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The influence of soil management on soil health: An on-farm study in southern Sweden

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ABSTRACT

Soil health reflects the capacity of a soil to provide ecosystem services. A major challenge of soil management is to support agricultural productivity without jeopardizing other ecosystem services. However, there is relatively little knowledge on how soil management affects soil health in real farm settings. This study investigated the impact of soil management on soil health indicators of 20 farm fields in southern Sweden. In addition, we collected samples from an adjacent unmanaged soil at each field, representing the potential soil health at each site. Soil health was quantified by measuring soil physical and biological indicators: wet aggregate stability, autoclaved-citrate extractable soil protein, organic matter, active carbon and heterotrophic soil respiration. Soil texture and pH were also measured. A soil management index was calculated for each field based on crop diversity, soil tillage, and application of organic amendments. Thereby, a high management index indicated a higher crop diversity, fewer tillage operations, and a higher number of organic amendments. Fields with a higher soil management index showed better soil health, with higher levels of aggregate stability, protein, active carbon, respiration, and organic matter. We found that soil management significantly affected all soil health indicators. Soil health of farm fields was generally poorer in comparison with unmanaged soil. Notably, the ratio of soil health of farm fields to unmanaged soils significantly increased with increasing soil management index. Our study shows that soil management is key for soil health, and that improved soil management comprising crop diversity, omission of tillage, and application of organic amendments promotes soil health.

1. Introduction

Agricultural production is one of the largest contributors of negative environmental impacts on the biosphere (Tilman et al., 2001; Foley, 2005). At the same time, the global population is increasing, accompanied by a predicted future increase in the demand for food, forage and fibres (Tilman et al., 2011; Alexandratos and Bruinsma, 2012; Hunter et al., 2017). Further pressure on global agricultural production is added by climate change, which is predicted to lead to an increase of both temperature and frequency of extreme weather events (Wheeler and von Braun, 2013). Reducing the negative environmental footprint of arable farming while sustaining food production is a major challenge for agriculture.

Soil health (or soil quality) refers to the capacity of soil to function as a living ecosystem that sustains plants, animals, and humans and support ecosystem services including agricultural production (e.g. Karlen et al., 2003; Kibblewhite et al. 2008). Healthy soils provide regulating and supporting ecosystem functions such as nutrient cycling, water infiltration and retention, gas exchange, pest and disease regulation, biodiversity, and storage of carbon, many of which highly impact agricultural productivity (Lowery et al., 1996; Van Bruggen and Semenov, 2000; Torsvik et al., 2002; Lal et al., 2007; Barrios, 2007; Drinkwater et al., 2017). Improving and sustaining soil health is therefore a key aspect of sustainable crop production.

Soil health is assessed using a set of indicators that encompass physical, chemical, and biological soil properties. A suitable indicator must have a strong association to the targeted soil function, be sensitive to soil management, replicable, and relatively inexpensive to analyse (Karlen et al., 2003; Andrews et al., 2004). 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). CASH provides a standardised test of soil health indicators related to land productivity and environmental impact in an agroecosystem context, which can be

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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 (Idowu et al., 2008; Moebius-Clune et al., 2016). Soil health and soil health assessments have 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, knowledge of how soil health can be managed through farming practices is still limited.

Soil management strategies that have been suggested promoting soil health relate primarily to increasing crop diversity, avoiding mechanical soil disturbance, and adding organic amendments (Kibblewhite et al., 2008; Moebius-Clune et al., 2016). There are, however, many options and combinations of specific soil management practices, depending on the context of the farming system. Crop diversity in arable fields can be achieved on a temporal scale (crop rotation) and spatial scale (several plant species at the same time, e.g. a cover crop mixture). Different crop types vary with 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 health (Kuzyakov and Domanski, 2000; Bending et al., 2002; Finney and Kaye, 2017). 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). Several studies have demonstrated positive effects of crop rotation diversification on soil health (Schjønning et al., 2002; Karlen et al., 2006; Congreves et al., 2015). Soil mechanical disturbance by tillage adversely affects soil organisms, and consequently, reduced tillage, in particular no-till, has been shown to improve soil biological properties (Altieri, 1999; Tiemann et al., 2015; Bender et al., 2016; Nunes et al., 2018). Moreover, minimising mechanical disturbance was shown to enhance soil health by improving aggregate stability thereby reducing erosion (Mikha and Rice, 2004; Jiao et al., 2006; Abid and Lal, 2009). However, these positive impacts often come at a cost of decreased yield in no-till systems (Soane et al., 2012). Application of organic amendments was shown to increase soil organic carbon content (Mikha and Rice, 2004; Blair et al. 2006) and aggregate stability (Jiao et al., 2006; Bottinelli et al., 2017), but the effect varies depending on initial content of soil organic matter (Oldfield et al., 2018). While many studies investigate single factors (e.g. crop rotation diversification), the combination of two or more management options (crop diversity, reduced tillage, organic amendments) may potentially have positive effects on soil health that is more than the sum of the single contributions (Kibblewhite et al., 2008).

There are only a few examples of on-farm studies regarding soil management effects on soil health (but see Franco-Vizcaíno, 1996; Wander and 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 amount of confounding factors, tend to be over-simplified in terms of system complexity. 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 (Whalen et al., 2003; Congreves et al., 2015; Alhameid et al., 2017; Nunes et al., 2018). However, commercial farms do often 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.

In this on-farm study, we investigated the impact of soil management practices on soil health in southern Sweden, using selected soil indicators from the established CASH protocol. The farms covered a range of typical soil management practices in the study region, including different levels of crop diversity, tillage and organic amendments. To compare the different management practices across fields, we calculated a soil management index for each field. The specific objectives of the study were to relate soil management to soil health, to quantify the relative sensitivity of the various soil health indicators to soil management and soil texture, and to relate the health of the managed farm-field soils to unmanaged soil.

2. Materials and method

2.1. Study sites

This study was carried out on twenty farms in the region of Skåne, in the south of Sweden (approximately 56N, 13E). The region has a mean annual (1981–2010) temperature of 8 °C and the mean annual (1981–2010) precipitation is 500–750 mm (data obtained from the Swedish Meteorological and Hydrological Institute, SMHI). The farms included both strict cropping enterprises as well as mixed livestock and cropping enterprises. In 2018, ca. 50% of all arable land was grown with cereals, ca. 8% with oilseed crops and 7% with sugar beet, while 21% were ley in Skåne (Swedish Board of Agriculture, http://jordbruksverket.se/swedishboardofagriculture). Farms were selected to represent typical farming systems in the region covering a range of soil management practices in terms of crop diversity, mechanical soil disturbance and application of external organic amendments.

One field (> 3 ha) was selected on each farm in cooperation with the farm manager. All fields were sampled in April 2018. Four fields had a winter crop growing at the time of sampling, while spring crops were planned on the remaining 16 fields (sampling took place before the crops were drilled; Supplementary Table S1). The preceding crop was a cereal on all but two fields (where it was rapeseed or quinoa). Information regarding crop rotation, organic amendment applications, and the general tillage regime (Supplementary Table S1) was collected for each field through interviews with the farm manager.

At each site, an additional sample was taken from an unmanaged soil (size of the unmanged site > 0.03 ha) that was identified adjacent to the field (at least 1 m distance from the field edge, and at least 1 m distance from roads and tracks). Although not pristine and the history was not known at each site, the unmanaged soil served as benchmark for the potential soil health at each site. Unmanaged soil was vegetated with natural grasses and herbs at all locations. Three unmanaged sites had shrubs and trees in addition.

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 CDI included cash crops, cover crops and forage crops. Here, we considered the crop rotation for the past five 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 external organic amendment during the past five years. We defined each index so that a higher index value represents a potentially more “soil health promoting” management, i.e. a higher crop diversity, fewer tillage operations, and a higher number of organic amendments.

The three indices were then aggregated into a soil management index (SMI) for each field. First, each index was normalised 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:

$$SMI_i = \sum \frac{1}{3}\left(\frac{CDI_i}{CDI_{max}} + \frac{YSDI_i}{YSDI_{max}} + \frac{OAI_i}{OAI_{max}}\right) \quad (1)$$

where *CDI* represents crop diversity index, *YSDI* represents years without mechanical soil disturbance, and *OAI* represents applications of organic amendments of the *ith* field and max the maximum measured value within our dataset. Normalisation and additive aggregation of indices is the most common method to build composite indices (e.g. Herzog et al., 2006).

2.3. Soil sampling and measurements

Soil samples were collected in April 2018, at a water content close to field capacity. The samples were taken as a spade slab of 15 cm depth, 10 cm width and 2.5 cm thickness according to the CASH guidelines (Moebius-Clune et al., 2016). At each site, soil was collected from five representative points within the field, and pooled to a composite sample. Samples from unmanaged soil were collected in the same way as samples from the field. All samples were kept in a cooler during transportation, and air-dried at room temperature at the end of each sampling day. The air-dried soil was passed through an 8 mm sieve according to the CASH guidelines (Moebius-Clune et al., 2016), and stored in plastic bags at 4 °C in the dark before analysis. For each field and each unmanaged site, soil texture was determined according to Kettler et al. (2001) and soil pH was measured in a 1:2 soil:deionised water slurry, following the CASH protocol (Moebius-Clune et al., 2016; Schindelbeck et al., 2016).

2.4. Soil health indicators

The soil health indicators included in this study were wet aggregate stability, autoclaved-citrate extractable soil protein, active carbon, heterotrophic soil respiration, and soil organic matter, comprising both soil physical and biological indicators. All these measurements could be done on sieved soil as mentioned above, implying that the measurements are little dependent on the in-situ soil pore structure that could be highly dynamic (Strudley et al., 2008). 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) 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 mm were spread on a 0.25 mm mesh sieve (diameter 200 mm), which was placed 0.5 m below the rainfall simulator. Reverse osmosis water was applied at a constant rate of 2.5 mm min^{-1} for 5 min, resulting in 2.5 J of energy impacting the soil. Aggregate stability was calculated as the percent of aggregates remaining on the sieve, correcting for solid particles > 0.25 mm.

Autoclaved-citrate extractable protein (Prot) is an indicator of organically-bound nitrogen that is easily mineralised by microbes. It was determined by adding 3 g of air-dry soil to an extraction solution of 0.02 M sodium citrate (pH 7). The solution was shaken at 180 rpm for 5 min and thereafter autoclaved at 121 °C at 100 kPa above atmospheric pressure for 30 min. The extract was clarified by centrifuging at 11,000 rpm for 4 min (a minor modification from the CASH protocol). The extract was then 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 (SOM) was analysed by mass loss on ignition at 500 °C for two hours (Nelson and Sommers, 1996). Active carbon (ActC) is a measure of easily-oxidisable organic matter. It was measured as permanganate oxidizable carbon. Approximately 2.5 g of air-dry soil (< 2 mm) was added to 20 ml 0.02 M potassium permanganate ($KMnO_4$) solution (pH 7.2). The extracts were shaken for 2 min at 120 rpm and allowed to settle for 8 min, resulting in 10 min 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 (Resp) is a measure of metabolic activity of the microbial community. Approximately 20 g of soil was weighed into a perforated aluminium weigh-boat and put in a plastic jar on top of two filter papers. A beaker filled with 9 ml 0.5 M KOH was put next to the weigh boat in the jar, serving as CO_2 trap. 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 four days at 23.5 °C. Finally, CO_2 respiration was determined by measuring electrical conductivity in the KOH trap 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.

2.5. Relative soil health index

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

$$RSH_i = \left(\frac{WAS_{if}}{WAS_{iu}} + \frac{Prot_{if}}{Prot_{iu}} + \frac{ActC_{if}}{ActC_{iu}} + \frac{Resp_{if}}{Resp_{iu}} + \frac{SOM_{if}}{SOM_{iu}}\right) \quad (2)$$

As mentioned elsewhere, the unmanaged soil served as reference of the potential soil health at each site. A RSH value of 5 indicates that the soil health of the managed field soil is at the level of the soil health of the unmanaged soil, while a low RSH value indicates a poor soil health of the field soil relative to the potential soil health.

2.6. Data analysis and statistics

Statistical analyses were performed using the R software version 3.5.1 (R Core Team, 2018). The texture triangle illustration was created using the R package “soiltexture” (Moeys, 2018). Differences in soil properties and soil health indicators between field and unmanaged soil were analysed using an analysis of variance (ANOVA). Shapiro-Wilk tests were applied to the residuals of the ANOVA models to check for the assumption of normality. In case the assumption was not met, non-parametric Kruskal-Wallis tests were carried out (Supplementary Tables S2 and S3). 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. Multiple linear regression analysis was used to analyse the influence of the SMI and sand content (sand) on soil health indicators (*y*) according to the following model: $y = a \times SMI + b \times sand + c$. Relative importance analyses were performed with the R package “relaimpo” (Grömping and Lehrkamp, 2015) and used to analyse to what extent soil management and soil texture influenced soil health indicators. The relationship between the SMI and the RSH was analysed using a linear regression. As done for ANOVA models, the residuals of the regression models were checked for normal distribution using Shapiro-Wilk tests (Supplementary Figs. S1 and S2). If residuals were not normally distributed, response variables of the regression models were transformed using the natural logarithm (Supplementary Fig. S2).

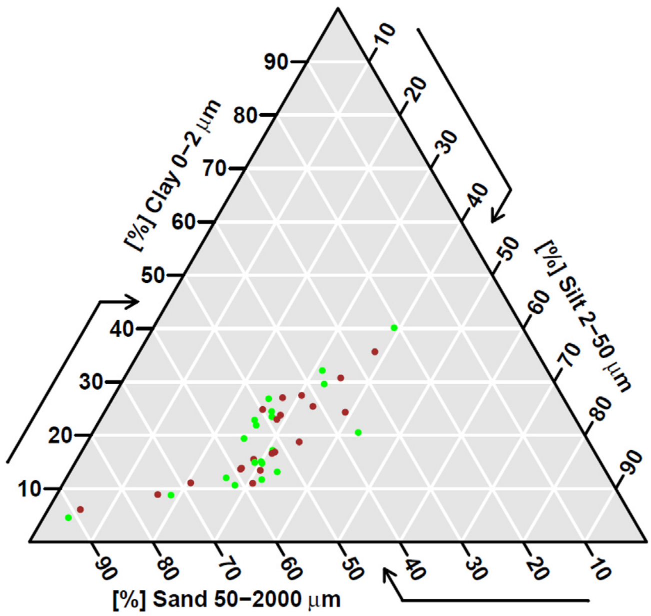

Fig. 1. Soil texture for each sample, displayed in a texture triangle. Brown points represent fields and green points represent unmanaged soil. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

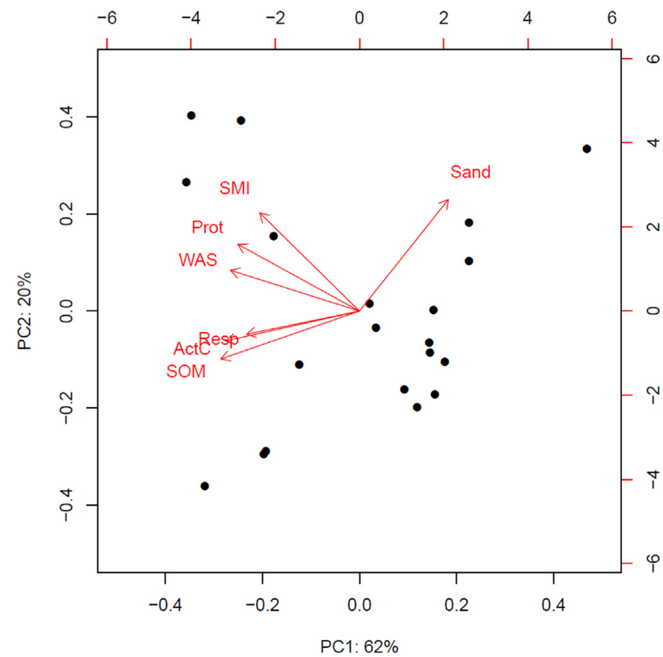

Fig. 2. Biplot obtained from principal components analysis based on the correlation matrix, showing the two first principal components (explaining 62% and 20%, respectively). Each point represents an individual field (n = 20), loadings represent soil health indicators, soil management index and soil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

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 (Fig. 1). Soil pH varied from 5.0 to 8.1. Neither soil texture nor soil pH differed significantly between farm fields and unmanaged soils ($p > 0.5$; Supplementary Table S2). The CDI varied from 2 to 88.8, the OAI was between 0 and 8, and the YSDI ranged from 0 to 3. The SMI ranged from 0.008 to 0.8 (Table 1). We tested different ways of calculating CDI, YSDI and OAI, respectively, but this did not significantly change the SMI or the relationships between soil health indicators and SMI presented in the following sections (not shown).

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 SMI, the sand content and the different soil health indicators (Fig. 2). The first two components explained 82% (first component: 62%; second component: 20%) of the total variance. Farms with a high SMI were associated with high WAS and high Prot (Fig. 2). Farms with a low sand content were associated with high ActC, Resp and SOM. However, high ActC, Resp and SOM were also found for farms with a high SMI. The principal component analysis also indicated that the SMI and the sand content were not related, as seen by the almost perpendicular direction between these two loadings.

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

	CDI	YSDI	OAI	SMI
Maximum	88.8	3	8	0.80
Minimum	2	0	0	0.008
Mean	14.8	0.75	1.4	0.20
Median	7	0	0.5	0.09

All soil health indicators were found to be positively related to the SMI and negatively correlated to the sand content ($p < 0.05$), and the regressions yielded multiple R^2 values between 0.42 and 0.75 (Fig. 3). The contribution of soil management and texture to the different soil health indicators was quantified with help of relative importance analyses, and results of these analyses are presented in Table 2. For WAS, soil management explained 53% of the total variance, while sand content explained 11%. The highest relative importance (55%) of soil management was observed for Prot. Sand content only explained 2% of the total variance in Prot. SOM, ActC and Resp were more sensitive to sand content than WAS and Prot. Nevertheless, soil management explained at least 15% of the variance for any soil health indicator (Table 2). The results show that all soil health indicators were significantly affected by site-specific soil management, but that they were also dependent on soil texture.

3.3. Soil health of field and unmanaged soils

All soil health indicators were significantly different between field and unmanaged samples (Table 3, Supplementary Table S3). On average, the soil health indicators had significantly lower values for field soil compared to unmanaged soil (Table 3). The largest difference between field and unmanaged soil was found for WAS, where the mean of the unmanaged soils was twice as high as the mean of the field soils. The smallest difference between field and unmanaged soils occurred for ActC, where the mean of the field soils had 1.2 times higher concentration than the mean of the unmanaged soils. The ratio of the individual soil health indicators between field and unmanaged soils varied between farms (Fig. 4a). The RSH, based on the ratio of soil health between field soil and unmanaged soil (Eq. (2)), ranged between 2.5 and 5.0 (Fig. 4a). We found a significant positive relationship

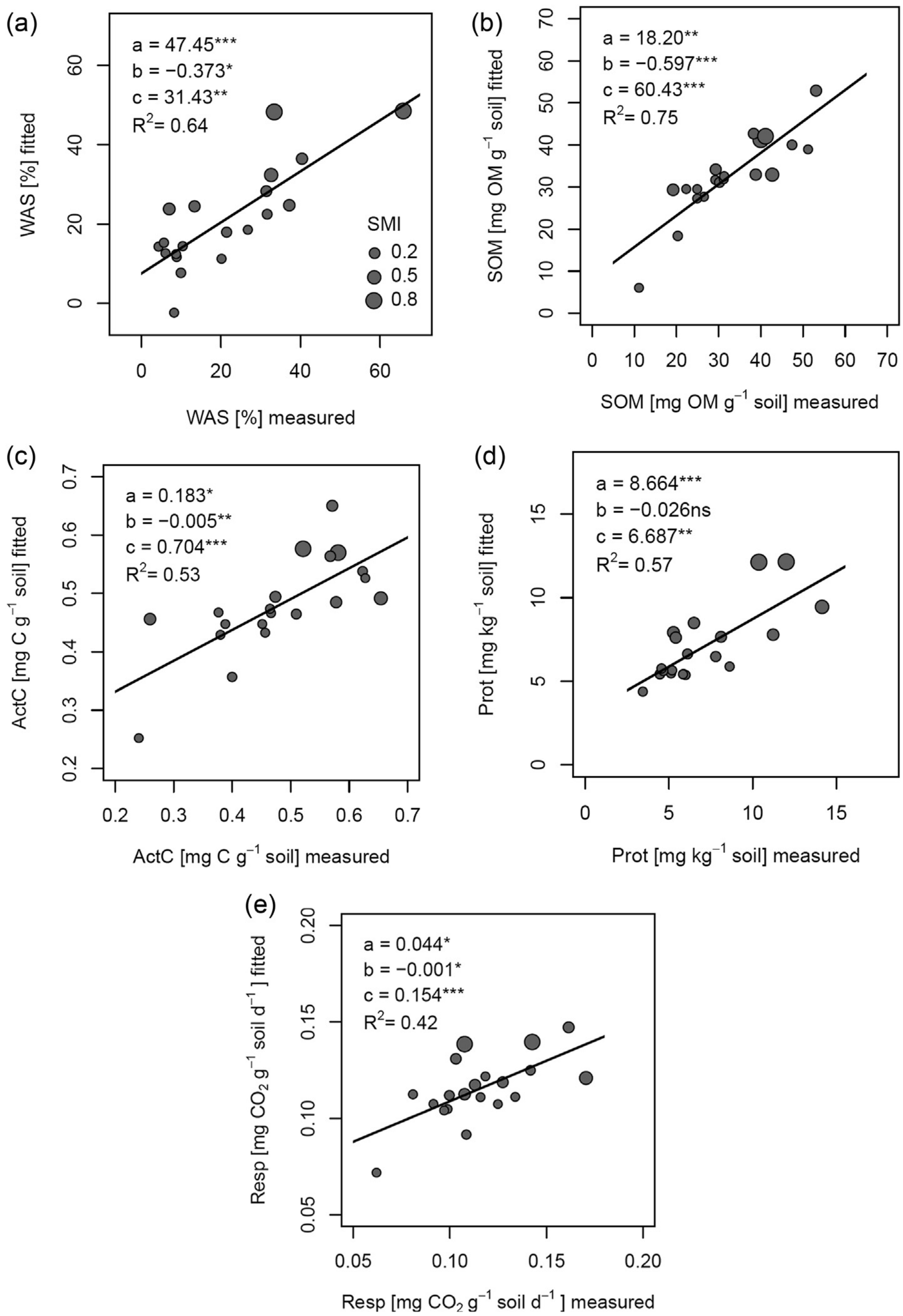

Fig. 3. Multiple linear regression models of the soil health indicators (a) wet aggregate stability (WAS), (b) soil organic matter content (SOM), (c) active carbon (ActC), (d) autoclaved-citrate extractable soil protein (Prot), and (e) heterotrophic soil respiration (Resp). The graphs show the relationship between the measured soil health indicator values and the estimated soil health indicator (y) using the regression model $y = a \times \text{SMI} + b \times \text{sand} + c$, where SMI is the soil management index (Eq. (1)) and sand the sand content (%). *, **, *** indicates significant regression coefficients at $p < 0.05$, $p < 0.01$ and $p < 0.001$, *ns* indicates non-significant regression coefficients. Circle size represents SMI, a larger size represents a higher SMI. R^2 represents multiple R^2.

Table 2
The relative importance of sand content and soil management index (SMI) in the multiple linear regressions shown in Fig. 3, as well as the multiple R^2, i.e. the variance that could be explained by the regression model.

Soil health indicator	SMI (%)	Sand (%)	R^2 (%)
Wet aggregate stability (WSA)	53	11	64
Soil organic matter (SOM)	16	59	75
Active carbon (ActC)	15	38	53
Heterotrophic soil respiration (Resp)	17	25	42
Autoclaved-citrate extractable soil protein (Prot)	55	2	57

between RSH and SMI ($R^2 = 0.34$, $p < 0.01$), indicating that a high SMI improves soil health (Fig. 4b).

4. Discussion

This study was conducted on commercial farms, which enabled us to consider the complexity of cropping systems and soil management decisions that farm managers are faced with. The focus was on the combined effects of crop diversity, avoidance of mechanical soil disturbance and application of organic amendments on soil health, and to what extent soil management influences soil health in relation to unmanaged soil. The on-farm design of the study also made it possible to include a large variation of soil texture in the dataset.

Our study included fields with a diversity of soil management practices in different cropping systems as practiced on commercial farms in southern Sweden. We did not compare different management

Table 3
Mean and standard deviation (SD) for soil health indicators for the 20 farms for field and unmanaged soil 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 according to the analysis of variance.

Soil health indicator	ANOVA	Mean (SD)		
		Field	Unmanaged	Complete dataset
Wet aggregate stability, WAS (%)	***	21.2 (16.0)	43.5 (18.0)	32.3 (20.2)
Soil organic matter content, SOM (g kg^{-1})	*	32.7 (11.2)	41.6 (12.8)	37.1 (12.7)
Active carbon, ActC (mg kg^{-1})	*	479 (1 1 6)	571 (1 0 3)	525 (1 1 7)
Heterotrophic soil respiration, Resp (mg CO_2 (g soil)$^{-1}$ (day)$^{-1}$)	***	0.11 (0.03)	0.19 (0.05)	0.15 (0.05)
Autoclaved-citrate extractable soil protein, Prot (mg g^{-1})	**	7.0 (2.9)	9.9 (3.0)	8.5 (3.2)

categories or single treatments (such as no-till vs. conventional tillage or continuous monoculture vs. crop rotation) as many previous studies on soil health. There are therefore some distinct differences in soil management between our study and previous studies. Farmers in our study region typically adapt tillage from year to year depending on crop, soil conditions, residues and weed pressure. Absence of tillage was also related with certain crops, for example, perennial forage ley in the rotation obviously implies absence of tillage for at least one year. Therefore, mechanical soil disturbance in our study was typical for southern Sweden but higher than in no-till systems. A low crop diversity

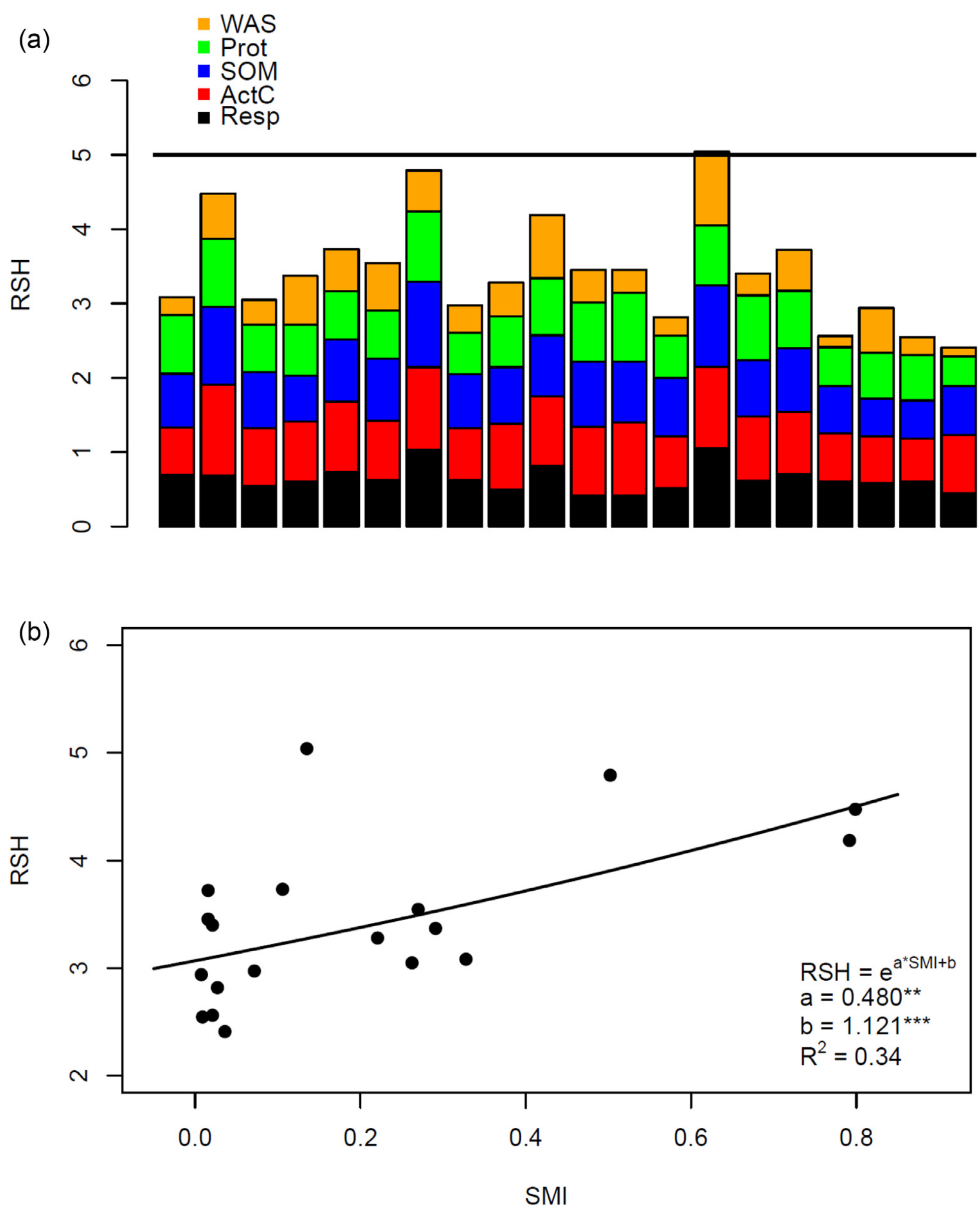

Fig. 4. (a) The different components of the relative soil health indicator (RSH, Eq. (2)) for each farm. The horizontal line (RSH = 5) represents the level of the unmanaged soil. Abbreviations: WAS = wet aggregate stability, Prot = autoclaved-citrate extractable soil protein, SOM = soil organic matter content, ActC = active C, Resp = heterotrophic soil respiration. (b) Relative soil health index (RSH) as a function of soil management index (SMI).

in our study meant 3–4 different crops within five years, which is more diverse than the maize-dominated rotations that are often included as reference in soil health studies carried out in North America. The differences in soil management may explain why our results show slightly different patterns than other soil health studies that are based on plot experiments with contrasting treatments, as will be discussed in the next sections. However, in agreement with previous studies, our results show that soil management significantly affects soil health, and that external organic input, a higher crop diversity and less mechanical soil disturbance enhance soil health.

4.1. The influence of soil management on soil health

Our results demonstrate that all the measured soil health indicators (WAS, Prot, ActC, Resp, and SOM) are affected by soil management (Fig. 3). Fields with a high SMI generally had higher values for all soil health indicators. Soil management significantly affected all soil health indicators, but the sensitivity to soil management varied between the soil health indicators (Table 2). We found the most significant management effects on WAS and Prot (Fig. 3; Table 2). A recent study using the CASH reported the most significant management effect for ActC, Resp and SOM (Nunes et al., 2018). A possible explanation for this discrepancy could be the differences in crop diversity between their and our study. Nunes et al. (2018) compared a continuous maize monoculture vs. continuous maize with interseeded cover crops. The addition of a new crop to a continuous monoculture significantly increases total as well as microbially bound soil organic carbon and nitrogen, while a further increase in crop diversity has little additional effects (McDaniel et al., 2014). None of the sampled fields in our study had a continuous monoculture. 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. Our measurements reflect the state of soil health at the time of sampling, and we can only speculate about the changes in soil health indicators during a crop rotation. For example, labile carbon and hence ActC increase during periods of forage leys, stimulated by increased root exudation of perennial compared with annual plants, and decrease during periods of annual crops (Haynes, 2000; Kuzyakov and Domanski, 2000; Finney and Kaye, 2017). It is therefore possible that ActC levels in our fields were higher during forage leys, but we did not sample in ley.

Root exudates and microorganisms produce soil binding compounds such as proteins and polysaccharides, which improve aggregate stability, while tillage is known to decrease aggregate stability (Bossuyt et al., 2001; Bronick and Lal, 2005). We found a strong effect of soil management on aggregate stability even though the fields were tilled. Apart from the positive impact of crop diversity on WAS stimulated by root exudates, manure application probably contributed to the positive effect of SMI on WAS. Manure has been shown to increase aggregate stability (Jiao et al., 2006; Wortmann and Shapiro, 2008). Manure is also known to increase soil and crop retention of applied nitrogen (Gardner and Drinkwater, 2009), which corroborates with the strong impact of SMI on Prot (Fig. 3). Furthermore, crop diversity is associated with Prot in our study. Fields with a high CDI often included legumes in the crop rotation. Leguminous crops supply the soil with organically bound nitrogen (Drinkwater et al., 2017) and thus increase Prot.

The regression model considering soil management and soil texture could explain as much as 42–75% of the variation in our data for all soil health indicators (Fig. 3; Table 2). Some of the remaining variation is perhaps due to soil management variables that were not included in the SMI. Quantity and type of organic amendments was not included because farmers typically do not know the exact composition or amount of the applied organic amendments. We did not differentiate between different types of tillage (e.g. mouldboard ploughing, chisel ploughing, disc harrowing) or account for tillage depth (e.g. various forms of reduced tillage). This would be difficult to quantify because there is a large variety of different reduced tillage methods and farmers adapt tillage intensity from year to year as mentioned above. However, it would be interesting to evaluate soil health in different soil layers (e.g. top few centimetres, lower topsoil) and including the subsoil in future studies.

4.2. The influence of soil texture on soil health indicators

Soil management significantly affected soil health, however, the soil health indicators were also influenced by soil texture. This study found that WAS and Prot were highly sensitive to soil management. As much as 53% (WAS) and 55% (Prot) of the variance could be explained by SMI (Table 3). Soil texture only accounted for 11% and 2% of the influence on WAS and Prot. ActC and Resp were less sensitive to soil management although the SMI still explained 15% and 17%, respectively, of the variance for these indicators. Soil texture explained 38% and 25% of the variance for ActC and Resp, respectively. For our fields, SOM was strongly controlled by soil texture, with 59% of the variance explained by sand content. Although SOM was less sensitive to soil management than to texture, the SMI still accounted for 16% of the variance.

Soil texture is known to affect soil health indicators (e.g. Nunes et al., 2018). Consequently, the CASH 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). Idowu et al. (2009) and Nunes et al. (2018) report higher levels of ActC, Resp and SOM in fine-textured soils, which is consistent with our results. It is well established that soil organic matter content generally increases with clay content (Oades, 1988). ActC and Resp are closely related to soil organic matter content, which explains the similar trend of ActC, Resp and SOM in relation to soil texture and SMI.

4.3. Soil health of field and unmanaged soil

Our results show that on average, all soil health indicators had significantly lower values for the agriculturally managed field soils compared with the unmanaged soils (Table 3). In this study, we used the unmanaged soil as a benchmark of the potential soil health at each site. Similarly, Wander and Bollero (1999) reported higher values for physical and biological soil health indicators for unmanaged soil in an on-farm study. The enhanced soil health of unmanaged soil compared with arable field soil is likely due to the absence of mechanical soil disturbance and the continuous vegetative cover and living roots in unmanaged soils.

To further explore the difference in soil health between field soil and unmanaged soil, we calculated a relative soil health index, RSH (Eq. (2)). We found that fields with a high SMI generally had a higher RSH, and show that the RSH significantly increases with SMI (Fig. 4b). As described earlier, the SMI was designed so that a higher index value represents a potentially more "soil health promoting management" reflected by a higher crop diversity, fewer tillage operations, and a higher number of organic amendments. Unfortunately, pristine sites (natural forest or grassland) do not exist in close vicinity to our fields, a problem in regions of intensive agriculture such as our study area and potentially similar landscapes in central and northern Europe. Several studies from e.g. Brazil have used soil under natural vegetation as reference, and this adds valuable information (e.g. Araujo et al., 2007; Guimarães et al., 2013; Sivla et al., 2016; Ortiz et al. 2017). The unmanaged sites used as benchmark in this study represented unmanaged but not pristine soil. It is possible that the RSH at each site would have been lower with reference to pristine soil. Importantly, we think it is unlikely that this would have changed the trend of higher RSH with higher SMI shown in Fig. 4b. The poorer soil health of the field soils relative to the unmanaged soils imply that soil physical and biological functions of arable fields in the south of Sweden are impaired to some extent, thereby reducing the provision of soil ecosystem services. The good news is that our results demonstrate that appropriate soil management improves soil health.

The positive relationship between soil health and the SMI found in our study may offer a possibility to develop subsidy schemes to farmers for environmental performance and provision of ecosystem services. Instead of assessing soil health based on field sampling and measurements, which are time-consuming and costly, farmers' performances could be payed based on the farms SMI. The SMI does not classify farms into strict categories (e.g. no-till vs. conventional tillage, organic vs. conventional farming) but considers the actual soil management (e.g. crop rotation, tillage). This is a strength, because soil management within cropping systems can vary considerably (Büchi et al., 2019). However, such an SMI-based subsidy scheme would need to be developed from a larger sample size than in our study, and the SMI might need to be refined by considering additional soil management practices (e.g. residue management, grazing). Moreover, we see a risk that knowledge of the interaction between soil management and soil health is lost when focusing on the SMI only. The strength of the CASH and similar tests is that they help farmers understand how soil management affects different soil health aspects, and guide farmers on how to change soil management to improve soil health.

5. Conclusion

This study investigated the impact of soil management on soil health on 20 farms in southern Sweden. The on-farm study allowed us to consider the range of soil management practices found in real-farm settings and to include variation in soil texture. We defined a soil management index (SMI) based on crop diversity, avoidance of mechanical soil disturbance, and application of organic amendments, such that a higher SMI reflected a higher crop diversity, less mechanical disturbance and higher number of organic amendments applications. The SMI could be refined in future studies by including further management practices (e.g. residue management, grazing). We found that soil health was positively affected by SMI. All measured soil health indicators were significantly influenced by soil management, but by various extents. We found a strong influence of soil management on aggregate stability and autoclaved-citrate extractable soil protein, while soil organic matter content, active carbon and heterotrophic respiration were more strongly influenced by soil texture than by soil management. We report that arable field soils generally have poorer soil health than unmanaged soil. However, the difference in soil health between field and unmanaged soils decreased with increasing SMI, i.e. improved soil management enhances soil health. Our results show that soil management is key to soil health, and suggest that a higher crop diversity, less mechanical soil disturbance and higher organic amendment inputs enhance soil health.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geoderma.2019.114010.

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