Sveriges lantbruksuniversitet
Swedish University of Agricultural Sciences

Department of Soil and Environment

The influence of soil management on soil health
– an on-farm study

Hanna Williams

Master's Thesis in Soil Science
Agriculture Programme – Soil and Plant Sciences

Examensarbeten, Institutionen för mark och miljö, SLU
2018:21

Uppsala 2018

The influence of soil management on soil health – an on-farm study

Hanna Williams

Supervisor: Thomas Keller, Department of Soil and Environment, SLU
Assistant supervisor: Tino Colombi, Department of Soil and Environment, SLU
Examiner: Bo Stenberg, Department of Soil and Environment, SLU

Credits: 30 ECTS
Level: Second cycle, A2E
Course title: Independent project/degree project in Soil Science – Master´s thesis
Course code: EX0430
Programme/Education: Agriculture Programme – Soil and Plant Sciences 270 credits
Course coordinating department: Department of Soil and Environment

Place of publication: Uppsala
Year of publication: 2018
Cover picture: photo by author, 2018
Title of series: Examensarbeten, Institutionen för mark och miljö, SLU
Number of part of series: 2018:21
Online publication: http://stud.epsilon.slu.se

Keywords: crop diversity, soil health assessment, indicator, soil quality, ecosystem services

Sveriges lantbruksuniversitet
Swedish University of Agricultural Sciences

Faculty of Natural Resources and Agricultural Sciences
Department of Soil and Environment

Abstract

The capacity of a soil to provide ecosystem services without negative impacts on the environment is defined as soil health. Healthy soils are a fundamental resource for agricultural production and our ability to feed a growing global population. We must therefore increase our understanding of how soil health is affected by soil management. This study investigated soil health on 20 farms in the south of Sweden, using samples of topsoil from farm fields and from unmanaged soil adjacent to the sampled field at each site. Soil health was assessed using the following physical, chemical, and biological indicators: wet aggregate stability, soil protein content, active carbon, soil respiration, and soil organic matter. We designed a soil management index based on crop diversity, avoidance of mechanical soil disturbance, and application of organic amendments, and evaluated its effect on individual soil health indicators and overall relative soil health. The results of this study showed that soil health was poorer in agricultural fields than unmanaged soils. Furthermore, a high soil management index resulted in higher values for individual soil health indicators. However, soil health indicators differed in how sensitive they were to soil management. We found that wet aggregate stability and soil protein content had a high sensitivity to soil management. Active carbon, soil respiration and soil organic matter content were less sensitive to soil management and more dependent on soil texture. Lastly, the results show that a high soil management index resulted in an improved overall soil health relative to the potential soil health represented by the unmanaged soil. Our results show that it is possible to promote soil health through high crop diversity, avoidance of mechanical soil disturbance, and application of organic amendments

Keywords: crop diversity, soil health assessment, indicator, soil quality, ecosystem services

Sammanfattning

Markens kapacitet att leverera ekosystemtjänster utan att negativt påverka miljön definieras som jordhälsa. Friska jordar är en grundläggande resurs för jordbruksproduktion och vår förmåga att mätta en växande global befolkning.Vi måste därför förbättra vår förståelse av hur jordhälsa påverkas av jordbruksmetoder. Denna studie undersökte jordhälsan på 20 skånska gårdar genom att analysera matjordsprover från åkermark och från ostörd jord bredvid åkern. Följande indikatorer användes för att bedöma jordhälsan: aggregatstabilitet, proteinhalt, labilt kol, markrespiration och mullhalt. Vi utformade ett brukningsindex baserat på jordbruksmetoder som omfattade varierad växtföljd, minimering av jordbearbetning samt spridning av organiska gödselmedel. Detta index användes sedan för att utvärdera hur kombinationen av dessa jordbruksmetoder påverkar enskilda indikatorer för jordhälsa såväl som total relativ jordhälsa. Resultaten visar att åkermark hade nedsatt jordhälsa jämfört med ostörd mark utanför åkern. Studien visar dessutom att jordbruksmetoder som främjar jordhälsa, här representerat av ett högt brukningsindex, resulterade i friskare jordar. Hur mycket man kan påverka indikatorer för jordhälsa genom jordbruksmetoder varierade dock. Enligt våra resultat hade jordbruksmetoder relativt stor påverkan på aggregatstabilitet och proteinhalt. Labilt kol, markrespiration och mullhalt var mindre påverkade av jordbruksmetoder utan styrdes till större del av jordarten. Slutligen visade studien att ett högt brukningsindex resulterade i friskare jordar, baserat på jämförelser med ostörd jord. Sammanfattningsvis påvisar denna studie att det är möjligt att skapa friskare jordar genom en varierad växtföljd, minimering av jordbearbetning och spridning av stallgödsel.

Nyckelord: växtföljd, jordhälsa, indikator, markkvalité, ekosystemtjänst

Populärvetenskaplig sammanfattning

Jordhälsa lyfter fram ett hållbart sätt att bruka åkermark på och kan vara avgörande för framtida livsmedelsproduktion. Fokus ligger på att värna den biologiska aktiviteten och skapa friska jordar. Denna studie har undersökt jordhälsan på 20 skånska gårdar.

Begreppet jordhälsa handlar om att ha en frisk och levande matjord som är full av biologisk aktivitet. En definition av jordhälsa är att en hälsosam jord är ett levande ekosystem som kan leverera ekosystemtjänster och funktioner som främjar växter, djur och människor, utan att påverka miljön negativt. Det man eftersträvar i en frisk jord är en god struktur, god vattenhushållning, tillräcklig mängd växttillgängliga näringsämnen, små populationer av växtskadegörare och växtpatogener samt stora populationer av nyttoorganismer. En frisk jord är därför mer motståndskraftig mot extremväder, vilket är viktigt för att hantera konsekvenser av klimatförändringen. En frisk jord kan dessutom ge stabila och goda skördar och är därför något som varje lantbrukare bör sträva efter.

Jordhälsa är mycket uppmärksammat i bland annat USA, men har inte studerats i någon större usträckning i Sverige. Enligt internationella studier vet man att man kan påverka jordhälsa genom vilka odlingsmetoder man använder. Några metoder är till exempel att ha en varierad växtföljd, minimera jordbearbetning och sprida stallgödsel. En varierad växtföljd som förlänger tiden som det finns levande rötter i jorden gör jorden friskare. Levande rötter utsöndrar ämnen som främjar den biologiska aktiviteten i marken och som håller samman jorden i aggregat. Genom att undvika jordbearbetning utsätts inte jorden för yttre påfrestningar från väder och vind och man lämnar markorganismernas livsmiljö ostörd. Spridning av stallgödsel matar jorden med kol och näringsämnen vilket gynnar både växter och markorganismer.

En hälsokontrollsundersökning för en människa innebär att man mäter olika värden och indikatorer och utfrån dessa bedömer hur frisk personen är. Samma koncept gäller när man bedömer hur frisk en jord är. Den här studien baseras på ett test för jordhälsa från USA. Vi mätte fem indikatorer för jordhälsa: aggregatstabilitet, extraherbart protein, labilt kol, markrespiration och mullhalt. Dessa indikatorer är kopplade till egenskaper och processer i jorden såsom markstruktur, olika näringsämnens kretslopp, biologisk aktivitet och kolinlagring.

Våra resultat visar att skånsk åkermark inte är så frisk som den skulle kunna vara. Mera glädjande resultat är att en varierad växtföljd, minimerad jordbearbetning och spridning av stallgödsel gör jorden friskare. Studien visar att alla undersökta indikatorer för jordhälsa går att påverka genom odlingsmetoder. Till exempel kan jordens sammanhållande förmåga, aggregatstabilitet, påverkas till 60 % av odlingsmetoder. Resultaten av denna studie bör leda till åtgärder hos lantbrukare och rådgivare för att förbättra odlingssystem och därmed främja jordhälsa. Nationellt och på EU-nivå bör man skapa policyprogram som finansiellt och regelmässigt främjar odlingssystem som stärker jordhälsa. En god jordhälsa hos vår åkermark är av största vikt för att försäkra en långsiktigt hållbar svensk livsmedelsproduktion.

Table of contents

1 Introduction

Agricultural production is one of the largest contributors of negative environmental impacts on the biosphere (Foley, 2005; Tilman et al., 2001). At the same time, the global population is increasing, followed by a predicted future increase in the demand for food, forage and fibers (Tilman et al., 2011; Alexandratos & Bruinsma, 2012; Hunter et al., 2017). Further pressure to the situation is added by the threat of climate change, which is predicted to lead to an increase of both temperature and frequency of extreme weather events (Wheeler & von Braun, 2013). These problems are further exacerbated by global degradation of soil resources (Oldeman, 1991), with the annual cost of soil degradation being estimated at € 38 billion in the European Union alone (Montanarella, 2007). There is therefore a great challenge of having to increase and sustain food production in a changing climate, while at the same time minimizing the negative environmental footprint of agriculture.

Ecological intensification has been suggested as a strategy to address these challenges (Godfray et al., 2010; Bommarco et al., 2013). Ecological intensification refers to maintenance or enhancement of crop productivity by the promotion of functional biodiversity as a part of agricultural practices, which allows complementing or replacing anthropogenic inputs with ecosystem services. Soil health is defined as "the continued capacity of the soil to function as a living ecosystem that sustains plants, animals, and humans" (Natural Resource Conservation Service, 2018). Within this definition is the recognition that healthy soils provide regulating and supporting ecosystem services such as nutrient cycling, infiltration, retention and supply of water, gas exchange, pest and disease regulation, maintained biodiversity, and storage of carbon, many of which highly impact agricultural productivity (Drinkwater et al., 2017; Lowery et al., 1996; Van Bruggen & Semenov, 2000; Torsvik et al., 2002; Lal et al., 2007; Barrios, 2007). Improving and sustaining soil health is therefore a key aspect of achieving ecological intensification

Soil health encompasses physical, chemical, and biological soil properties, and is often used interchangeably with the term soil quality, although soil health is sometimes preferred because of the greater emphasis on biological and dynamic aspects of soil (Bünemann et al., 2018). Soil health has received increasing attention in the context of sustainable agriculture in the past few decades, both in the scientific and the farming community (Bünemann et al., 2018). However, to improve and sustain soil health, we need to increase our knowledge of how soil health can be managed through farming practices. To be able to evaluate and quantify soil health, indicators of soil functions are needed. A suitable indicator should have a strong correlation to the targeted soil function, be sensitive to soil management, replicable, and relatively inexpensive to analyze (Andrews et al., 2004; Karlen et al., 2003). There are several sets of soil health assessment analyses available for evaluation of soil physical, biological and chemical indicators (Karlen et al., 2008). One of these is the Comprehensive Assessment of Soil Health (CASH) which was developed in the northeastern United States. The purpose of CASH is to provide a standardized test of soil health indicators related to land productivity and environmental impact in an agroecosystem context (Idowu et al., 2008; Moebius-Clune et al., 2016). It comprises analyses of biological indicators (active carbon, soil protein content, soil respiration, soil organic matter content), physical indicators (wet aggregate stability, available water capacity, penetration resistance), and chemical indicators (pH and available nutrients). Active carbon is a measure of the labile carbon in the soil (Weil et al., 2009). Labile carbon is the portion of organic matter that is easily available for soil microbes and has a high turn-over rate in the soil food web (Moebius-Clune et al., 2016). Soil protein content is a measure of the organically bound nitrogen in the soil that is easily mineralized by microbial organisms (Moebius-Clune et al., 2016). Soil respiration is a measure of the metabolic activity of the soil microbial community (Haney & Haney, 2010). Soil organic matter is a measure of the total amount of organic material in the soil (Lal, 2009). Wet aggregate stability is a measure of soil aggregates resistance to disintegration when subjected to rainfall (Moebius-Clune et al., 2016). Available water capacity is a quantification of plant available water in the soil. Penetration resistance reflects the force needed for roots to penetrate the soil (Moebius-Clune et al., 2016). Soil pH and available nutrients are indicators that are included in general nutrient analyses and influence or quantify plant nutrient availability. The information gathered by these indicator analyses can be summarized and used as a tool for farmers and farm advisors to identify soil health constraints and develop a management plan to improve and sustain soil health (Moebius-Clune et al., 2016).

A common set of management strategies has been suggested as soil health promoting (Moebius-Clune et al., 2016; NRCS, 2012). These are: increasing crop diversity, avoiding mechanical soil disturbance, and adding organic amendments. There are, however, many options and combinations of specific soil management practices within each strategy, depending on the context of the farming system. Crop diversity in agricultural fields is most commonly achieved through crop rotation, i.e.

plant diversity on a time scale. However, in forage leys or cover crops, crop diversity occurs on a spatial scale (i.e. several plant species at the same time). Different crop types vary in regard to root distribution, chemical composition of crop residues, and quantity and quality of root exudates, and thus differ in their direct and indirect influence on soil structure and soil microbes (Kuzyakov & Domanski, 2000; Finney & Kaye, 2017; Bending et al., 2002). A high plant diversity is linked to high soil microbial diversity (Steinauer et al., 2015; Eisenhauer et al., 2017). This in turn influences several aspects of soil health, as soil microbes are involved in the majority of soil processes and functions (Barrios, 2007). There are several studies showing that crop diversity affects soil health. Karlen et al. (2006) showed in a long-term field experiment that crop rotations including oat and ley resulted in lower soil bulk density, and higher aggregate stability, organic matter content, and microbially bound carbon, compared to crop rotations of continuous corn and corn/soybean. Another long-term field plot experiment showed that a crop rotation including wheat in addition to corn and soybean increased soil health, and that including lucerne in the rotation resulted in even higher soil health scores (Congreves et al., 2015). On-farm studies also show that farms with a crop rotation including a forage ley in comparison to crop rotation with only annual crops had higher microbial biomass C and higher aggregate stability (Schjønning et al., 2002). Tillage generally has a negative effect on soil organisms, which in turn negatively influences soil health (Altieri, 1999; Bender et al., 2016). There are several studies showing that minimizing the amount of mechanical disturbance improves soil health. No-till leads to higher aggregate stability, and reduced erosion and surface runoff (Jiao et al., 2006; Mikha & Rice, 2004; Abid & Lal, 2009). No-till is also found to increase soil organic matter content in the surface layer and improve several soil biological properties (Nunes et al., 2018; Tiemann et al., 2015). However, the large variations in climate, inherent soil properties, and soil and crop management practices can result in both increased and decreased yield of no-till systems (Soane et al., 2012). Application of organic amendments such as manure, slurry and compost is a way of adding organic matter and nutrients to the soil. The addition of nutrients in organic form results in a recoupling of C and N cycling, in comparison to the current widespread use of inorganic fertilizers. This has the potential of reducing N losses (Gardner & Drinkwater, 2009) and increasing soil biological activity (Drinkwater & Snapp, 2007), which is supported by data from long-term field experiments. Application of varying types of organic amendments resulted in increased soil organic carbon content according to Blair et al. (2006) and Mikha & Rice (2004). Physical soil properties, such as aggregate stability and hydraulic conductivity have also been reported to increase with application of organic amendments (Bottinelli et al., 2017; Jiao et al., 2006). However, the effect of external organic amendments can vary greatly depending on the initial content of soil organic matter (Oldfield et al., 2018). There are also studies showing that combined effects of soil health promoting management practices have a positive impact on soil health (Nunes et al., 2018; Alhameid et al., 2017; Whalen et al., 2003).

There are only a few examples of on-farm studies regarding soil management effects on soil health (Franco-Vizcaíno, 1996; Wander & Bollero, 1999), but a large body of literature on soil management practices and their effect on soil health based on results from field plot experiments. On-farm research offers the opportunity to study realistic systems in terms of scale, management practices and constraints faced by farm managers (Drinkwater, 2002). Field plot experiments, while reducing the number of confounding factors, tend to be over-simplified in terms of system complexity and often only run for short periods of time. As an example of this, previous studies of how soil management influences soil health have mostly been done by comparing no-till with conventional tillage systems in field plot experiments, sometimes with the addition of crop diversity effects or application of organic amendments (Nunes et al., 2018; Congreves et al., 2015; Alhameid et al., 2017; Whalen et al., 2003). However, many commercial farms do not follow such strict management categories but adjust tillage from year to year depending on crop and preceding crop, soil and weather conditions, amount of crop residues, and weed pressure. Soil management practices on commercial farms are therefore diverse and cannot simply be categorized into no-till, reduced tillage and moldboard ploughed systems (Büchi et al., 2018).

The purpose of this study was to obtain on-farm data from commercial farms in southern Sweden and study the impact of soil management practices on soil health indicators, using selected analyses of the established CASH protocol. The farms cover a range of typical soil management practices in the study region, including different degrees of management practices that may promote soil health. More specifically, we aimed to answer the following questions: i) Does soil management influence soil health? And if so, (ii) how sensitive are the different soil health indicators to soil management? And finally, (iii) what is the state of soil health in arable soils in the south of Sweden, and can it be improved by soil management? To evaluate the different management practices across fields, we calculated a soil management index for each field. Soil health was assessed by analyzing wet aggregate stability, soil protein content, active carbon, soil respiration, and soil organic matter content.

2 Material and method

2.1 Study sites

This study was carried out on twenty farms in the region of Skåne, in the south of Sweden (latitude of approximately 56°N, 13°E). The region has a mean annual temperature of 8 °C (SMHI, 2018a) and the mean annual precipitation is 500-750 mm (SMHI, 2018b). The farms included both strict cropping enterprises as well as mixed livestock and cropping enterprises. Farms were selected to represent typical farming systems in the region yet covering a range of soil management practices in terms of crop diversity, mechanical soil disturbance and application of external organic amendments.

A field suitable for soil health testing was selected on each farm in cooperation with the farm manager. All fields were sampled in April 2018. Information regarding crop rotation, organic amendment applications, and the general tillage regime was recorded for each field through interviews with the farm manager. Special care was taken to make sure the preceding crop was similar on all fields, to minimize confounding factors. The preceding crop was a cereal for all fields except two, for which it was rapeseed and quinoa, respectively. The state of the fields at the time of sampling varied: some were untouched since the last harvest, some had been ploughed, and some were grown with an over-wintering cash crop or a cover crop.

At every site, an additional sample was taken from an area of unmanaged soil that was identified adjacent to the field. This area was vegetated with grasses and herbs, and sometimes sparsely located shrubs and trees. The unmanaged soil was not pristine, in some cases it was subjected to mowing or run-off and maintenance of nearby roads. Nevertheless, the unmanaged area was perceived as the best available benchmarks for the potential soil health at that site.

2.2 Soil management index

For each field, we quantified the crop diversity, the frequency of mechanical soil disturbance (tillage), and the number of applications of external organic amendments. A crop diversity index (CDI) was calculated by multiplying the number of crop species grown per year with the total number of species in the crop rotation as suggested by Tiemann et al. (2015). The crop diversity index included both cash crops, cover crops and forage crops. For this study, we considered the crop rotation for the past 5 years. Avoidance of mechanical soil disturbance was quantified using a "years without soil disturbance index" (YSDI) based on the number of years without any tillage. We defined an organic amendment index (OAI) as the number of applications of any type of external organic amendment during the past five years. The amounts of organic amendments were not considered. Each index was designed so that a higher index value represents higher frequency of potentially soil health promoting management.

The three indices were then aggregated into a soil management index (SMI) for each field. First, each index was normalized with respect to its maximum value in our data set. This was done to overcome different magnitudes between the indices, which otherwise would have created an unbalanced contribution to the aggregated soil management index. Finally, the three indices were aggregated into the soil management index (SMI) through equal weighting and using the arithmetic mean:

$$\mathrm{SMI} = \left(\frac{CDI_i}{CDI_{max}} + \frac{YSDI_i}{YSDI_{max}} + \frac{OAI_i}{OAI_{max}}\right)/3 \qquad (1.)$$

where *CDI* represents crop diversity index, *YSDI* represents years without mechanical soil disturbance, and *OAI* represents applications of organic amendments of the i^{th} field and *max* the maximum measured value in our dataset.

2.3 Soil sampling

Soil sampling was done in April 2018, at a water content close to field capacity. The samples were taken as a spade slab of soil 15 cm deep, 10 cm wide and 2.5 cm thick according to the CASH guidelines (Moebius-Clune et al., 2016). At each site, soil was collected from five points within the field. The points were selected to represent the field. Areas of the field that were known to have a different soil type were excluded. A composite sample was made by mixing soil from each point in a bucket and then collecting the soil sample into a plastic bag. In addition, samples were also taken from an unmanaged soil adjacent to the sampled field. Samples of unmanaged soil were collected in the same fashion as samples from the field. Samples were kept in a cooler during transportation and laid out to airdry at room temperature at the end of each sampling day. The air-dried soil was sieved into two fractions, < 8 mm and < 2 mm, according to the CASH guidelines (Moebius-Clune et al., 2016), and stored in plastic bags at 4 °C before analysis.

2.4 Soil texture and pH

Texture was determined by dispersing a recorded weight of approximately 14 g of air dry soil (< 2 mm aggregate size) in 3% sodium hexametaphosphate and shaking for two hours at 150 rpm (Kettler et al., 2001). The dispersed soil was then forced through a 0.053 mm sieve, collecting the sand particles from the sieve in an ovenproof dish. The still suspended silt and clay particles were collected in a 1000 ml beaker of 15 cm height. The silt and clay suspension was left to settle for 2 hours, after which the still suspended clay particles were poured out and the remaining silt particles were collected. The silt and sand fractions were oven dried at 105 °C for at least 12 hours. Soil pH was measured in a 1:2 soil:deionized water slurry, which was shaken at 45 rpm for five minutes, and then left to settle for one hour before pH was measured using a Seven Easy pH-meter (Mettler Toledo, Greifensee, Switzerland).

2.5 Soil health indicator analyses

The soil health indicator analyses included in this study were wet aggregate stability, soil protein, active carbon, soil respiration, and soil organic matter. The methods of the analyses are described below, all of which were done according to the CASH protocol (Schindelbeck et al., 2016).

Wet aggregate stability was determined by rainfall simulation using a Cornell Sprinkle Infiltrometer (Ogden et al., 1997; Schindelbeck et al., 2016). Approximately 30 g of air dry soil aggregates in the size fraction of 0.25-2.00 mm was spread on top of a 0.25 mm sieve with a diameter of 200 mm. The sieve was mounted within a funnel containing a 380 mm diameter filter paper to collect the <0.25 mm failed aggregates. Reverse osmosis water was applied from the infiltrometer from 500 mm height at a constant rate of 2.5 mm/min for 5 minutes, resulting in 2.5 J of energy impacting the soil. Aggregate stability was calculated as the percentage of aggregates remaining on the sieve, correcting for solid particles > 0.25 mm.

Autoclaved-citrate extractable protein (Soil protein) was determined according to the CASH protocol. Air dry soil (3 g, < 8 mm aggregate size) was added to an extraction solution of 0.02 M sodium citrate (pH 7). The solution was shaken at 180 rpm for 5 minutes and thereafter autoclaved at 121°C for 30 minutes. The extract was clarified by centrifuging at 11’000 rpm for 4 minutes (a minor modification from the CASH protocol). Lastly it was quantified by bicinchonic acid assay against a bovine serum albumin standard curve for soil protein. The plate reader used was a Spectra Max 384 Plus, with the software SoftMaxPro 6.2.2 (Molecular Devices, Sunnyvale, CA, USA).

Soil organic matter content was analyzed as mass loss of ignition at 500 °C for two hours (Nelson & Sommers, 1996).

Active Carbon (ActC) was measured as permanganate oxidizable carbon. Approximately 2.5 g of air dry soil, (< 2 mm aggregate size) was added to 20 ml 0.02 M potassium permanganate (KMNO4) solution (pH 7.2). The extracts were shaken for 2 min at 120 rpm and allowed to settle for 8 minutes, resulting in 10 minutes total reaction time. An aliquot of the extract was diluted 100 times in preparation for absorbance measurement at 550 nm (Thermo Fisher Scientific, Genesys 20, model 4001/4). Absorbance was calibrated using standard curves and converted to mg active carbon per kg soil using the equation of Weil et al. (2009).

Heterotrophic soil respiration was measured according to the CASH protocol (Haney and Haney, 2010; Schindelbeck et al., 2016). Approximately 20 g of soil (< 8 mm aggregate size) was weighed into a perforated aluminum weigh-boat and put in a plastic jar on top of two filter papers. A beaker filled with 9 ml of 0,5 M KOH was put next to the weigh boat in the jar. Using a pipette, distilled water (7.5 ml) was added on the side of the jar to rewet the soil through capillary rise. The jar was sealed with double lids and incubated for 4 days at 23.5 °C. The amount of CO_2 respired by the soil microbes and subsequently absorbed by the KOH trap during the incubation was determined by measuring the change in electrical conductivity using a WTW ProfiLine Cond 3310 electrical conductivity meter. Several blank jars (no soil) were included in the set up to measure the atmospheric background CO_2.

2.6 Overall relative soil health

To estimate the overall soil health of the sampled fields, we calculated a relative soil health index. For each site, the soil health indicator values for the field soil were divided by the respective value for the unmanaged soil. The relative soil health index was then obtained by aggregating the indicator ratios using equal weighting:

$$\text{Relative soil health index} = \left(\frac{WAS_{if}}{WAS_{iu}} + \frac{Prot_{if}}{Prot_{iu}} + \frac{Act\ C_{if}}{Act\ C_{iu}} + \frac{Resp_{if}}{Resp_{iu}} + \frac{SOM_{if}}{SOM_{iu}}\right) \qquad (2.)$$

where *WAS, Prot, Act C, Resp, and SOM* denote wet aggregate stability, soil protein content, active carbon, soil respiration, and soil organic matter content, respectively, of the field soil (*f*) and unmanaged soil (*u*) for the i^{th} site.

A high relative soil health index is interpreted as a healthier soil, based on the assumption that the unmanaged soil represents the potential soil health at that site.

2.7 Data analysis and statistics

Statistical analyses were performed using the R software version 3.5.1 (R Core Team, 2018). Differences in soil properties and soil health indicators between field and unmanaged soil samples were analyzed using an analysis of variance (ANOVA).

A principal component analysis was performed to explore how the 20 farms were distributed in relation to the measured soil health indicators, the soil management index and soil texture. This analysis was performed based on the correlation matrix of the measured values. The factors included in the principal component analysis were: soil management index, sand content, wet aggregate stability, soil protein, active C, soil respiration, and soil organic matter. Multiple linear regression analysis was used to analyze the influence of soil management index and sand content on soil health indicators according to the following model:

$$\mathrm{y} = \mathrm{a} * \mathrm{SMI} + \mathrm{b} * \mathrm{sand} + \mathrm{c} \qquad (3.)$$

where y represents the soil health indicator, SMI represents soil management index, sand represents sand content, a and b denote correlation coefficients for soil management index and sand content respectively, and c is the intercept.

A relative importance analysis was performed with the assistance of the R package “relaimpo” (Grömping & Lehrkamp, 2015) and used to analyze to what extent soil management and soil texture influenced soil health indicators. The relationship between soil management and the overall relative soil health score was analyzed using a simple linear regression. The texture triangle illustration was created using the R package “soiltexture” (Moeys, 2018).

3 Results

3.1 Basic soil properties and soil management

A wide range of soil textural classes were represented among the 20 farms. Clay, silt and sand contents varied from 4.6% to 40.2%, 4.0% to 43.0%, and 20.8% to 91.4% respectively (Figure 1). There was no difference in sand content between field samples and unmanaged soil samples ($p = 0.92$). The pH of the soil samples varied from 5.0 to 8.1, with no significant difference in pH between field samples and unmanaged soil samples ($p = 0.67$) (Table 2).

The crop diversity index varied from 2 to 88.8. The organic amendment index varied from 0 to 8. The years without soil disturbance index varied from 0 to 3 years. The soil management index values ranged from a minimum of 0.2 to a maximum of 0.8 (Table 1). We tested different ways of calculating indices and aggregating the indices into a soil management index, but this did not significantly change the regression equations shown in Figure 3 or the results of the relative importance analysis (not shown).

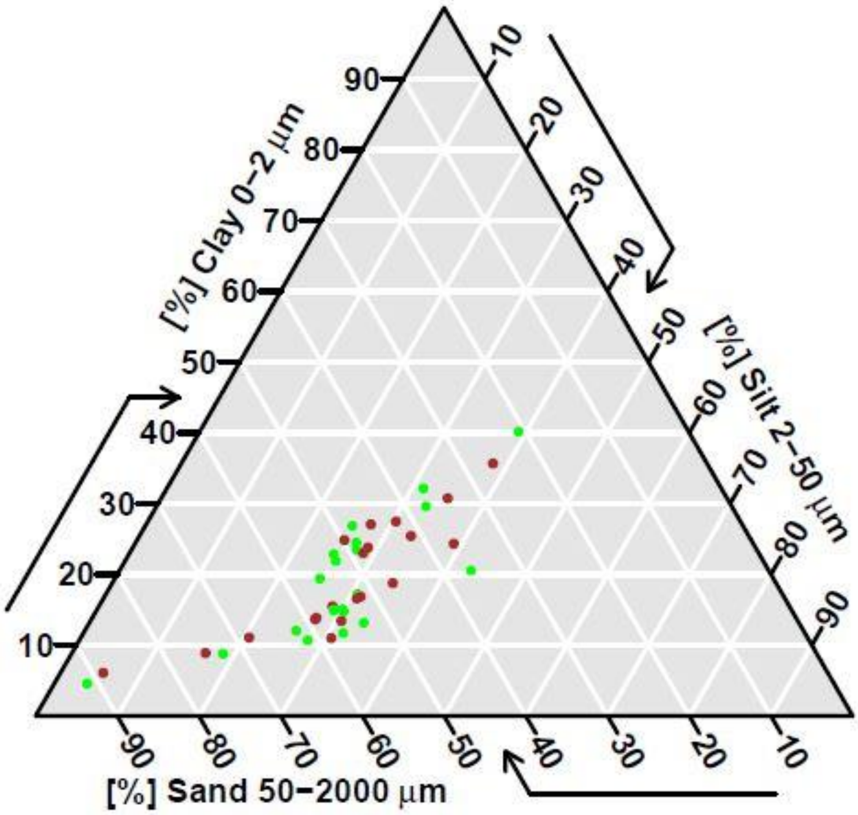

Figure 1. Soil texture for each sample, displayed in a texture triangle. Brown points represent field samples and green points represent unmanaged soil samples.

Table 1. *Maximum, minimum, mean, and median values for the crop diversity index (CDI), years without soil disturbance index (YSDI), organic amendment index (OAI), and the aggregated soil management index (SMI).*

	CDI	YSDI	OAI	SMI
max	88.8	3	8	0.80
min	2	0	0	0.008
mean	14.8	0	1.4	0.20
median	7	0	0.5	0.09

3.2 Influence of soil management and texture on soil health indicators

The results from the principal component analysis provided evidence that the different farms were diverse regarding the soil management index, the sand content and the different soil health indicators (Figure 2). The first two components explained 82% (component 1: 62%; component 2: 20%) of the total variance. Farms with a high soil management index showed a high wet aggregate stability and high soil protein content, indicated by the similar direction of these loadings. Farms with a low sand content had high active C, soil respiration and soil organic matter content, indicated by the opposite direction of these loadings. However, these indicators were also connected to farms with a high soil management index, indicated by these loadings leaning towards the direction of the soil management loading. The principal component analysis also indicated that the soil management index and the sand content were not related, represented by the almost perpendicular direction between these two loadings.

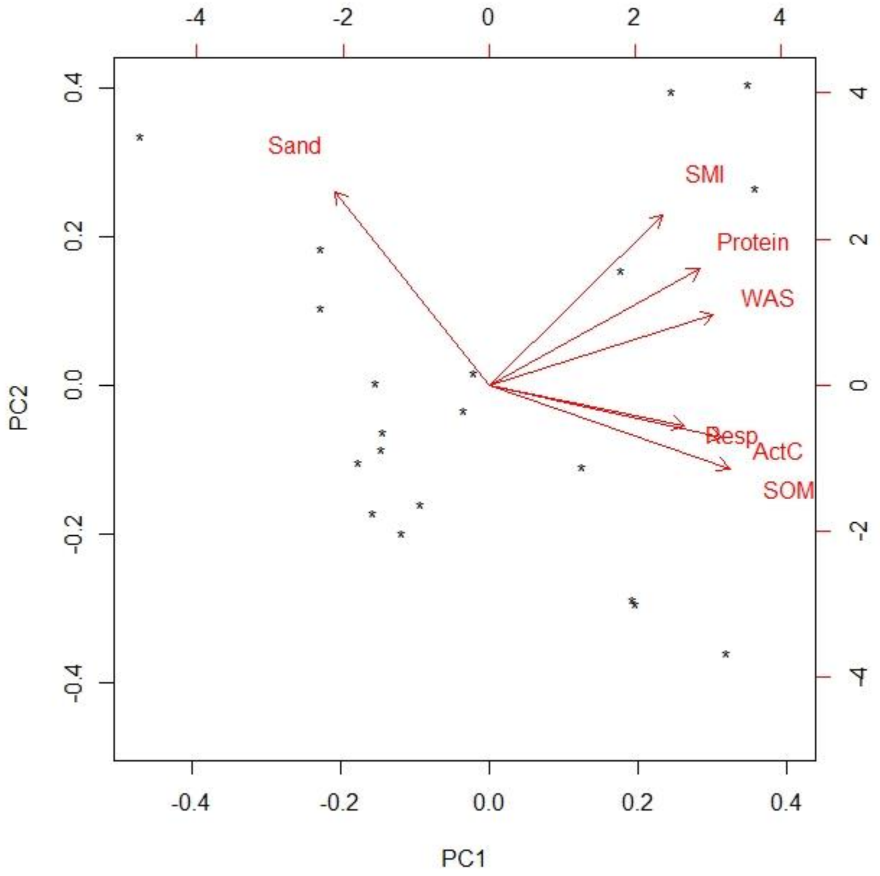

Figure 2. Biplot obtained from the principal components analysis based on the correlation matrix, showing the two first principal components (explaining 62% and 20%, respectively). Each asterisk represents an individual field *(n* = 20), loadings represent soil health indicators, soil management index and soil texture. Descriptors: *SMI* = soil management index, *sand* = sand content, *WAS* = wet aggregate stability, *Act C* = active C, *protein* = soil protein, *Resp* = soil respiration, *SOM* = soil organic matter.

All soil health indicators were found to be positively related to the soil management index and negatively correlated to sand content (Figure 3). Wet aggregate stability as a function of the soil management index and sand content explained 64% of the variance ($R^2 = 0.64$, $p < 0.001$). Soil management explained 53% and the sand content explained 11% of the variance, according to the relative importance analysis (Table 2), indicating a high sensitivity to soil management. Soil protein content as a function of the soil management index and sand content explained 57% of the variance ($R^2 = 0.57$, $p < 0.001$). Soil protein had the highest sensitivity to soil management indicated by the variance for soil protein content being explained by soil management to 55% and only 2% being due to sand content (Table 2). Active carbon as a function of the soil management index and sand content explained 53% of the variance ($R^2 = 0.53$, $p<0.01$). Active carbon explained 15% of the total variance, and sand content explained 38%. Soil respiration as a function of the soil management index and sand content explained 42% of the variance, which was somewhat lower than other indicators ($R^2 = 0.42$, $p <0.05$). For soil respiration, soil management explained 17% of the total variance and 25% was explained by sand content. Soil organic matter as a function of the soil management index and sand content explained 75% of the variance ($R^2 = 0.75$, $p <0.01$), and was the indicator that was least sensitive to soil management. The variance of soil organic matter content was only to 16% explained by soil management. Sand content had a higher relative importance and explained 59% of the total variance for soil organic matter content.

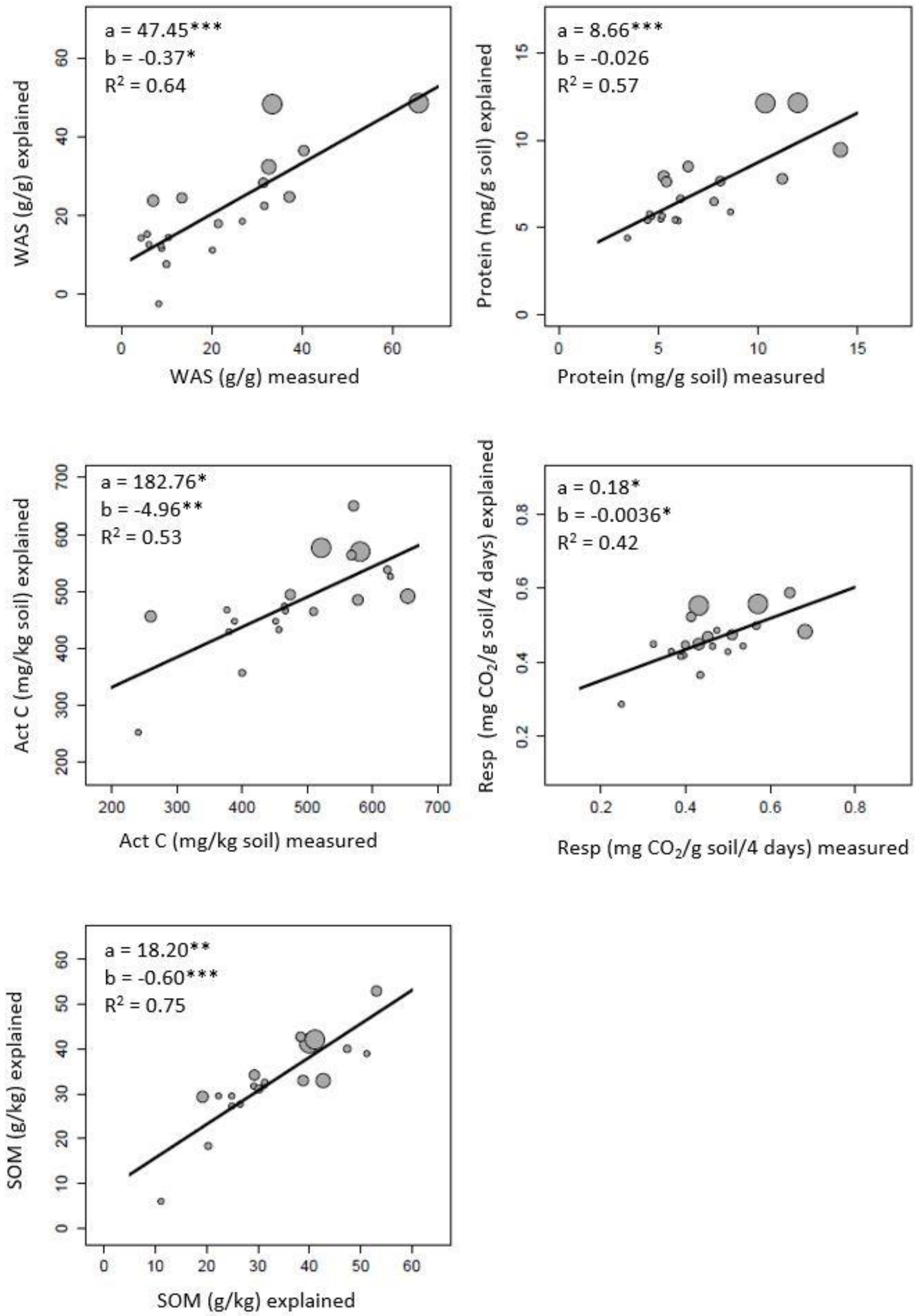

Figure 3. Multiple linear regression models of the soil health indicators wet aggregate stability (WAS), active C (Act C), soil protein (Protein), soil respiration (Resp), and soil organic matter (SOM). The model shows the relationship between the measured soil health indicator values and the soil health indicator values that can be explained by the statistical model, by using the soil management index (SMI) and sand content as independent variables. Regression equation: y = a*SMI + B*sand + intercept. *, **, *** indicates significant regression coefficients at $p < 0.05$, $p < 0.01$ and $p < 0.001$,

respectively. Circle size represents SMI value, a larger size represents a higher SMI. R^2 represents multiple R^2.

Table 2. *The relative importance of the variables sand content and soil management index in the multiple linear regressions, as well as the R^2, i.e the variance that can be explained by the regression model.*

Soil health indicator	SMI (%)	Sand (%)	R^2 (%)
Wet aggregate Stability	53	11	64
Soil protein	55	2	57
Active carbon	15	38	53
Soil respiration	17	25	42
Soil organic matter	16	59	75

3.3 The effect of soil management on overall soil health

All soil health indicators had significantly lower values for field samples compared to the unmanaged soil samples (Table 3). The largest difference was found for wet aggregate stability where the mean of the unmanaged soil was two times higher than the mean of the field soil. The smallest difference occurred for active carbon where the mean of the field soil had 1.2 times higher concentration than the mean of the unmanaged soil.

Table 3. *Mean and standard deviation (SD) for soil health indicators for the 20 farms for field and unmanaged soil samples respectively, as well as for the complete dataset. ***, **, and * represent significance levels of $p < 0.001$, $p < 0.01$, and $p < 0.05$ respectively between field and unmanaged soil values according to the analysis of variance*

Soil health indicator	ANOVA	Mean (SD)		
		Field	Unmanaged	Total dataset
Wet aggregate stability (%)	***	21.2 (16.0)	43.5 (18.0)	32.3 (20.2)
Soil protein (mg/g)	**	7.03 (2.88)	9.88 (2.95)	8.46 (3.22)
Active carbon (mg/kg)	*	479 (116)	571 (103)	525 (117)
Soil respiration (mg CO_2/g soil/4 days)	***	0.46 (0.10)	0.75 (0.19)	0.61 (0.21)
Soil organic matter content (g/kg)	*	32.7 (11.2)	41.6 (12.8)	37.1 (12.7)

The relative soil health index, based on the ratio of each soil health indicator between field soil and unmanaged soil, estimates the overall soil health. The ratio of each soil health indicator between managed and unmanaged soils contributed varying amounts to the overall relative soil health index for each farm (Figure 4a). The overall relative soil health index as a function of the soil management index is shown in Figure 4b ($p = 0.007$, $R^2 = 0.34$). A high soil management index was positively correlated to the relative soil health index, which could be described by the following regression equation: relative soil health index = 1.71 * SMI + 3.1.

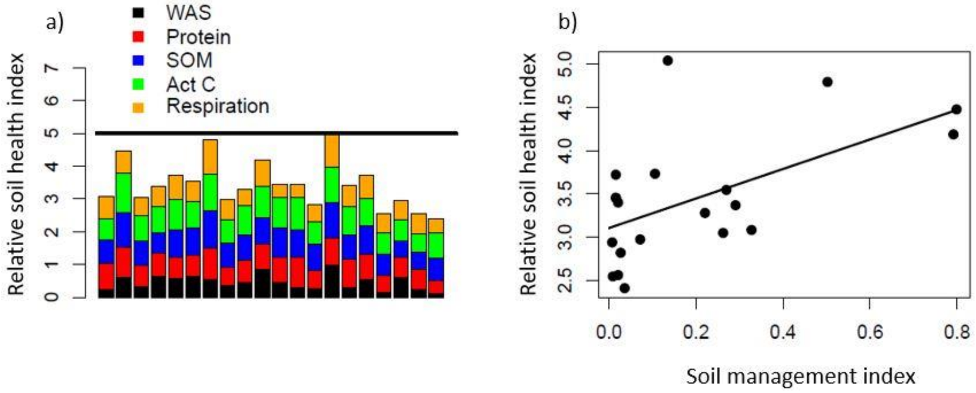

Figure 4. a) The contribution of each soil health indicator ratio to the relative soil health index for each farm. The line represents the maximum value for the relative soil health index according to Equation 2. Abbreviations: WAS = wet aggregate stability, Protein = soil protein content, SOM = soil organic matter content, Act C = active C, Respiration = soil respiration. b) Relative soil health index as a function of soil management index (multiple $R^2 = 0.34$, $p = 0.007$).

4 Discussion

This study was conducted on commercial farms, which enabled us to include the complexity of cropping systems and soil management decisions that farm managers are faced with, in the study design. The focus was on the combined effect of crop diversity, avoidance of mechanical soil disturbance, and application of organic amendments, and to what extent they influence soil health. These management practices were selected because they are currently practiced on commercial farms in the studied region. The on-farm design of the study also made it possible to include a large variation of soil texture in the dataset.

An important factor to mention when comparing the results of our study to previous studies on soil health and soil management is that most previous studies have been done by comparing different management categories, such as no-till vs conventional tillage or a continuous monoculture crop vs diverse crop rotation in field plot experiments (Nunes et al., 2018; Congreves et al., 2015; Idowu et al., 2008). Our study did not compare categorically different management systems but included fields with a diversity of soil management practices in different cropping systems practiced on commercial farms in southern Sweden. This results in some distinct differences in management factors between our study and previous studies. For example, the longest period without mechanical soil disturbance was three years in our study, which is much shorter compared with the above-cited studies that included systems that had been under no-till for at least 5-10 years. In our study, the absence of tillage was mostly related to the growing of certain crops, such as perennial forage leys or overwintering crops planted in the autumn. This excluded the need for seedbed preparation and therefore resulted in years without mechanical soil disturbance. Our study also differs from the cited examples in terms of crop diversity. For example, a low crop diversity in this study consisted of 3-4 crops, which is much more diverse than the continuous corn rotations that are often studied in North America. It is therefore not surprising that our results show slightly different patterns than other soil health studies. Nevertheless, the general results are similar: it is possible to promote soil health though soil management.

4.1 The influence of soil management on soil health

Our results demonstrate that all the quantified soil health indicators (wet aggregate stability, soil protein content, active C, soil respiration and soil organic matter content) were affected by soil management (Figure 3). The results show that soils with a high soil management index generally had higher values for all soil health indicators, but that the sensitivity to soil management varied between the soil health indicators. We found the most significant management effects on wet aggregate stability and soil protein content (Figure 3). Another study using CASH reported the most significant management effect for active carbon, soil respiration, and soil organic matter content (Nunes et al., 2018). A possible explanation for this variation could be the differences in crop diversity between this study and our study. Nunes et al. (2018) compared a continuous corn rotation with a corn rotation that included a cover crop each year. The addition of a new crop to a continuous monoculture significantly increases total soil organic carbon and nitrogen as well as microbially bound carbon and nitrogen (McDaniel et al., 2014). However, further increases in crop diversity was shown to have diminishing returns on the increased content of both total and microbially bound carbon and nitrogen in the soil (McDaniel et al., 2014). None of the sampled fields in our study had a continuous monoculture, which could be a reason why we did not find as significant management impacts on carbon related soil health indicators as were found by Nunes et al. (2018). The strong effect of soil management on wet aggregate stability, but weaker relationship with active carbon, soil respiration and soil organic matter content seen in our study could also be explained by the fact that our study investigated the combined effect of various-soil management practices (crop diversity, tillage, organic inputs), in contrast to other studies that quantified single (isolated) management factors such as conventional tillage vs. no-till or crop rotation vs. monoculture. Furthermore, management practices change from year to year depending on the crop in practical farming (in contrast to field experiments with predefined factors). This creates a complex system with many possible feedback loops. However, our study only reflects the present state of soil health, and we may only speculate in the fluctuations in soil health indicators which might take place during a crop rotation. The strong effect of soil management on wet aggregate stability, but weaker relationship with active carbon, soil respiration and soil organic matter seen in our study may partly be explained by such fluctuations. It is known that labile carbon, such as active carbon, increases during periods of perennial leys and decreases during periods of annual crops, without changes to soil organic matter (Haynes, 2000). High levels of labile carbon are an indicator of high microbial activity. This can, for example, be boosted by perennial plants due to their larger root biomass and increased root exudation, compared to annual plants (Kuzyakov & Domanski, 2000; Finney & Kaye, 2017). By this reasoning, it is possible that active carbon levels in some of the sampled soils of our study were higher during the time of an established perennial ley but decreased rapidly due to the termination of the ley and subsequent cultivation of annual crops. Root exudates and microbial organisms produce soil binding compounds such as glomalin and polysaccharides, which increases aggregate stability, while tillage decreases aggregate stability (Bossuyt et al., 2001; Bronick & Lal, 2005). However, our study showed a strong effect of soil management on aggregate stability even though some fields had been cultivated with annual plants most recently and had been subjected to recent tillage. Perhaps aggregate stability is a less dynamic property than active carbon and soil respiration. Therefore, the beneficial effects of soil management during the crop rotation may still have a strong effect on aggregate stability while they may have declined more rapidly for active carbon and soil respiration. However, the strong relationship between soil management and aggregate stability could also be due to application of manure, which has been shown to increase aggregate stability (Wortmann & Shapiro, 2008; Jiao et al., 2006). The strong relationship between soil protein content and soil management seen in this study (Figure 3) could also be influenced by application of manure. Soil protein content is a measure of organically bound nitrogen (Moebius-Clune et al., 2016). Manure supplies nitrogen in organic form to the soil and thus recouples the nitrogen and carbon cycle in the soil, compared to application of mineral nitrogen (Drinkwater et al., 2017). This has been shown to increase soil and crop retention of applied nitrogen (Gardner & Drinkwater, 2009). Crop diversity may also explain the strong relationship between soil protein content and soil management. Fields with a high crop diversity in our study often included legumes in the crop rotation. Leguminous crops also supply the soil with organically bound nitrogen (Drinkwater et al., 2017) and thus influences soil protein content.

The quantified values of soil health indicators could also be influenced by soil management variables that were not included in the soil management index. One such variable is the different soil conditions at the time of sampling. Some fields had been tilled recently, while others had been moldboard plowed the previous autumn. Other fields had not been touched since harvest the previous year, while some had a winter crop growing on them. All these scenarios could potentially impact the values of the measured soil health indicators. Particularly moldboard plowing could have an effect since this type of tillage results in an inversion of the soil. Therefore, the crop residues from the previous season were located below the sampling depth of this study. This reduces the amount of fresh organic matter in the topsoil which could influence the biological indicators measured in this study (Soane et al., 2012).

4.2 The influence of soil texture on soil health indicators

Soil health is affected by soil management; however, the soil health indicator values are also governed by soil texture. This study found that wet aggregate stability and soil protein are highly sensitive to soil management, as much as 53% and 55 %, respectively, of the variance was influenced by soil management (Table 3). Soil texture only accounted for 11% and 2% of the influence on soil health for wet aggregate stability and soil protein. Active carbon and soil respiration were not as sensitive to soil management. However, soil management still explained 15% and 17%, respectively, of the variance for these indicators. Soil texture explained 38% and 25% of the variance for active carbon and soil respiration, respectively. Soil organic matter content was strongly controlled by soil texture, with 59% of the variance explained by sand content. Although soil organic carbon content was less sensitive to soil management than to texture, soil management still accounted for 16% of the variance.

Soil texture is acknowledged to affect soil health indicator values by other studies. The CASH soil health score takes soil texture into account when scoring soil health indicators (Moebius-Clune et al., 2016), as do other soil health assessment approaches (Andrews et al., 2004). Nunes et al. (2018) also report soil health results based on soil texture differences. Although Nunes et al. (2018) did not specifically investigate the effect of soil texture on soil health, it is seen that active carbon, soil respiration and soil organic matter have higher values in finer soil texture. A similar relationship was observed by Idowu et al. (2009). In our study soil organic matter, and the other indicators, decreased with increasing sand content. This relationship is supported by the well-established fact that soil organic matter generally increases with clay content (Oades, 1988). Active carbon and soil respiration are indicators that are closely related to soil organic matter content, which may explain why soil texture had a larger influence than soil management on these indicators.

Since soil texture has a large influence on many soil health indicators it is important to take soil texture into account when assessing soil health. This is especially important when comparing soils with substantial differences in soil texture. Failure to account for soil texture would otherwise lead to unjust comparisons of soil health.

Regardless of this, our study shows that all the soil health indicators were sensitive to soil management, which means that soil health can be improved or sustained by appropriate soil management.

4.3 Improvement of relative soil health through appropriate soil management

Our results clearly show that all soil health indicators had significantly lower values for the agriculturally managed soil compared to the unmanaged soil (Table 2). This supports our assumption that the unmanaged soil could serve as a benchmark for the potential soil health at each site. A similar pattern of unmanaged soil having higher values for physical and biological soil health indicators has been seen previously for on-farm studies (Wander & Bollero, 1999). This is probably due to the absence of soil disturbance at unmanaged areas, as well as the continuous vegetative cover and living roots in the soil. These factors can, as previously discussed, influence soil processes that are beneficial to soil health.

To further explore the difference in soil health between field soil and unmanaged soil, and to see if a similar pattern was expressed for the overall soil health, we calculated a relative soil health index. The relative soil health index was obtained by aggregating the ratio between the field soil and the unmanaged soil for each soil health indicator (Eq. 2). The results show that the relative soil health index is positively correlated to the soil management index. This demonstrates that fields with a high soil management index had a more intact overall soil health relative to the potential soil health at that site (Figure 4.b). When analyzing these results, it is important to keep in mind that this way of assessing soil health is dependent on the conditions of the unmanaged soil. At some sites the unmanaged soil was affected by nearby roads or other activities, which could possibly influence the soil health. However, considering the significant differences between field soil and unmanaged soil seen in this study, and the care taken to select suitable unmanaged areas, we consider our data to be reliable.

These results are an example of how assessment of soil health can provide valuable information on how to sustainably cultivate soils. Each soil health indicator is related to soil functions and soil processes (Moebius-Clune et al., 2016). The lower indicator values for the field soils imply that physical and biological functions of arable fields in the south of Sweden are impaired to some extent. This could mean that the delivery of soil ecosystem services is threatened, which can have negative consequences on crop productivity and the resilience of farming systems (Hedlund & Harris, 2012; Bommarco et al., 2013). However, our results also show that appropriate soil management can improve and sustain soil health of arable fields. A more widespread implementation of such soil health promoting management is therefore crucial to achieve sustainable farming systems through ecological intensification. Further research is needed to facilitate adoption of soil health promoting management. For example, there is a need to increase our knowledge of how some soil health management practices can be implemented under Swedish conditions.

Best management practices on how to apply cover cropping and no-till are examples of future areas for applied research. Another research area is the mechanistic understanding of soil processes and functions that drive the beneficial soil health effects. An increased understanding of how a specific management practice affects soil processes may motivate farmers to adopt such a practice. Lastly, further on-farm research is needed to reflect the actual conditions on commercial farms. Conducting on-farm research can be challenging with many confounding factors. The strength of our study was the quantification of specific soil management practices into a soil management index, instead of using general farming system categories that often include a large variation of management practices (Williams & Hedlund, 2013; Büchi et al., 2018). Furthermore, the design of management indices was carefully done with the aim to clearly represent how soil health management strategies are implemented in terms of specific management practices on farms in southern Sweden. This approach could be used in future on-farm soil health studies that may face similar circumstances regarding soil management.

In summary, our results demonstrate that it is possible to improve and sustain soil health through appropriate soil management. A healthy soil enhances supporting and regulating ecosystem services (Hedlund & Harris, 2012). Thus, healthy soils will produce sufficient crop yields, reduce the need for anthropogenic input, and better withstand extreme weather events. This knowledge has implications on local, national and global scales. Locally, soil health promoting management and their benefits to soil health should be encouraged by farm advisors. Further research on how to design farming systems that maximize soil health could be conducted in collaboration with farm managers and farm advisors. Nationally, facilitation of soil health promoting management practices should be supported through policy programs and agricultural subsidies. On a global scale, soil health is vital for increasing the resilience of agricultural production, mitigating climate change, and reducing the environmental footprint of food production (Lal, 2016).

5 Conclusions

This study investigated the impact of soil management on soil health. The considered management practices were: crop diversity, avoidance of mechanical soil disturbance, and application of organic amendments, as these have been suggested to promote soil health. Our results demonstrate that there is a clear positive relationship between soils managed according to soil health management strategies and soils with good soil health, when differences in soil texture are accounted for. The results also show that soils from arable fields generally had a poorer soil health in comparison to unmanaged soil. However, fields managed according to soil health management strategies had a more intact soil health in comparison to the potential soil health of unmanaged soil next to the field. Therefore, implementation of soil health promoting management practices should be encouraged. Healthy soils strengthen supporting and regulating soil ecosystem services, which increases the resilience of agroecosystems and the sustainability of food production.

6 Acknowledgements

I would first like to thank the farmers that participated in this study for letting me take samples of their soil, for sharing their ideas on soil health and soil management, and for taking their time to provide me with agronomic data from the sampled fields. I am also thankful to the agronomists at HIR Skåne AB for helping me find farms that were suitable for this study.

I am also very grateful to the Soil health team at the Cornell Soil Health Lab for taking care of me as an intern and for teaching me every little detail about the Comprehensive Assessment of Soil health test. They have also provided great support over email during my laboratory work at SLU.

I would also like to thank my main supervisor, Professor Thomas Keller, Department of Soil and Environment, SLU, he has been a great support during the whole project: from the first idea for a grant proposal, to the finishing touches of the thesis. My co-supervisor Tino Colombi, postdoc, Department of Soil and Environment, SLU, has also been very helpful with assistance of the statistical analysis and with cheering me on during the progress of the thesis.

I would also like to acknowledge university and laboratory staff at SLU for answering random questions and assisting me with my laboratory analyses.

Lastly, I would like to thank the Royal Swedish Academy of Agriculture and Forestry for financial support (grant no. GFS2017-0114).

References

Abid, M. & Lal, R. 2009. Tillage and drainage impact on soil quality: II. Tensile strength of aggregates, moisture retention and water infiltration. *Soil and Tillage Research*, 103(2): 364–372.

Alexandratos, N. & Bruinsma, J. 2012. *World agriculture towards 2030/2050*: the 2012 revision. ESA Working paper FAO, Rome.

Alhameid, A., Ibrahim, M., Kumar, S., Sexton, P. & Schumacher, T.E. 2017. Soil Organic Carbon Changes Impacted by Crop Rotational Diversity under No-Till Farming in South Dakota, USA. *Soil Science Society of America Journal,* 81(4): 868.

Altieri, M.A. 1999. The ecological role of biodiversity in agroecosystems. In *Invertebrate Biodiversity as Bioindicators of Sustainable Landscapes*. Elsevier: 19–31.

Andrews, S.S., Karlen, D.L. & Cambardella, C.A. 2004. The soil management assessment framework. *Soil Science Society of America Journal*, 68(6): 1945–1962.

Barrios, E. 2007. Soil biota, ecosystem services and land productivity. *Ecological Economics*, 64(2): 269–285.

Bender, S.F., Wagg, C. & van der Heijden, M.G.A. 2016. An Underground Revolution: Biodiversity and Soil Ecological Engineering for Agricultural Sustainability. *Trends in Ecology & Evolution*, 31(6): 440–452.

Bending, G.D., Turner, M.K. & Jones, J.E. 2002. Interactions between crop residue and soil organic matter quality and the functional diversity of soil microbial communities. *Soil Biology and Biochemistry*, 34(8): 1073–1082.

Blair, N., Faulkner, R.D., Till, A.R. & Poulton, P.R. 2006. Long-term management impacts on soil C, N and physical fertility. *Soil and Tillage Research*, 91(1–2): 30–38.

Bommarco, R., Kleijn, D. & Potts, S.G. 2013. Ecological intensification: harnessing ecosystem services for food security. *Trends in Ecology & Evolution*, 28(4): 230–238.

Bossuyt, H., Denef, K., Six, J., Frey, S.D., Merckx, R. & Paustian, K. 2001. Influence of microbial populations and residue quality on aggregate stability. *Applied Soil Ecology*, 16(3): 195–208.

Bottinelli, N., Angers, D.A., Hallaire, V., Michot, D., Le Guillou, C., Cluzeau, D., Heddadj, D. & Menasseri-Aubry, S. 2017. Tillage and fertilization practices affect soil aggregate stability in a Humic Cambisol of Northwest France. *Soil and Tillage Research*, 170: 14–17.

Bronick, C.J. & Lal, R. 2005. Soil structure and management: a review. *Geoderma*, 124(1–2): 3–22.

Büchi, L., Georges, F., Walder, F., Banerjee, S., Keller, T., Six, J., van der Heijden & Charles, R. 2018. The hidden side of cropping systems classification: actual differences and similarities in cropping practices between conventional, no-till and organic farming. *European Journal of Agronomy*, Under review.

Bünemann, E.K., Bongiorno, G., Bai, Z., Creamer, R.E., De Deyn, G., de Goede, R., Fleskens, L., Geissen, V., Kuyper, T.W., Mäder, P., Pulleman, M., Sukkel, W., van Groenigen, J.W. & Brussaard, L. 2018. Soil quality – A critical review. *Soil Biology and Biochemistry*, 120: 105–125.

Congreves, K.A., Hayes, A., Verhallen, E.A. & Van Eerd, L.L. 2015. Long-term impact of tillage and crop rotation on soil health at four temperate agroecosystems. *Soil and Tillage Research*, 152: 17–28.

Drinkwater, L.E. 2002. Cropping Systems Rsearch: Reconsidering Agricultural Experimental Approaches. *HortTechnology*, 12(3): 355–361.

Drinkwater, L.E., Schipanski, M., Snapp, S. & Jackson, L.E. 2017. Ecologically Based Nutrient Management. In *Agricultural Systems*. Elsevier: 203–257. http://linkinghub.elsevier.com/retrieve/pii/B9780128020708000074 27 August 2018.

Drinkwater, L.E. & Snapp, S.S. 2007. Nutrients in Agroecosystems: Rethinking the Management Paradigm. In *Advances in Agronomy*. Elsevier: 163–186. http://linkinghub.elsevier.com/retrieve/pii/S0065211304920032 27 August 2018.

Eisenhauer, N., Lanoue, A., Strecker, T., Scheu, S., Steinauer, K., Thakur, M.P. & Mommer, L. 2017. Root biomass and exudates link plant diversity with soil bacterial and fungal biomass. *Scientific Reports*, 7(1). http://www.nature.com/articles/srep44641 3 August 2018.

Finney, D.M. & Kaye, J.P. 2017. Functional diversity in cover crop polycultures increases multifunctionality of an agricultural system M. Cadotte, ed. *Journal of Applied Ecology*, 54(2): 509–517.

Foley, J.A. 2005. Global Consequences of Land Use. *Science*, 309(5734): 570–574.

Franco-Vizcaíno, E. 1996. Soil Quality in Central Michigan: Rotations with High and Low Diversity of Crops and Manure. In *Methods for assessing Soil Quality*. Madison, Wis., USA: Soil Science Society of America. https://dl.sciencesocieties.org/publications/books/pdfs/sssaspecialpubl/methodsforasses/327 2 April 2017.

Gardner, J.B. & Drinkwater, L.E. 2009. The fate of nitrogen in grain cropping systems: a meta-analysis of 15N field experiments. *Ecological Applications*, 19(8): 2167–2184.

Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M. & Toulmin, C. 2010. Food Security: The Challenge of Feeding 9 Billion People. *Science*, 327(5967): 812–818.

Grömping, U. & Lehrkamp, M. 2015. *Package 'relaimpo'. Relative importance of regressors in linear models.*

Haney, R.L. & Haney, E.B. 2010. Simple and Rapid Laboratory Method for Rewetting Dry Soil for Incubations. *Communications in Soil Science and Plant Analysis*, 41(12): 1493–1501.

Haynes, R.J. 2000. Labile organic matter as an indicator of organic matter quality in arable and pastoral soils in New Zealand. *Soil Biology and Biochemistry*, 32(2): 211–219.

Hedlund, K. & Harris, J. 2012. Delivery of Soil Ecosystem Services: From Gaia to Genes. In *Soil Ecology and Ecosystem Services*. Oxford University Press: 98–110.

Hunter, M.C., Smith, R.G., Schipanski, M.E., Atwood, L.W. & Mortensen, D.A. 2017. Agriculture in 2050: Recalibrating Targets for Sustainable Intensification. *BioScience*, 67(4): 386–391.

Idowu, O.J., van Es, H.M., Abawi, G.S., Wolfe, D.W., Ball, J.I., Gugino, B.K., Moebius, B.N., Schindelbeck, R.R. & Bilgili, A.V. 2008. Farmer-oriented assessment of soil quality using field, laboratory, and VNIR spectroscopy methods. *Plant and Soil*, 307(1–2): 243–253.

Idowu, O.J., van Es, H.M., Abawi, G.S., Wolfe, D.W., Schindelbeck, R.R., Moebius-Clune, B.N. & Gugino, B.K. 2009. Use of an integrative soil health test for evaluation of soil management impacts. *Renewable Agriculture and Food Systems*, 24(3): 214–224.

Jiao, Y., Whalen, J.K. & Hendershot, W.H. 2006. No-tillage and manure applications increase aggregation and improve nutrient retention in a sandy-loam soil. *Geoderma*, 134(1–2): 24–33.

Karlen, D.L., Andrews, S.S., Wienhold, B.J. & Zobeck, T.M. 2008. Soil quality assessment: past, present and future. *Publications from USDA-ARS/UNL Faculty.1203*.

Karlen, D.L., Ditzler, C.A. & Andrews, S.S. 2003. Soil quality: why and how? *Geoderma*, 114(3–4): 145–156.

Karlen, D.L., Hurley, E.G., Andrews, S.S., Cambardella, C.A., Meek, D.W., Duffy, M.D. & Mallarino, A.P. 2006. Crop Rotation Effects on Soil Quality at Three Northern Corn/Soybean Belt Locations. *Agronomy Journal*, 98(3): 484.

Kettler, T.A., Doran, J.W. & Gilbert, T.L. 2001. Simplified Method for Soil Particle-Size Determination to Accompany Soil-Quality Analyses. *Soil Science Society of America Journal*, 65(3): 849.

Kuzyakov, Y. & Domanski, G. 2000. Carbon input by plants into the soil. Review. *Journal of Plant Nutrition and Soil Science*, 163(4): 421–431.

Lal, R. 2009. Challenges and opportunities in soil organic matter research. *European Journal of Soil Science*, 60(2): 158–169.

Lal, R. 2016. Soil health and carbon management. *Food and Energy Security*, 5(4): 212–222.

Lal, R., Follett, R.F., Stewart, B.A. & Kimble, J.M. 2007. Soil carbon sequestration to mitigate climate change and advance food security: *Soil Science*, 172(12): 943–956.

Lowery, B., Hickey, W.J., Arshad, M.A. & Lal, R. 1996. Soil water parameters and soil quality. In *Methods for assessing soil quality*. Madison, Wis., USA: Soil Science Society of America: 143–155.

McDaniel, M.D., Tiemann, L.K. & Grandy, A.S. 2014. Does agricultural crop diversity enhance soil microbial biomass and organic matter dynamics? A meta-analysis. *Ecological Applications*, 24(3): 560–570.

Mikha, M.M. & Rice, C.W. 2004. Tillage and manure effects on soil and aggregate-associated carbon and nitrogen. *Soil Science Society of America Journal*, 68(3): 809–816.

Moebius-Clune, B.N., Moebius-Clune, D.J., Gugino, B.K., Idowu, O.J., Schindelbeck, R.R., Ristow, A.., van Es, H.M., Thies, J.E., Shayler, H.A., McBride, M.B., Wolfe, D.W. & Abawi, G.S. 2016. *Comprehensive Assessment of Soil Health - The Cornell Framework Manual*. Third Edition. Ithaca: Cornell University. http://www.css.cornell.edu/extension/soil-health/manual.pdf 12 April 2017.

Moeys, J. 2018. soiltexture: *Functions for soil texture plot, classification and transformation*. https://CRAN.R-project.org/package=soiltexture.

Montanarella, L. 2007. Trends in land degradation in Europe. In *Climate and land degradation*. Springer: 83–104. http://link.springer.com/chapter/10.1007/978-3-540-72438-4_5 11 April 2017.

Natural Resource Conservation Service. 2018. Soil Health. https://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/health/.

NRCS. 2012. Farming in the 21st century - a practical approach to improve soil health.

Nunes, M.R., van Es, H.M., Schindelbeck, R., Ristow, A.J. & Ryan, M. 2018. No-till and cropping system diversification improve soil health and crop yield. *Geoderma*, 328: 30–43.

Oades, J.M. 1988. The retention of organic matter in soils. Biogeochemistry, 5(1): 35–70.

Ogden, C.., Van Es, H. & Schindelbeck, R.R. 1997. Miniature rain simulator for field measurement of soil infiltration. *Soil Science Society of America Journal*, 61(4): 1041–1043.

Oldeman, L.R. 1991. Global Extent of Soil Degradation. *ISRIC Bi-Annual Report* 1991-1992, pp19-36. http://library.wur.nl/isric/fulltext/isricu_i26803_001.pdf 13 April 2017.

Oldfield, E.E., Wood, S.A. & Bradford, M.A. 2018. Direct effects of soil organic matter on productivity mirror those observed with organic amendments. *Plant and Soil*, 423(1–2): 363–373.

R Core Team. 2018. *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing. URL https://www.R-project.org/.

Schindelbeck, R.R., Moebius, B.N., Moebius-Clune, D.J., Kurtz, K.. & Van Es, H. 2016. Cornell University Comprehensive Assessment of Soil Health Laboratory Standard Operating Procedures. https://soilhealth.cals.cornell.edu/files/2015/03/CASH-Standard-Operating-Procedures-030217final-u8hmwf.pdf 13 April 2017.

Schjønning, P., Elmholt, S., Munkholm, L.J. & Debosz, K. 2002. Soil quality aspects of humid sandy loams as influenced by organic and conventional long-term management. Agriculture, *Ecosystems & Environment*, 88(3): 195–214.

SMHI. 2018a. Normal årsmedeltemperatur | SMHI. http://www.smhi.se/klimatdata/meteorologi/temperatur/normal-arsmedeltemperatur-1.3973 2 August 2018.

SMHI. 2018b. Normal uppmätt årsnederbörd, medelvärde 1961-1990 | SMHI. http://www.smhi.se/klimatdata/meteorologi/nederbord/normal-uppmatt-arsnederbord-medelvarde-1961-1990-1.4160 2 August 2018.

Soane, B.D., Ball, B.C., Arvidsson, J., Basch, G., Moreno, F. & Roger-Estrade, J. 2012. No-till in northern, western and south-western Europe: A review of problems and opportunities for crop production and the environment. *Soil and Tillage Research*, 118: 66–87.

Steinauer, K., Tilman, D., Wragg, P.D., Cesarz, S., Cowles, J.M., Pritsch, K., Reich, P.B., Weisser, W.W. & Eisenhauer, N. 2015. Plant diversity effects on soil microbial functions and enzymes are stronger than warming in a grassland experiment. *Ecology,* 96(1): 99–112.

Tiemann, L.K., Grandy, A.S., Atkinson, E.E., Marin-Spiotta, E. & McDaniel, M.D. 2015. Crop rotational diversity enhances belowground communities and functions in an agroecosystem D. Hooper, ed. *Ecology Letters*, 18(8): 761–771.

Tilman, D., Balzer, C., Hill, J. & Befort, B.L. 2011. Global food demand and the sustainable intensification of agriculture. *Proceedings of the National Academy of Sciences*, 108(50): 20260–20264.

Tilman, D., Fargione, J., Wolff, B., D'antonio, C., Dobson, A., Howarth, R., Schindler, D., Schlesinger, W.H., Sinmerloff, D. & Swackhamer, D. 2001. Forecasting Agriculturally Driven Global Environmental Change. *Science*, 292(5515): 281–284.

Torsvik, V., Øvre\a as, L. & Thingstad, T.F. 2002. Prokaryotic diversity–magnitude, dynamics, and controlling factors. *Science*, 296(5570): 1064–1066.

Van Bruggen, A.H. & Semenov, A.M. 2000. In search of biological indicators for soil health and disease suppression. *Applied Soil Ecology, 15(1): 13–24.*

Wander, M.M. & Bollero, G.A. 1999. Soil Quality Assessment of Tillage Impacts in Illinois. Soil Science Society of America Journal, 63(4): 961–971.

Weil, R.R., Islam, K.., Stine, M.., Gruver, J.. & Samson-Liebig, S.. 2009. Estimating active carbon for soil quality assessment: A simple method for laboratory and field use. *American Journal of Alternative Agriculture*, 18(1): 3–17.

Whalen, J.K., Hu, Q. & Liu, A. 2003. Compost applications increase water-stable aggregates in conventional and no-tillage systems. *Soil Science Society of America Journal*, 67(6): 1842–1847.

Wheeler, T. & von Braun, J. 2013. Climate Change Impacts on Global Food Security. *Science*, 341(6145): 508–513.

Williams, A. & Hedlund, K. 2013. Indicators of soil ecosystem services in conventional and organic arable fields along a gradient of landscape heterogeneity in southern Sweden. *Applied Soil Ecology*, 65: 1–7.

Wortmann, C.S. & Shapiro, C.A. 2008. The effects of manure application on soil aggregation. *Nutrient Cycling in Agroecosystems,* 80(2): 173–180.