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Agricultural practices that enhance soil structure improve crop yields of Swedish farms

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ABSTRACT

Agricultural intensification has increased crop yields but resulted in negative consequences for soil health. Here, we investigated the impact of agricultural practices on soil health and crop yields and their interactions across 67 farmer fields in Sweden. To investigate if those factors could explain differences in crop performance between fields, we asked each farmer to select a “good” field with high and/or stable yield and a contrasting “poor” field. At each field, we measured the soil health indicators: plant available water capacity, penetration resistance, wet aggregate stability, bulk density, cation exchange capacity, pH, soil organic matter content (SOM) and basal respiration. Five-year agricultural management information including tillage, crop rotation, application of organic fertilizers and pesticides, and crop yields were obtained from the farmers. Basal respiration was the most sensitive indicator, positively associated with higher crop diversity, more frequent organic fertilizer use, less frequent fungicide use, and lower tillage intensity. Benefits of less intense tillage on soil health was shown by positive relationships between tillage intensity to aggregate stability and SOM. Soil health indicators could not explain differences in yield between “good” and “poor” fields. However, in the “poor” fields, higher yield was associated with more frequent pesticide use, suggesting larger pest, disease and/or weed problems. In the “good” fields, higher crop yield was not directly related to specific practices but associated with higher aggregate stability and SOM and lower bulk density, highlighting the importance of prioritizing practices that enhance soil structure.

1. Introduction

Soils are a vital natural resource for society and provide many functions and ecosystem services. Soils support crop growth, nutrient cycling, storage and decomposition of organic matter, regulation of water and provide habitat for a plethora of organisms (Powlson et al., 2011; Yang et al., 2020). Soil health is broadly defined as the capacity of soils to perform key functions which support humans, plants, and animals while maintaining or improving environmental quality (Doran and Parkin, 1994). Agricultural intensification practices lead to increased crop yields, yet often at the expense of other ecosystem services (Wachter et al., 2019). In many countries, intensification of agriculture has led to soil degradation (FAO and ITPS, 2015; Kopittke et al., 2019), primarily caused by monocropping, intensive tillage, frequent application of synthetic fertilizers and pesticides, the use of heavy farm equipment, and irrigation (Aćin et al., 2023). This has contributed to acidification, erosion, compaction, chemical pollution or salinization of soils (FAO and ITPS, 2015), which together pose serious risks to the health and long-term productivity of soils (Farooq et al., 2019). Considering that natural processes that can restore soil health are slow and hence restauration may take decades (De et al., 2020; McLauchlan et al., 2006; Rosenzweig et al., 2016), there is a need to identify

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agricultural management that maintain or improve soil health.

Soil health is typically assessed by measuring a set of physical, chemical, and biological soil properties, referred to as "soil health indicators" (Bünemann et al., 2018; Cardoso et al., 2013; Moebius-Clune et al., 2016; Raghavendra et al., 2020). Improved soil health has been associated with increased cropping system diversity and reduced tillage intensity (Balota et al., 2014; Mitchell et al., 2017; Nunes et al., 2018; Wulanningtyas et al., 2021), and with organic farming (Ghabbour et al., 2017; Reeve et al., 2016; van Es and Karlen, 2019; Walder et al., 2023). However, no-till and organic farming generally comes at the cost of reduced crop yields (de la Cruz et al., 2023; Knapp and van der Heijden, 2018; Pittelkow et al., 2015). This shows that there are trade-offs between soil functions. It is therefore important to identify practices that maximise synergies between crop yields and soil health. Since regional context, i.e., pedo-climatic and socio-economic conditions, and conversely, bio-physical limitations and socio-technical barriers, largely influences which management practices can and will be used (e.g., Heller et al., 2024), it is most relevant to study how management practices influence soil health and crop yields in on-farm settings.

To date, most research related to this objective has been performed on experimental field trials comparing single management practices or "categories" such as no-till versus tillage (Nunes et al., 2018; Roper et al., 2017; Sainju et al., 2021), monocropping versus diversified crop rotations (Agomoh et al., 2020; Nouri et al., 2019; Yang et al., 2024), or organic versus conventional practices (Fließbach et al., 2007; Mazzoncini et al., 2010; Suja et al., 2017; van Es and Karlen, 2019). On-farm studies take representative management practices into account, but because practices as well as pedo-climatic conditions vary between farms and across fields, this induces variability, which poses challenges for identifying relationships between agricultural management, soil health and crop yields. Moreover, many farmers change management practices between years to adapt to yearly variations in crops, weather, and pest and weed pressure. Findings from one region do not necessarily apply to other pedo-climatic and agricultural contexts, thus limiting the broader-scale implications that can be drawn from a given study. Many studies on management effects on soil health and crop yields have been carried out in the United States (Crespo et al., 2024; Crookston et al., 2021; Malone et al., 2023; Nouri et al., 2019; Nunes et al., 2018; Roper et al., 2017; Sainju et al., 2021; Svedin et al., 2022; van Es and Karlen, 2019; Wade et al., 2020), while less information is available for other regions and climatic zones. Humid continental and subarctic climates, such as in Scandinavia, are characterised by limited possibilities regarding main and cover crops (Sjulgård et al., 2022), and cold and moist soil conditions that can make no-till challenging (Soane et al., 2012), hence limiting possibilities to enhance soil health. In these regions, the length of the growing season will increase significantly due to climate warming, which will allow growing "new" crops (Eckersten and Kornher, 2012) but bears a risk of more intensive crop production "moving" northwards (Franke et al., 2022; King et al., 2018). It is therefore also crucial that agricultural management practices maintain or enhance soil health to secure food production in these regions.

The overall aims of this study were to evaluate the effects of agricultural management practices on soil health and crop yields and their interactions under on-farm conditions, and to identify if such relationships can explain differences in crop performance between fields. We established a network of farms in two major cropping regions in the south of Sweden, where the farmers were asked to select a "good" and a "poor" field with regard to crop yield level and stability. At these fields, we measured different soil health indicators and we asked the farmers to provide agricultural management data. The specific objectives were to i) assess the influence of tillage intensity, crop species diversity, the use of organic fertilizers and pesticides on biological, physical and chemical soil health indicators, and to ii) identify which management practices and which soil health indicators that favour crop yield and explain differences in crop performance between fields (between "good" and "poor" fields).

2. Materials and methods

2.1. Study sites

The study was carried out in an on-farm network in the Swedish counties Västra Götaland and Östergötland. These regions are two of the most important cropping areas in Sweden. Västra Götaland is the county with most arable land (460,000 ha) and Östergötland the county with the third most arable land in Sweden (200,000 ha) (SCB, 2024a). The farm network included 67 fields belonging to 32 different commercial farms (Fig. 1). The study area spanned 250 km from west to east at a latitude of approximately 58°N. The two counties Västra Götaland and Östergötland were selected because day length, altitude and mean annual temperature are similar in both regions. However, precipitation at this latitude in Sweden decreases from west to east. Mean annual precipitation (1991–2020) was between 611 mm at the location for the field with the lowest mean annual precipitation and 952 mm at the field with the highest. Mean annual temperature varied between the lowest of 6.5 °C and the highest of 7.8 °C at the locations of the fields. Soil textural classes of the 67 agricultural fields were clay (30 %), silty clay (12 %), silty clay loam (16 %), clay loam (33 %), silt loam (2 %), sandy loam (7 %).

In the selected farms, a range of soil management practices, crop rotations and farm systems (e.g., with and without livestock, conventional or organic farming) were represented that are typical for the region. The study included 18 farms in Västra Götaland and 14 farms in Östergötland (Fig. 1). The farms included both conventional (50 fields) and organic management systems (17 fields). Moreover, farms with livestock (20 farms) and without livestock (12 farms) were included.

2.2. Soil sampling and in situ measurements

For *in situ* measurements and soil sampling in 2021, we targeted the cultivation of winter-sown cereals as the cash crop in 2021 to ensure that the conditions at the time of soil sampling were similar across the different fields. In a few cases (n = 11) a crop other than winter wheat (oat, rye, timothy, field bean or winter rape) was grown at the time of sampling. Each farmer selected at least two fields on his or her farm, representing a "good" field with stable and/or high yields, and a "poor" field with unstable and/or lower yields. This may introduce some

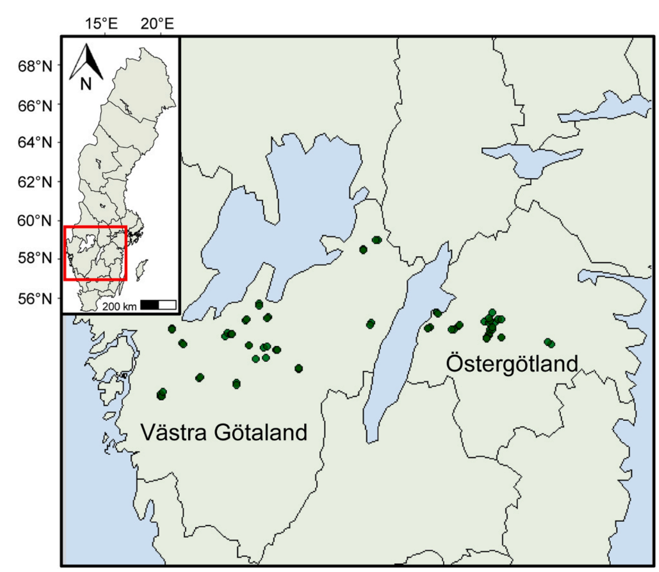

Fig. 1. In the top left corner, a map of Sweden with the location of the study area highlighted. The large map displays the location of the 67 arable fields included in the study in the counties Västra Götaland (to the left) and Östergötland (to the right).

subjectivity (i.e., different evaluations by different farmers), however, the long-term experience and observations of the farmers make the selection of "good" and "poor" a robust selection within each farm. We aimed to determine whether soil health differed between "good" and "poor" fields, and if the soil health indicators could explain differences in crop yield between fields.

Soil samples were collected in all fields between the middle of June and the beginning of July 2021. Soil samples were collected at five locations in each field, arranged in a quincunx pattern with one sampling location in the middle of the field. A total of 335 loose soil samples and undisturbed soil cores (5 cm in height, 7.2 cm inner diameter) were taken in the topsoil. We focused on topsoil because this soil layer is more strongly influenced by management operations compared to subsoil layers. Intact soil core samples were collected at 10–15 cm depth, while loose samples were taken between 0 and 20 cm depth with a spade and then pooled and homogenized for each field. The loose soil was then air-dried and sieved through a 2 mm sieve prior to further analysis. Additionally, *in situ* penetration resistance measurements were conducted between the end of August and the beginning of September 2021, with 15 measurements at each field.

2.3. Soil health indicators

A number of soil health indicators were selected to cover chemical, biological and physical properties that are representative for a range of soil functions (Bagnall et al., 2023; Bünemann et al., 2018; Cardoso et al., 2013; Raghavendra et al., 2020). We determined plant available water capacity, SOM, pH, bulk density, cation exchange capacity, subsoil penetration resistance, soil basal respiration and wet aggregate stability. Chemical and biological indicators were measured on loose soil, while the physical properties were obtained from both loose soil and the soil core samples. Soil texture was determined for each field using the pipette method (Messing et al., 2024) and used as a co-variable in most analyses.

2.3.1. Chemical soil health indicators

Soil pH was determined on dried soil in a 1:5 soil-water suspension. Cation exchange capacity was measured at pH 7, by extracting the soil with 1 M ammonium acetate solution and then titrating with 0.1 M NaOH to pH 7. The base cations were analysed using an inductively coupled plasma-optical emission spectrometer (ICP-OES).

2.3.2. Biological soil health indicators

Soil basal respiration was assessed at a standardized soil moisture (65 % of water holding capacity, WHC) and temperature conditions (20 °C) by measuring CO_2 respired by soil microorganisms using a Respicond respirometer (Respicond IV, Nordgren Innovations, Djäkneboda, Sweden) described in Nordgren (1988). Water holding capacity was estimated by saturating subsamples of loose soil from above for 2 h in funnels with filter paper, draining excess water overnight (samples were covered to avoid water losses through evaporation), and oven-drying the samples at 105 °C for 24 h. Soil samples were weighed before and after, yielding gravimetric water content at water holding capacity.

For the incubation experiment, 20 g of air-dried soil was rewetted to approximately 65 % water holding capacity and then pre-incubated at 20 °C for seven days in 250 ml air-tight jars After the pre-incubation period, the jars were placed in a respirometer with a 0.3 M KOH CO_2 trap for one week. The trapped dissolved CO_2 was continuously measured at one-hour intervals from the electrical conductivity of the solution using platinum electrodes integrated into the respirometer. Near steady-state CO_2 emission rates were achieved after three days. Hence, the last four days of measurements were used in the analyses. The measured CO_2 rates were then subtracted by the average CO_2 rates obtained from empty jars ('blanks') reflecting atmospheric background CO_2. SOM content of the soils was analysed after the incubation period by mass loss on ignition.

2.3.3. Physical soil health indicators

Plant available water capacity was calculated as the difference in soil water content between field capacity and the permanent wilting point. Water content at field capacity was assessed by saturating the intact soil cores slowly from below. After saturation, the samples were equilibrated to −10 kPa on ceramic plates. Soil water content at the permanent wilting point was assessed gravimetrically by equilibrating sieved soil (2 mm) to −1500 kPa on ceramic plates in high-pressure chambers.

Bulk density was determined after drying the soil core samples at 105 °C for 48 h. Wet aggregate stability was measured using a Cornell Sprinkle Infiltrometer (Cornell University, Ithaca, NY) that simulates rainfall. Air-dried soil with aggregates between 0.25 – 2 mm was placed on a mesh sieve under 2.5 J of rainfall energy for five minutes. Wet aggregate stability was calculated as the percentage of aggregates remaining on the sieve, after subtracting the weight of slaked soil and the remaining stones on the sieve (> 0.25 mm) (Moebius-Clune et al., 2016).

Soil penetration resistance was measured *in situ* using a hand-held penetrologger (Royal Eijkelkamp Company, Netherlands) in 1 cm depth intervals to a depth of 40 cm at 15 locations in each field. Because 29 fields were tilled before measuring penetration resistance, we only analysed the subsoil measurements between 20 and 40 cm to remove the influence of tillage. Gravimetric soil moisture content was on average 23 % (standard deviation = 5.4 %) at the time of penetrometer measurements.

2.4. Weather, agricultural management and crop yield data

Daily average temperatures for each field were obtained from the Swedish Meteorological and Hydrological Institute (SMHI), available from the Precipitation Temperature Hydrologiska Byråns Vattenmodell (PTHBV) climate database. The database includes gridded and interpolated weather data with a resolution of 4 km x 4 km (SMHI, 2023). Mean annual temperature was calculated for the reference period between 1991 and 2020 and was obtained for each field based on its centroid coordinates.

Agricultural management data and crop yields were obtained from the farmers. Farmers were asked to provide management data during the five years prior to sampling (i.e., from 2017 to 2021), including information regarding crop rotation, cover crops, tillage method, tillage depth, crop yield, and if they used pesticides and organic fertilizers. Unfortunately, the management data could not be obtained for 18 of the 67 fields. For the fields where the crop data was not available from the farmer, the crop rotation was obtained from field-level data from the Swedish Land Parcel Identification System database, managed by the Swedish Board of Agriculture. For analyses involving other management practices (e.g., tillage, organic fertilization and pesticide use), the 18 fields with missing information were not included in those analyses.

Due to the varying management practices between years and across fields, different management indices were calculated to compare fields. A functional crop diversity index (CDI) was calculated for each field based on the crop rotation and calculated over the five years as:

$$CDI = \left(\sum_{i=1}^{5} CG_i\right) \times \left(\frac{\sum_{i=1}^{5} S_i}{5}\right) \quad (1)$$

where CG is the number of functional crop groups, divided into i) cereals, ii) ley, iii) legumes, iv) potatoes and v) oil seeds, and S is the number of species including cover crops in year i. In leys, the number of crop species was unknown for three conventional fields and in that case the average number of crop species in leys obtained from the other conventional fields was used.

Two indices of agricultural amendments were determined for the period 2017–2021. A pesticide use index was calculated as the average number of pesticide categories (insecticides, herbicides and fungicides) used in each year, and the frequency with organic fertilizer application was assessed.

The soil tillage intensity rating (STIR) was calculated to compare soil disturbance between fields. STIR was developed by the USDA–NRCS (2007), and includes all tillage operations from the last harvest until sowing of the next crop. A higher value of STIR indicates greater disturbance and more frequent soil tillage operations. The soil tillage intensity rating was calculated for each field and year as:

$$STIR = \sum_{i=1}^{n} (TT_i \times 3.25) \times (Speed_i \times 0.5) \times Depth_i \times AD_i \quad (2)$$

where *TT* is the tillage type factor (1.0 for ploughing, 0.8 for mixing and some inversion operations, 0.4 for subsoiler and 0.15 for roller), *AD* is the share of the area disturbed by tillage (a value between zero and one), and where the depth is given in inches and the speed in mph for each individual field operation in year *i*. Where the tillage depth was unknown, the most common depth for the same tillage operation obtained from the other farmers was used. For the speed and disturbed area (*AD*), we used default values included in the RULES2 software developed by USDA–NRCS (2007).

Crop yields were obtained from the farmers, and average crop yields from the years 2017–2021 for the major crops at the county level in Västra Götaland and Östergötland were obtained from Statistics Sweden (SCB, 2024b). Minor crops such as timothy, lucerne and red and white clover are not included in that database, and therefore those crops were not considered for further crop yield analyses (6 cases out of 179). Species composition of leys is not included in the database provided by Statistics Sweden, and therefore, we did not consider leys in our crop yield analyses (20 cases out of 179). For each crop, an average yield per county (Västra Götaland or Östergötland) for each year between 2017 and 2021 was calculated ($\bar{Y}$). Based on this yearly county averages, a relative yield (RY) for each field was calculated as:

$$RY = \frac{\left(\sum_{i=1}^{n} \frac{Yfield_{i,j} - \bar{Y}_{i,j,k}}{\bar{Y}_{i,j,k}} \times 100\% \right)}{n}, \quad n \geq 3 \quad (3)$$

where Y_{field} is the crop yield for a specific field and year, and $\bar{Y}$ is the average county yield, *i* indicates the year, *j* the crop species and *k* the county where the field is located. The relative yield was only used for fields where there was at least three years of crop yield and county yield data combinations available, resulting in 29 fields (out of 67). A positive relative yield implies that a field performed better than the county average, while a negative relative yield indicates a lower yield than the county average.

2.5. Statistical data analysis

Multiple linear regression models were used to test relationships between agricultural management indices, soil health indicators, and relative crop yield, while accounting for differences in climatic conditions and soil texture (Eqs. 4–6). The models used were:

$$SHI = MI + clay + prec + \varepsilon \quad (4)$$

$$RY = SHI + clay + prec + \varepsilon \quad (5)$$

$$RY = MI + clay + prec + \varepsilon \quad (6)$$

where *SHI* represents an individual soil health indicator (i.e. SOM, basal respiration, subsoil penetration resistance, bulk density, pH, wet aggregate stability, cation exchange capacity, or plant available water capacity), *MI* represents an individual management index (i.e., crop diversity index (*CDI*), the frequency of organic fertilizers application (*Org-fert*), soil tillage intensity rating (*STIR*) or the pesticide index (*Pest*)), and *RY* is the relative yield. Clay content (*clay*) and the mean annual precipitation (*prec*) for the reference period 1991–2020 were included as explanatory variables, to account for the textural variability and precipitation among fields. ε is the error term. The long-term average precipitation was used as the climatic factor due to the differences in precipitation between fields (as noted above, mean annual temperature was similar between fields). All variables used in the multiple linear regression models were normalized from zero to one. Sharpiro–Wilks tests were used to check for normality from the multiple linear regression residuals, and if not normally distributed ($p < 0.05$), the response variables were log-transformed.

In addition, Mann-Whitney U tests were used to assess significant differences in soil health indicators between fields with ley in the crop rotation and fields without ley, and for differences in relative yield between categories such as county, the "good" versus "poor" fields, and between organic and conventional cropping systems. Kendall correlation was used to assess the relationship between clay content and each soil health indicator, correlations between individual soil health indicators, and to evaluate relationships between the frequency of pesticide application and basal respiration for each pesticide category. Principal component analyses with scaled variables were used to illustrate differences in management practices between fields. All statistical analyses were conducted using R version 4.2.1 (R Core Team, 2024). The packages used for creating figures and graphs were ggplot2, ggspatial and fmbs and for processing and analysing the data were the packages dplyr, sf and factoextra used (Dunnington et al., 2023; Kassambara and Mundt, 2020; Nakazawa, 2024; Pebesma et al., 2024; Wickham et al., 2024, 2023).

3. Results

3.1. Variation in pedo-climatic conditions, agricultural management practices and crop yields

Soil health indicator values differed between fields (Table S1). We found positive relationships between SOM and wet aggregate stability, and negative relationships between bulk density and SOM and wet aggregate stability, respectively (Figure S1). Clay content was positively correlated with cation exchange capacity and basal respiration (Kendall correlation: $p < 0.001$, $r = 0.6$ and $p < 0.001$, $r = 0.3$ respectively), while plant available water capacity was negatively related to clay content (Kendall correlation: $p < 0.001$, $r = -0.5$; Figure S1).

Management indices varied between fields and indicated a high diversity of agricultural management practices across the relatively small geographical area (Fig. 2, Table S2). Fig. 2 illustrates the different management indices for the individual fields, grouped into "good" and

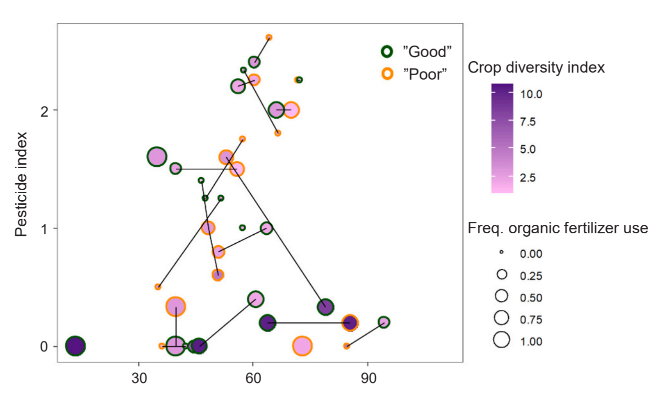

Fig. 2. Scatterplot between soil tillage intensity rating and the pesticide index, colour-coded for crop diversity index, and with the size of symbols corresponding to the frequency of years with organic fertilizer use for the period 2017–2021. The borders of the symbols are colour-coded for "good" and "poor" fields. Lines are drawn between fields belonging to the same farm.

"poor" fields. In the figure, the length of the lines that connect fields of the same farm indicates how similar or different fields are in terms of pesticide application and tillage intensity. With a few exceptions, lines between fields within a farm were shorter than the distance between farms, which means that the management indices were in general more similar between fields of the same farm than across farms. Fields belonging to a certain farm also tended to have similar organic fertilization and crop diversity index, indicated by similar size and colour of symbols in Fig. 2, while this was more heterogeneous between farms. Fig. 2 also illustrates that a higher crop diversity index was related to a lower pesticide index and higher frequency of organic fertilizer application (Kendall correlation: $p = 0.007$, $r = -0.3$ and $p = 0.002$, $r = 0.35$ respectively; Table S3).

We also explored if there were differences in management practices as a function of soil texture, location of the fields, and if they were organic or conventional managed. There were no clear differences in agricultural management practices across soil textures, nor between the two counties Västra Götaland and Östergötland. However, there were differences in management practices between organic and conventional fields (Figure S2). In general, organic fields had a higher crop diversity index and a lower pesticide index, and organic farms used organic fertilizers more often than conventional fields (Table S4), which was expected due to the restrictions in organic agriculture (Bengtsson et al., 2005; Mahanta et al., 2021)., Across all fields, there was no significant difference in any soil health indicator between "good" and "poor" fields (Figure S3). However, the relative crop yield was in general higher in the "good" compared to the "poor" fields, with higher average yields in the "good" fields every year (Fig. 3). The relative yield in the "good" fields was on average 10 %, 52 %, 4 %, 23 % and 8 % higher than in the "poor" fields in 2017, 2018, 2019, 2020 and 2021, respectively. Relative yields were generally higher in conventional fields than in organic fields, with significant differences in the years 2018, 2019 and 2020 ($p = 0.005$, 0.04 and < 0.001 respectively, Figure S4). There was no significant difference in relative yield between the counties Östergötland and Västra Götaland (Figure S4).

3.2. Relationships between soil health indicators and management indices

We found significant relationships between tillage intensity and SOM, soil basal respiration and wet aggregate stability (Table 1). More intensive tillage was related to lower SOM, lower basal respiration, and lower wet aggregate stability. There was also a positive relationship between the frequency of organic fertilizer application and basal respiration. Subsoil penetration resistance (20–40 cm depth), cation exchange capacity, plant available water capacity and bulk density were not significantly correlated with management practices (Table 1). In addition, we found that a higher crop diversity index was related to increased basal respiration (Table 1). Basal respiration was also significantly higher in fields that included ley in the crop rotation than in fields without leys ($p = 0.01$; Figure S3).

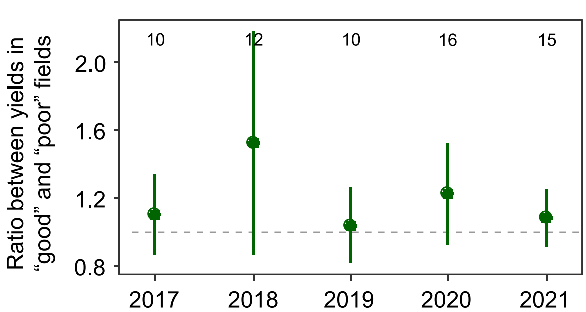

Fig. 3. Mean and standard deviation of relative crop yield (2017–2021) of within-farm differences between fields categorized as "good" and "poor" by farmers. The numbers displayed on top indicate the number of field pairs for the selected year.

Table 1
Multiple linear regression coefficients from assessing relationships between agricultural management indices (soil tillage intensity rating (STIR), frequency of years with organic fertilizer use (Org-fert), crop diversity index (CDI) and the pesticide index (Pest)) and soil health indicators (soil organic matter content (SOM), basal respiration, subsoil penetration resistance (PR), bulk density, pH, wet aggregate stability (WAS), cation exchange capacity (CEC) and plant available water capacity (PAWC)). Regression coefficients for precipitation and soil texture are shown in Table S5. The response variables pH and cation exchange capacity were log-transformed to ensure normal distribution of residuals (Table S5). Variables of significance are denoted as * $p \leq 0.05$, ** $p \leq 0.01$ and *** $p \leq 0.001$.

	STIR	Org-fert	CDI	Pest
SOM [%]	**−0.48*** **	0.16	0.16	−0.07
Basal respiration [mg CO_2-C (g soil)$^{-1}$ day^{-1}]	**−0.37***	**0.42****	**0.44*** **	**−0.37***
Subsoil PR [MPa]	0.12	0.23	−0.15	0.12
Bulk density [g cm^{-3}]	0.05	−0.06	0.06	−0.11
pH	−0.22	0.44	−0.13	0.29
WAS [%]	**−0.52*** **	0.18	0.03	−0.12
CEC [cmol kg^{-1}]	−0.55	0.09	−0.36	0.20
PAWC [%]	0.08	−0.17	0.11	−0.15

The pesticide index (including all types of pesticides) was negatively correlated with basal respiration (Table 1). Assessing pesticide types individually (i.e. herbicides, insecticides and fungicides) revealed that basal respiration significantly decreased with fungicide use ($p = 0.012$; Fig. 4), but no relationship between basal respiration and herbicide use was found. Insecticides were applied only on a few fields for more than one year, and hence it was not possible to assess robust trends between insecticide use and basal respiration.

3.3. Relationships between crop yield, management and soil health

Higher relative yields in "good" fields compared to "poor" fields could not be explained by differences in soil health or by differences in management. Therefore, we did separate analyses for "good" and "poor" fields to investigate whether and which soil health indicators and agricultural management practices could explain yield variations across "good" fields, and which properties that would possibly explain crop yield levels in "poor" fields. Moreover, our analyses revealed that organic fields (two "good" and two "poor" fields) were different from the conventional fields, with lower relative yields (Fig. 3), higher crop diversity index, and lower pesticide index (Fig. 2, Table S4). In addition to analysing organic and conventional fields together, we therefore made a second set of multiple linear regression analyses for the relationships between relative yield and management practices for the conventional fields only.

Tillage intensity and the frequency of organic fertilizer application could not explain relative yield for either the "good" or "poor" fields. However, a higher pesticide index and a lower crop diversity index were associated with higher relative yield in the "poor" fields ($p < 0.05$; Table 2). When organic fields were excluded, i.e., when we analysed conventional fields only, the crop diversity index could no longer explain relative yield. However, there was still a positive relationship between a higher pesticide index and higher relative yield in the "poor" fields.

We found no significant relationship between management indices and relative crop yield in the "good fields" (Table 2). However, crop yields in "good" fields were influenced by soil health. In the "good" fields, a higher relative yield was significantly related to higher SOM and WAS and to lower bulk density. In the "poor" fields, none of the soil health indicators were significantly related to the relative yield (Table 3). Our analyses suggest that different soil health and agricultural management aspects influenced crop yields in the "good" and "poor"

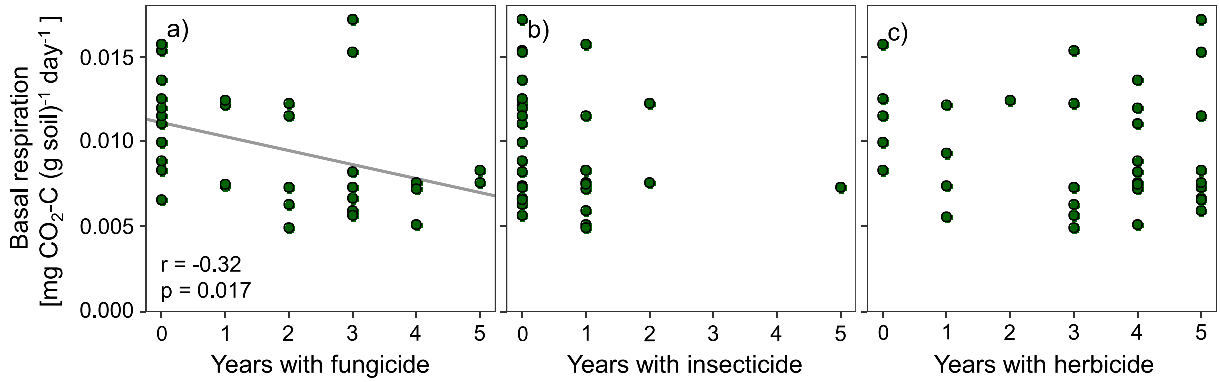

Fig. 4. Scatterplots between basal respiration and the number of years with the use of a) fungicides, b) insecticides and c) herbicides. Kendall correlation coefficient (r), regression line and p-value are given for the significant correlation ($p < 0.05$).

Table 2
Multiple linear regression coefficients from assessing relationships between relative crop yield and management practices (soil tillage intensity rating (STIR), frequency of years with organic fertilizer use (Org-fert), crop diversity index (CDI) and pesticide index (Pest)). Regression coefficients for precipitation and soil texture are shown in Table S6. The relationships were assessed separately for "good" and "poor" fields, either with all fields included or for conventional fields only. Variables of significance are denoted as * $p \leq 0.05$, ** $p \leq 0.01$ and *** $p \leq 0.001$.

	"Good" fields (n = 16)	"Good" fields, only conventional (n = 14)	"Poor" fields (n = 13)	"Poor" fields, only conventional (n = 11)
STIR	−0.37	−0.14	−0.29	0.73
Org-fert	−0.25	−0.24	−0.03	−0.16
CDI	−0.16	−0.17	**−1.26***	−0.71
Pest	0.51	−0.15	**1.20*****	**1.61****

Table 3
Multiple linear regression coefficients from assessing relationships between relative crop yield and soil health indicators (soil organic matter content (SOM), basal respiration, subsoil penetration resistance (PR), bulk density, pH, wet aggregate stability (WAS), cation exchange capacity (CEC) and plant available water capacity (PAWC)) for the "good" (n = 16) and "poor" (n = 13) fields. Regression coefficients for precipitation and soil texture are shown in Table S7. The response variable relative crop yield was log-transformed to ensure normal distribution of residuals in the models with pH and cation exchange capacity for the "good" fields (Table S7). Variables of significance are denoted as * $p \leq 0.05$, ** $p \leq 0.01$ and *** $p \leq 0.001$.

	"Good" fields	"Poor" fields
SOM [%]	**0.82***	0.78
Basal respiration [mg CO_2-C (g soil)$^{-1}$ day^{-1}]	0.13	−0.15
Subsoil PR [MPa]	−0.15	−0.23
Bulk density [g cm^{-3}]	**−0.68***	−0.01
pH	−0.40	0.15
WAS [%]	**1.39****	0.74
CEC [cmol kg^{-1}]	1.07	0.74
PAWC [%]	−0.09	0.36

fields. In "good" fields, crop yield increased with enhanced soil structure, while in "poor" fields, crop yields seemed more limited by weed, disease and/or pest problems.

4. Discussion

4.1. Soil basal respiration is highly sensitive to agricultural management

Basal respiration is an indicator for soil microbial activity widely used in soil health assessments (Cardoso et al., 2013; Mann et al., 2019; Moebius-Clune et al., 2016; Semenov et al., 2025; Williams et al., 2020). Soil microorganisms drive key processes and functions in the soil, such as breaking down organic matter and making nutrients available to plants (Alori et al., 2024; Wang et al., 2024). Basal respiration was the only soil health indicator affected by all agricultural management practices assessed in our study (Table 1 and Figure S3). Organic fertilizers add carbon to the soil, which promotes growth and reproduction of microorganisms (Ge et al., 2010; Naorem et al., 2021). Increased crop species diversity may favour microorganisms due to increased diversity of food resources, such as variations in litter and root exudates (Doornbos et al., 2012; Eisenhauer et al., 2017). Perennial leys in a crop rotation reduce soil disturbance, which, together with the increased inputs of organic matter from leys (Crème et al., 2018; Hu et al., 2024) likely contributed to our finding that a higher SOM was associated with lower tillage intensity (Table 1). Basal respiration was negatively related to tillage intensity, which we attribute to the overall higher SOM in fields with lower soil disturbance. Basal respiration was negatively related to fungicide use (Fig. 4), which aligns with previous studies showing that fungicides can negatively impact non-targeted microorganisms (Baćmaga et al., 2016; Chen et al., 2001; Karpun et al., 2021).

In addition, our results showed higher wet aggregate stability with lower tillage intensity (Table 1), which aligns with earlier studies (Kasper et al., 2009; Rieke et al., 2022; Song et al., 2019). A higher aggregate stability can improve physical protection of SOM inside soil aggregates (Six et al., 2000), and SOM has been shown to be important for the formation and stability of soil aggregates (Karami et al., 2012; Sonsri and Watanabe, 2023). In contrast, intensive tillage results in destruction of macroaggregates, which accelerates the decomposition of SOM and as a long-term result reduces SOM stocks and basal respiration.

The relationships between basal respiration and all management indices show that basal respiration is a sensitive soil health indicator (Table 1 and Figure S3). Soil health indicators should be sensitive to management "by definition" (e.g., Bünemann et al., 2018), as only sensitive soil health indicators are useful to evaluate effects of management practices in a short timeframe. Basal respiration is a measure of microbial activity, and does not reveal information about the microbial community composition or function (Semenov et al., 2025). Microbial communities differ between soils and sites, and different microbial communities (even when resulting in the same basal respiration) could have different site-specific impacts on crop growth (Wang et al., 2024). To better understand the impact of agricultural management practises on the soil microbiome and their influence on crop yield, microbial community and function need to be assessed. Nevertheless, basal respiration measurements might serve as a first useful (and cheap) step to diagnose whether changes in management practices affect soil health.

4.2. Higher crop yield is associated with higher SOM, higher aggregate stability, and lower bulk density

Relative crop yields in the "good" fields were positively related to SOM and wet aggregate stability, and negatively correlated with bulk density (Table 3). Earlier research has demonstrated that well-structured soils with stable aggregates positively influence crop yields. This is largely because good soil structure facilitates the movement of water and nutrients, increase aeration and promote root growth (Amézketa, 1999; Sainju et al., 2022). In contrast, a high bulk density that is indicative of soil compaction negatively affects crop growth by increasing soil mechanical resistance to root growth, reducing water availability and accessibility to crops, and impeding soil aeration (Shah et al., 2017; Shaheb et al., 2021).

A global meta-analysis revealed positive relationships between crop yield and SOM, up to a certain level of SOM (Oldfield et al., 2019). In Sweden, Kätterer and Bolinder (2024) found that higher SOM increased plant available water capacity in a long-term field experiment, suggesting this was the main reason for increased crop yields in soils with higher SOM. In addition, higher SOM has been shown to improve soil aeration (Colombi et al., 2019), and crops can be favoured by slowly-released nutrients that are stored in SOM (Fageria, 2012). This is especially important in cropping systems with low fertilizer input (Lal, 2020; Schjønning et al., 2018). Our findings of higher yields in soils with higher SOM, higher aggregate stability and lower bulk density are therefore likely caused by the known positive effects of good and stable soil structure and availability and accessibility of sufficient nutrients on crop performance.

4.3. Differences in yield between "good" and "poor" fields could not be explained by soil health

Soil health indicators assessed in this study could not explain differences between "good" and "poor" fields (Figure S3). As in any soil health assessment, the number of indicators in our study was limited, and hence additional soil properties might potentially explain differences in crop yield between "good" and "poor" fields, such as microbial community structure (Chen et al., 2024; Upadhyay et al., 2024; Xing et al., 2025), nutrient levels (Guto et al., 2012; Mann et al., 2019; Sainju et al., 2021), soil depth (Calviño et al., 2003; SGU, 2021) and subsoil properties (Dang et al., 2006). Other factors, aside from soil properties, could also contribute to differences in yield between "good" and "poor" fields, such as differences in topography that in turn influences the field hydrology (Quinn et al., 1991), drainage (Mourtzinis et al., 2021), or pests, diseases and weed problems (Strand, 2000). Indeed, a previous study assessing differences between farmer-identified "good" and "poor" fields found that farmers often attributed the "poor" fields with disease problems and poor field drainage (O'Neill et al., 2021). Aligned with this, we found that a higher pesticide use index was related to higher relative crop yields in the "poor" fields (Table 2). This suggests that weeds, pests and/or diseases could be a larger problem in the "poor" than in the "good" fields. We therefore advise to also include further factors, such as pests, weeds, diseases, drainage and field topography in further assessments of relationships between management practices, soil health and crop yield.

The non-significant relationships between management indices and relative crop yields in the "good" fields (Table 2) could result from the large variation in management practices between years and across farms, which is typical for on-farm studies (Dupla et al., 2022; Malone et al., 2023; Tu et al., 2021). Many farmers adapt agricultural management practices from year to year and make management decisions during the growing season, depending on the crop, the preceding season's crop, weather conditions, weed, disease and pest pressure, and more (Anderson et al., 2020; Robert et al., 2016). Therefore, a high relative yield may not necessarily be related to a specific management practice but to the best year-to-year adapted practices for a particular field. Based on the findings that higher crop yield was associated with higher wet aggregate stability, higher SOM and lower bulk density in the "good" fields, our results demonstrate the importance of prioritizing management practices that – within the local site-specific context of each field – improve these soil properties.

5. Conclusions

Our on-farm study revealed associations between soil health indicators, agricultural management practices and crop yields in Sweden. Basal respiration was found to be positively related with higher crop diversity, more frequent organic fertilizer use, less frequent fungicide use and lower tillage intensity, indicating that basal respiration is a sensitive soil health indicator. In addition, wet aggregate stability and SOM were positively related to lower tillage intensity, showing benefits of reduced tillage on soil health. The measured soil health indicators could not explain yield differences between "poor" and "good" fields, nor could they explain yield differences among the "poor" fields. Yet we found that a higher pesticide index was related to higher relative yield in the "poor" fields, suggesting that weeds, pests and/or diseases may have been a larger problem in these fields. This demonstrates that other factors than the soil properties and management practices assessed here contribute to the lower field performance in those fields relative to the "good" fields, and further investigations are needed to identify the limiting factors in the "poor" fields. We therefore advise future assessments to also include other factors such as pest, weeds, diseases, drainage, or field topography when assessing relationships between soil health, management practices and crop yield. In the fields identified by farmers as "good", higher crop yield was related to higher SOM, higher wet aggregate stability and lower bulk density, illustrating the importance of soil structure for crop production. However, the yield was not related to management practices in those fields, probably because many of the farmers adjust their practices from year to year to prevailing soil and crop condition. To enhance soil health and in turn crop yield, farmers should adjust practices suited to their local context that promote higher SOM, aggregate stability and lower bulk density.

CRediT authorship contribution statement

Tino Colombi: Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Sjulgard Hanna:** Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Elsa Coucheney:** Writing – review & editing, Supervision, Methodology. **Gina Garland:** Writing – review & editing, Supervision, Methodology. **Thomas Keller:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

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. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2025.127812.

Data availability

The data that has been used is confidential.

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