increase the amount of fungi, particularly AMF (**paper I** and **II**), which may have positive effects on crop nutrition and soil stabilization. I also show that seasonal effects on the microbial community may be stronger than that of tillage (**paper III**), and that highly educated farmers are more likely to use conservation tillage (**paper IV**).

Benefits such as better erosion control, and reduced labor and fuel requirement from conservation tillage, need to be weighed against increased pesticide use, yield reduction, and possibly increased N_2O emission. In addition, the success of using conservation tillage is influenced by factors such as soil type, climate, crop rotation, and also on the experience and knowledge of the farmer. Evaluation of each site may therefore be necessary to be able to recommend a tillage practice. Plowing is currently the dominating tillage practice, but I believe that the use of conservation tillage with rotational plowing will increase in the future. At least on soil where yields are similar between tillage systems, as it may improve farm economy, and possibly reduce agricultural environmental impact.

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