Journal of Sustainable Agriculture and Environment

Global Initiative of
Sustainable Agriculture and Environment
Harnessing Natural Resources

RESEARCH ARTICLE OPEN ACCESS

Compost Application Enhances Soil Health and Maintains Crop Yield: Insights From 56 Farmer-Managed Arable Fields

Anna Edlinger[1,2,3] | Chantal Herzog[1,2] | Gina Garland[1,4] | Florian Walder[1,4] | Samiran Banerjee[1] | Sonja G. Keel[5] | Jochen Mayer[6] | Laurent Philippot[7] | Sana Romdhane[7] | Marcus Schiedung[8] | Michael W. I. Schmidt[8] | Benjamin Seitz[1] | Chloé Wüst-Galley[5] | Marcel G. A. van der Heijden[1,2]

[1]Plant-Soil Interactions Group, Agroscope, Zurich, Switzerland | [2]Department of Plant and Microbial Biology, University of Zurich, Zurich, Switzerland | [3]Wageningen Environmental Research, Wageningen University & Research, Wageningen, Netherlands | [4]Soil Quality and Use Group, Agroscope, Zurich, Switzerland | [5]Climate and Agriculture Group, Agroscope, Zurich, Switzerland | [6]Nutrient Flows Group, Agroscope, Zurich, Switzerland | [7]Université Bourgogne Franche-Comté, INRAE, Institut Agro, Agroécologie, Dijon, France | [8]Department of Geography, University of Zurich, Zurich, Switzerland

Correspondence: Anna Edlinger (anna.edlinger@wur.nl) | Marcel G. A. van der Heijden (marcel.vanderheijden@botinst.uzh.ch)

Received: 30 October 2024 | **Revised:** 17 December 2024 | **Accepted:** 18 December 2024

Funding: This study was supported by Stiftung Mercator Schweiz (grant 31BD30-1724662) and Schweizerischer Nationalfonds zur Förderung der Wissenschaftlichen Forschung (31003A_166079), awarded to Marcel G. A. van der Heijden.

Keywords: compost | crop cover | management system | soil health | solid digestate

ABSTRACT

Introduction: Improving soil health while maintaining crop yield is a key challenge for farmers. So far, only a few studies assessed the effects of compost and solid digestate application on soil health and plant yield under practical on-farm conditions across both organic and conventional cropping systems.

Materials and Methods: This study examined 56 arable fields in Switzerland, managed either conventionally ($n = 39$) or organically ($n = 17$) by individual farmers. Fields were categorised based on their fertilisation history: standard fertilisation ($n = 21$), including livestock manure, slurry, and mineral fertilisers (reference), or with additional compost ($n = 26$) or solid digestate ($n = 9$) amendments. Soil health was assessed based on eight chemical, biological, and physical soil health indicators.

Results: Compost use, but not solid digestate use, was associated with enhanced average soil health (+ 31% over reference fields), driven by increases in basal respiration (+ 45%), cation exchange capacity (+ 42%), fungal richness (+ 18%), and marginally higher soil organic carbon stocks (+ 28%). These differences were consistent across management systems, despite site variability. Clay content and extended periods of crop cover also positively influenced soil health. Wheat yields were 21% lower under organic management but unaffected by compost or digestate use.

Conclusion: These findings suggest that using compost alongside practices like extended periods of crop cover can effectively promote soil health while maintaining yields in practical farming scenarios, offering a means to balance multiple sustainability goals simultaneously.

Joint first authors in alphabetical order; Anna Edlinger and Chantal Herzog contributed equally to the study.

1 | Introduction

Intensive agricultural land use has led to significant soil degradation across Europe, including soil erosion, biodiversity loss, decreased soil organic carbon (SOC), and an overall decline in soil health (Panagos et al. 2024; Tsiafouli et al. 2015). Finding ways to maintain or improve soil health without compromising yields is a central goal for farmers, scientists and policymakers.

Soil health, used here synonymously with soil quality, is defined as the continued capacity of soils to function as a living ecosystem that sustains plants, animals and humans (Lehmann et al. 2020). Numerous studies have shown that healthy soils generally positively impact plant yield, disease suppression and overall system performance (Banerjee and van der Heijden 2023; Qiao et al. 2022; Romero et al. 2024). Commonly assessed indicators of soil health include soil structure, nutrient contents and SOC, as they relate to critical functions such as carbon sequestration, nutrient cycling and primary production (Bünemann et al. 2018). Biological aspects of soil health, however, remain underexplored and are often limited to general metrics like microbial biomass or respiration (Bünemann et al. 2018). Additionally considering metrics like species richness is crucial for assessing a soil's ability to provide habitat, especially given that the majority of the Earth's biodiversity can be found belowground (Anthony, Bender, and van der Heijden 2023).

Organic fertilisation is a common strategy to improve both soil health and crop yield (Diacono and Montemurro 2010). Controlled field experiments have shown that bulky organic soil amendments that have undergone pre-processing like composting (e.g., green waste composts) or anaerobic digestion (e.g., solid digestates from biogas plants) can positively affect SOC compared to sole mineral fertilisation (Fuchs et al. 2008; Zhao et al. 2022). In addition to improving soil health, studies have shown that these amendments can increase crop yields by enhancing nutrient availability and improving soil structure, which supports root growth and water retention (Diacono and Montemurro 2010; Möller and Müller 2012). However, in practice, fertilisation strategies typically combine soil amendments (compost or digestates) with other mineral or organic fertilisers (slurry, manure, liquid digestates). Furthermore, amendments can be applied at variable rates and qualities, and in combination with a range of management practices (tillage, crop rotation, management systems etc.) across different soil types. Given the potential variability and numerous interacting factors, it remains unclear whether compost and digestate amendments can evidently improve soil health and crop yields under practical on-farm conditions. Notably, studies assessing the effects of compost application have often been limited to conventionally managed fields, and there is a lack of systematic research comparing compost applications in both organic and conventional farming systems. This is important because the benefits of compost application in organically managed fields may not mirror those in conventional fields due to differing baseline SOC levels and practices that already enhance soil health (Mäder et al. 2002).

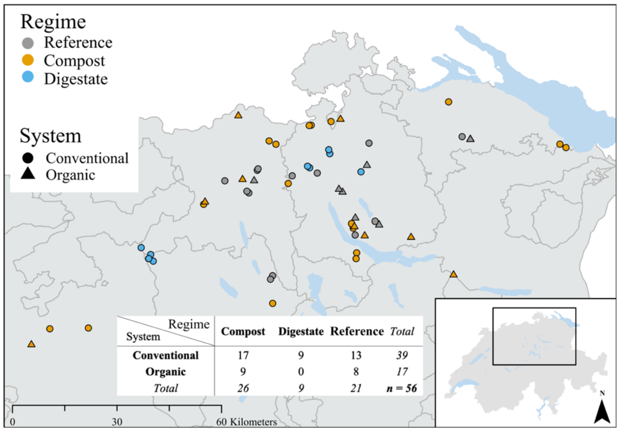
To address these uncertainties, this study aims to investigate: (1) whether the application of compost and solid digestate by farmers enhances soil health in arable fields, (2) whether similar effects are observed in both organic and conventional systems, (3) whether cereal yields are affected by these soil amendments and (4) how the effects of these amendments compare to other factors influencing soil health and yield, including management practices and environmental context. To answer these questions, we examined soil health and wheat yields across 56 Swiss arable fields, each uniquely managed by individual farmers with varying histories of organic amendment use. This approach provided a snapshot of how management history and environmental context interact to shape soil health and crop yields (Garland et al. 2021; Walder et al. 2023). We hypothesised that fields amended with compost and solid digestate in the past would exhibit higher soil health, with the effects on specific aspects of soil health (i.e., biological, chemical and physical) differing due to the distinct characteristics of these amendments. Additionally, we hypothesised that both amendments would help maintain or increase crop yields, thereby supporting a balance between crop production and soil health.

2 | Materials and Methods

2.1 | Field Sites and Management Systems

An observational study was conducted in 2017, investigating soil health and crop yield in 56 farmer-managed arable fields across the Swiss Midland (Figure 1). The region is characterised by a temperate climate, with a mean annual temperature of 9°C and a mean annual precipitation of 1159 mm (Table 1). All fields were rain-fed.

The selected sites included 39 conventionally and 17 organically managed fields, with organic fields differing from conventional ones by not being treated with synthetic pesticides and mineral fertilisers (Table 1). For comparability, fields were included when cultivated with winter wheat (*Triticum aestivum*) and subjected to tilling. Fields were considered in the study when compost or solid digestates had been applied at least twice in the decade before sampling (2008–2017), with the most recent



Regime / System	**Compost**	**Digestate**	**Reference**	*Total*
Conventional	17	9	13	*39*
Organic	9	0	8	*17*
Total	*26*	*9*	*21*	***n = 56***

FIGURE 1 | Map of Switzerland showing the 56 study sites across the Swiss Midland. Each site was assigned to one of five management groups based on the organic amendment regime and management system. [Source: FSO, Swisstopo (2020)].

TABLE 1 | Management practices and environmental conditions across arable fields categorised by compost (CO), solid digestate (SD) or neither of the two amendments (reference, R) under conventional (conv.) or organic (org.) management. The table captures the natural variability in individual farmer practices within these categories. Values are reported as means with standard deviations in parentheses.

	CO-conv. ($n = 17$)	CO-org. ($n = 9$)	SD-conv. ($n = 9$)	R-conv. ($n = 13$)	R-org. ($n = 8$)
Total org. fertiliser C input (Mg ha^{-1})[a]	11.2 (5.2)	9.6 (6.8)	9.1 (2.8)	7.3 (2.8)	5 (1.8)
Sum CO C input (Mg ha^{-1})[a]	7.3 (4.4)	6.4 (6.3)	0 (0)	0 (0)	0 (0)
Sum SD C input (Mg ha^{-1})[a]	0 (0)	0 (0)	6 (3.3)	0 (0)	0 (0)
Sum other fertiliser C inputs (Mg ha^{-1})[a]	3.8 (4.5)	3.2 (2.1)	3.1 (1.6)	7.3 (2.8)	5 (1.8)
Time since last CO or SD use (yr)[b]	1.2 (0.9)	1.3 (1)	0.8 (0.2)	—	—
Available N applied (kg ha^{-1})[c]	136 (40.9)	79.2 (35)	165 (36.2)	183 (45.2)	120 (122)
Available P applied (kg ha^{-1})[c]	61.2 (78.5)	104 (73.5)	56.2 (51.5)	80 (49.6)	125 (158)
Crop cover during crop rotation (%)[a]	94.1 (6.9)	97.8 (3.1)	93.7 (4.4)	93.4 (6.3)	96.4 (3.8)
Leys in crop rotation (%)[a]	16.8 (30.3)	30.9 (23.9)	11.5 (18.1)	32.3 (29.7)	36.8 (30.4)
No. of tillage events[c]	1.9 (0.3)	2 (0)	1.8 (0.4)	1.9 (0.3)	2 (0.5)
Max. tillage depth (cm)[c]	18.4 (5.3)	20.1 (4.9)	18.2 (4.7)	15 (3.3)	17.8 (4.9)
Fungicide application events[c]	0.8 (1)	0 (0)	1.1 (0.9)	1 (0.9)	0 (0)
Herbicide application events[c]	1.7 (0.5)	0 (0)	1.1 (0.3)	1.2 (0.4)	0 (0)
Insecticide application events[c]	0.2 (0.4)	0 (0)	0.1 (0.3)	0.2 (0.4)	0 (0)
pH[c]	7.3 (0.3)	7.3 (0.5)	7 (0.6)	7.1 (0.4)	7 (0.5)
Sand (%)[c]	35.9 (12.8)	35.7 (11.6)	40.8 (10.7)	37.6 (13)	35.4 (10.5)
Silt (%)[c]	37.4 (8.6)	33.3 (3.9)	36.3 (9)	38.5 (9)	36.5 (4.3)
Clay (%)[c]	22.7 (7.8)	26.7 (8.6)	19.9 (4.8)	20.7 (8)	24.8 (9.3)
Mean annual temperature (°C)[d]	8.9 (0.3)	8.8 (0.6)	9.1 (0.1)	9 (0.2)	9.1 (0.2)
Mean annual precipitation (mm)[d]	1141 (122)	1202 (147)	1159 (72)	1180 (111)	1114 (103)
Altitude (masl)	487.7 (92.9)	492.6 (129.3)	497.2 (48.6)	468 (55)	521 (94.3)

[a] Assessed over the five years before sampling.
[b] Missing fertilisation dates for 17 fields, replaced by the mean of the given months/years.
[c] Assessed in the year before sampling.
[d] 1970–2000 averages extracted from the Worldclim database (Fick and Hijmans 2017).

application between 2013 and 2017, alongside other fertilisers. Both organic and conventional fields received organic fertilisers, such as manure, slurry, and liquid digestate (Table 1; Supporting Information S1: Figure A1), representing the Swiss standard fertilisation practice as a reference.

To test whether amendments of compost and solid digestate influenced soil health and crop yields compared to the standard fertilisation regime, fields were divided into ones that received compost (from green waste), solid digestates (the solid fraction after solid-liquid separation of fermented biogenic waste from households, food production, gardens, or green areas) or reference fields, receiving neither compost or digestates. Furthermore, we differentiated between organic and conventional management (with the solid digestate group including only conventional fields, as its use is uncommon in organic farming), resulting in five groups: (1) conventional fields with compost amendments ($n = 17$), (2) conventional fields with solid digestate amendments ($n = 9$), 3) conventional reference fields without compost or solid digestate amendments ($n = 13$), (4) organic fields with compost amendments ($n = 9$), and (5) organic reference fields without compost or solid digestate amendments ($n = 8$) (Figure 1).

2.2 | Crop Management

The variety of management practices implemented by farmers is a major source of variability in soil health and crop yields in on-farm studies (Walder et al. 2023). To capture this, participating farmers were asked to complete a questionnaire detailing the management history of their fields over the past 5 years (Table 1). The questionnaires drafted in the German language can be found in Supporting Information S2. The data collected were used to estimate carbon inputs from organic fertilisers and crop residues, the proportion of crop cover and leys in the crop rotation, and to calculate a management intensity index, as described in detail in Supporting Information S1 (pages 2–7).

2.3 | Soil and Wheat Sampling

Soil sampling occurred from mid-May to mid-July 2017. Samples were collected within a 10 m radius of a GPS reference point, at least 15 m from field borders (Supporting Information S1: Figure A3). A composite of six soil cores (3 cm diameter) was divided into 0–20 cm (topsoil) and 20–40 cm (subsoil). Subsamples of topsoil were sieved to 2 mm and stored at −20°C for molecular analysis. For physicochemical measurements, samples were sieved to 2 mm, dried at 40°C for 48 h, and a subsample was ground for elemental analysis. Bulk density was estimated from four undisturbed cylinder samples (100 cm^3) at 10 and 30 cm depths. Soil aggregate stability and basal respiration were assessed from four undisturbed samples taken to 20 cm using a Humax soil corer (5 cm diameter) and stored at 5°C.

In mid-July 2017, wheat biomass was collected by relocating the GPS points and sampling four randomly selected areas within the same radius using a 50 × 50 cm quadrat. Yield samples were dried at 40°C for 24 h, threshed, and weighed. Wheat yield was averaged across the four replicates per site. To standardise measurements and ensure comparability, grain moisture content was adjusted to 9%, which corresponds to the equilibrium moisture content under the environmental conditions at the time of assessment and aligns with levels safe for long-term storage (Magan et al. 2010).

2.4 | Soil Analyses

2.4.1 | Physicochemical and Microbial Activity

Soil texture, calcium carbonate ($CaCO_3$), potential cation exchange capacity (CEC), total nitrogen (N), available phosphorus (P) and potassium (K), pH, SOC were measured using Swiss standard protocols (Swiss federal research stations 1996). Soil basal respiration (microbial respiration) was analysed by measuring CO_2 released over 72 h in pre-incubated samples (Swiss Federal Research Stations 1996). Soils (equivalent to 20 g dry soil) were pre-incubated at 22°C and 50% water holding capacity for 7 days to stabilise microbial communities. During the 72-h incubation, CO_2 was trapped in a 0.025 N NaOH solution, and CO_2 concentration was determined by titrating the alkali with 0.025 N HCl. Basal respiration was calculated based on the amount of HCl used, with 22 mg CO_2 corresponding to 1 mL of 1 M HCl (Swiss federal research stations 1996; Jäggi 1976; Isermeyer 1952). More information on the used methods can be found in Supporting Information S1 (pages 8–9).

Soil aggregation was estimated using a wet sieving method on 8 mm sieved soils, separating large macroaggregates (> 2000 µm), small macroaggregates (250–2000 µm), free microaggregates (53–250 µm) and a free silt and clay fraction (< 53 µm), and correcting for aggregate-sized sand to reduce variation due to differences in soil textures (Six et al. 1998; van Bavel 1950). The mean weight diameter (MWD), a commonly used index to describe the stability of soil, was calculated using the following formula:

$$MWD = \sum_i S_i P_i \tag{1}$$

where S_i is the average diameter (µm) of the i^{th} fraction (i.e., macroaggregate, microaggregate, etc.) and P_i is the proportion of the soil present in this fraction.

2.4.2 | Microbial Richness

Bacterial and fungal richness was assessed as described in Garland et al. (Garland et al. 2021). In brief, DNA was extracted from 250 mg soil of each sample using the DNeasy PowerSoil-htp 96 well DNA isolation kit (Qiagen, France). A high-throughput sequencing approach was employed to characterise bacterial and fungal communities (Berry et al. 2011; Banerjee et al. 2019). The V3-V4 region of the bacterial 16S rRNA gene was amplified using primers 341 F (CCTACGGGNGGCWGCAG) and 805 R (GACTACHVG GGTATCTAATCC), and the fungal ITS region was amplified using primers ITS1F (CTTGGTCATTTAGAGGAAGTAA) and ITS4 (TCCTCCGCTTATTGATATGC). Sequences of bacterial 16S rRNA genes were generated using a MiSeq platform while the fungal ITS region was sequenced using the PacBio SMRT Sequencing platform (Pacific Biosciences, CA). Sequences were quality filtered (GC range 30%–70%, minimum mean quality score 20) and clustered into operational taxonomic units (OTUs) based on 97% similarity. Taxonomic assignments were made using the SILVA v128 database for bacteria (Pruesse et al. 2007) and the UNITE v7.2 database for fungi (Kõljalg et al. 2005). Bacterial and fungal richness were calculated based on rarefied OTU tables (11,000 and 2000 sequences per sample, respectively). More information can be found in the Supporting Information S1 (pages 9–10).

2.4.3 | Bulk Density and SOC Stock Calculation

To estimate the bulk density of the fine soil ($BD_{\text{fine soil}}$ [g cm^{-3}]), the cylinder samples ($\text{volume}_{\text{sample}} = 100\ \text{cm}^3$) were dried for 24 h at 105°C to obtain the dry weight ($\text{mass}_{\text{sample}}$ [g]). Afterwards, the samples were washed through a 2 mm sieve to determine the weight of rock fragments which were > 2 mm ($\text{mass}_{\text{rock fragments}}$ [g]). The $BD_{\text{fine soil}}$ was calculated by correcting for rock fragments accordingly:

$$BD_{\text{fine soil}} = \frac{mass_{\text{sample}} - mass_{\text{rock fragments}}}{volume_{\text{sample}} - \frac{mass_{\text{rock framgents}}}{\rho_{\text{rock fragments}}}} \tag{2}$$

The median mass of samples and rock fragments over the four-cylinder replicates was used and a density of 2.65 g cm^{-3} was assumed for the rocks fragments. The bulk density of one site could not be determined due to very high rock content, and this site was excluded from further analysis.

Soil carbon stock refers to the mass of SOC per unit area for a specified depth (Lee et al. 2009). On average, organic sites exhibited lower bulk densities than conventional sites in the topsoil, particularly in the control groups without compost or solid digestate (Supporting Information S1: Figure A4). To account for variations in bulk density and ensure a fair comparison of SOC stocks across sampled fields, we applied the minimum equivalent soil mass (minESM) approach (Swiss federal research stations 1996). Six samples showed either very low fine soil bulk densities (minimum = 0.68 g cm^{-3}) and/or a high rock fragment fraction (maximum = 46%), resulting in small total fine soil masses (Supporting Information S1: Figure A5). Therefore, the reference soil mass for the minESM calculation was determined using the remaining samples. Further details and formulas are provided in Supporting Information S1 (pages 10–11).

2.5 | Soil Health Indicators and Index

To evaluate physical, chemical and biological soil health we selected eight indicators: SOC stocks, aggregate stability, bulk density, fungal richness, bacterial richness, basal respiration, CEC and nutrient availability (average z-score of available P, K, and total N). All indicators were measured in the topsoil (0–20 cm), except SOC stocks, where subsoil was also included. A soil health index (SHI) was calculated to consider the interconnectedness of these parameters, following approaches commonly used in soil multifunctionality and health studies (Garland et al. 2021; Walder et al. 2023; Romero et al. 2024). The SHI was calculated by averaging the normalised z-scores of all soil indicators (Bünemann et al. 2018), with bulk density multiplied by −1. Although basal respiration indicates CO_2 emissions, it represents active microbial communities essential for soil functions such as nutrient cycling and is indicative of a soil's habitat function. Therefore, it was considered a positive contributor to soil health (Bünemann et al. 2018).

2.6 | Statistics

Statistical analyses were performed using R version 4.3.3 (R Core team 2013). To assess differences between amendment groups, a two-way ANCOVA was used, adjusting group means for covariation due to the diversity of locations and management practices across sites, which were identified through a multi-model inference approach (Terrer et al. 2016) using the glmulti package (Calcagno 2020). The following predictors were considered: latitude, longitude, altitude, mean annual precipitation, mean annual temperature, clay content and pH. For crop management, the percentage of leys, crop cover, management intensity and estimated C inputs from crop residues and organic fertilisers were considered. The relative importance of predictors was assessed by calculating the percentage of the sum of squares contributing to the total sum of squares for each ANCOVA model.

To explore relationships between individual predictors and response variables, linear, quadratic and logarithmic regression models were tested. Additionally, a structural equation model (SEM) was employed to assess the direct and indirect effects of compost and management systems on all soil health indicators and yield, using the lavaan package (Rosseel 2012). A more detailed description of the statistical analyses can be found in the Supporting Information S1 (page 12).

3 | Results

3.1 | Soil Health and Yield in the Amendment Groups and Management Systems

Average soil health (SHI) was highest in fields that received compost amendments within the past 5 years (Figure 2A). After correcting for key site-specific and management covariates, SHI in compost-amended fields was, on average, 31% higher than in the reference group across both management systems ($p = 0.012$; Supporting Information S1: Table A5). No significant difference was found between the solid digestate and reference groups, nor between organic and conventional systems in terms of SHI. Grain yields were 21% lower in organic fields ($p < 0.001$), but no significant yield differences were observed between compost and solid digestate groups (Figure 2B; Supporting Information S1: Table A5). There was no significant correlation between soil health and yield (Figure 2C).

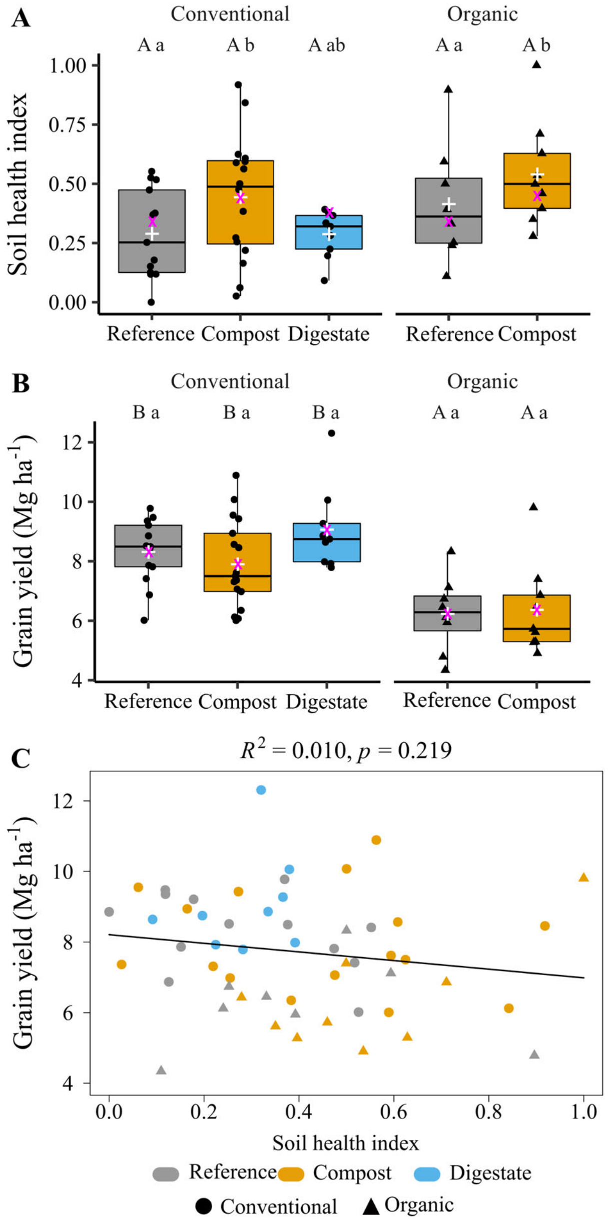


FIGURE 2 | Average soil health (A) and grain yield (B) under different organic amendment regimes and management systems. Bold lines represent medians, boxes show the first and third quartiles, "+" marks raw means, and "X" marginal means adjusted for covariates (Figure 4). Capital letters indicate significant differences between management systems, and lowercase letters between amendment regimes. Panel (C) shows the relationship between average soil health and grain yield.

For individual soil health indicators, the differences between the organic amendment groups and management systems varied (Figure 3A; Supporting Information S1: Tables A4, A5). For

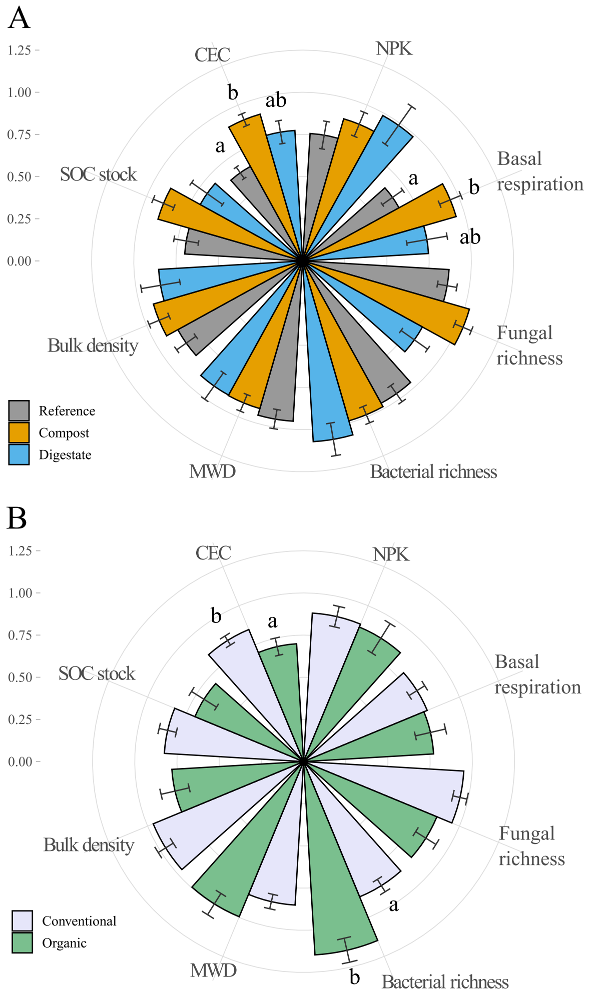


FIGURE 3 | Main effects of organic amendment regimes (A) and management system (B) on soil health indicators. Significant differences ($p < 0.05$) are marked with different letters. Soil health indicators are scaled between 0 and 1.

example, compost-amended fields showed higher CEC (+ 42%, $p < 0.001$), basal respiration (+ 45%, $p = 0.014$), SOC stocks (+ 28%, $p = 0.151$) and fungal richness (+ 18%, $p = 0.083$) compared to the reference group, while aggregate stability, bulk density and bacterial richness were unaffected (Figure 3A). Organic fields had significantly lower CEC (–17%, $p = 0.016$), but higher bacterial richness compared to conventional fields (32%, $p = 0.002$) (Figure 3B; Supporting Information S1: Table A5), along with marginally higher aggregate stability and lower bulk density (Supporting Information S1: Table A4).

3.2 | Relative Importance Soil Health Predictors

The organic amendment group explained 7% ($p = 0.019$) of the total variation in SHI, relative to environmental and other crop management predictors. Clay content was the most influential environmental predictor, accounting for 27% of the variation in SHI ($p < 0.001$) and strongly correlating with all individual soil health indicators, except fungal richness and bulk density (Figures 4, 5). For SOC stocks, CEC, and soil nutrients (NPK), clay content explained 50%, 67%, and 31% of the total variation, respectively (all $p < 0.001$). The positive relationship between clay content and soil health was further supported by regression analysis ($R^2 = 0.594$, $p < 0.001$; Supporting Information S1: Figure A6A) and structural equation modelling. Soil pH was a key covariate for soil nutrients, basal respiration, and fungal and bacterial richness.

Crop cover explained 3-9% of the variation in overall soil health, SOC stocks, CEC, basal respiration, and soil aggregation. Simple regression confirmed a significant relationship between crop cover and SHI ($R^2 = 0.168$, $p < 0.001$; Supporting Information S1: Figure A6B). Additionally, organic fertiliser C inputs predicted SOC stocks (4%, $p = 0.044$), and crop-based C inputs predicted bacterial richness (9%, $p = 0.003$) (Figure 4).

3.3 | Direct and Indirect Effects of Environmental and Management Factors on SOC, Soil Health and Yield

The SEM revealed strong covariances between soil health indicators driven by location-specific variables and management practices. SOC was particularly correlated with other soil health indicators, especially CEC, basal respiration, soil nutrients, and bulk density ($p < 0.001$) (Figure 5; Supporting Information S1: Table A6). Both site-specific and management variables were largely associated with SOC stocks, either directly or indirectly. The positive relationship between SOC and SHI was further supported by regression analysis ($R^2 = 0.848$, $p < 0.001$; Supporting Information S1: Figure A7).

Consistent with the ANCOVA results (Supporting Information S1: Table A4), the SEM found no significant effect of organic management on soil health indicators. Crop cover was positively associated with multiple indicators, including MWD ($p = 0.031$), basal respiration ($p = 0.018$), CEC ($p = 0.033$), and SOC stock ($p = 0.003$).

Also for compost amendments and organic fertiliser C inputs, the SEM results largely aligned with the ANCOVA findings. However, differences between the two methods were observed in the strength and significance of some relationships, such as the stronger effects of compost on fungal richness ($p = 0.005$) and marginal associations with basal respiration ($p = 0.064$) and SOC stock ($p = 0.072$).

Grain yields were primarily driven by the management system ($p < 0.001$), explaining 25% of the total variation (Figure 3). The SEM also indicated a significant correlation between yield and CEC ($p = 0.005$) and a marginal correlation with SOC stock ($p = 0.069$).

4 | Discussion

4.1 | Compost Application can Promote Soil Health Under On-Farm Conditions

In this study, compost use was associated with a 31% improvement in soil health compared to reference fields where compost had not been applied in the past decade. This result confirms findings from controlled trials and provides new

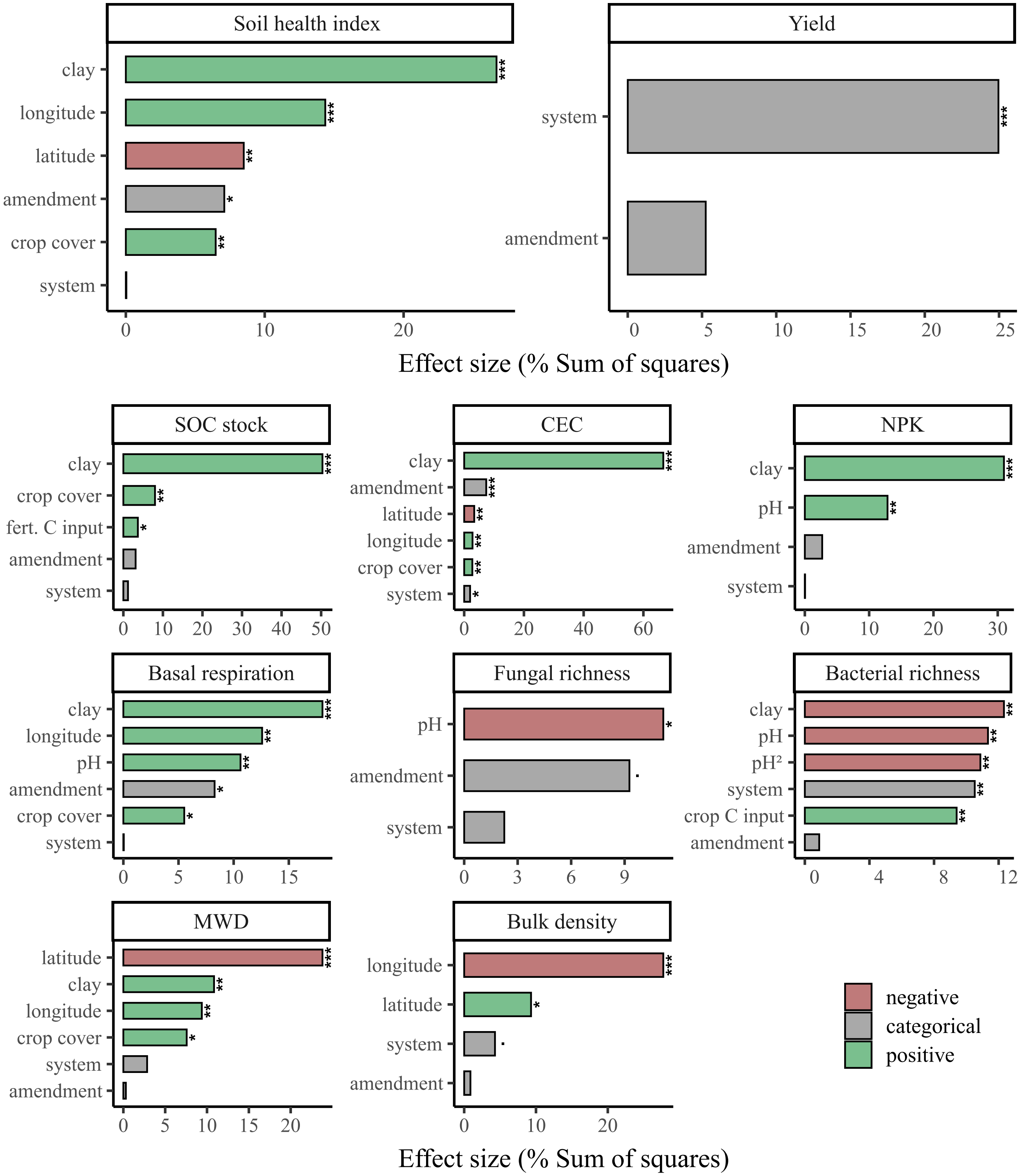


FIGURE 4 | Effect sizes of the management system, organic amendment regime, and covariables for soil health indicators, SHI, and yield, expressed as the percentage of total variation explained (sum of squares). Bar colours represent positive (green) and negative (red) correlations between covariables and dependent variables, while factorial predictors (system, organic amendment types) are shown in grey. Full model coefficients and *p*-values are provided in Supporting Information S1: Table A4.

evidence that farmer-applied compost can enhance soil health under practical on-farm conditions, despite variability in amounts, frequency, and interactions with other fertilisers, management practices, and environmental conditions (Table 1). Notably, the positive effect of compost application was observed in both conventionally and organically managed fields, with a similar magnitude of improvement across both systems. This implies that compost can significantly enhance soil health

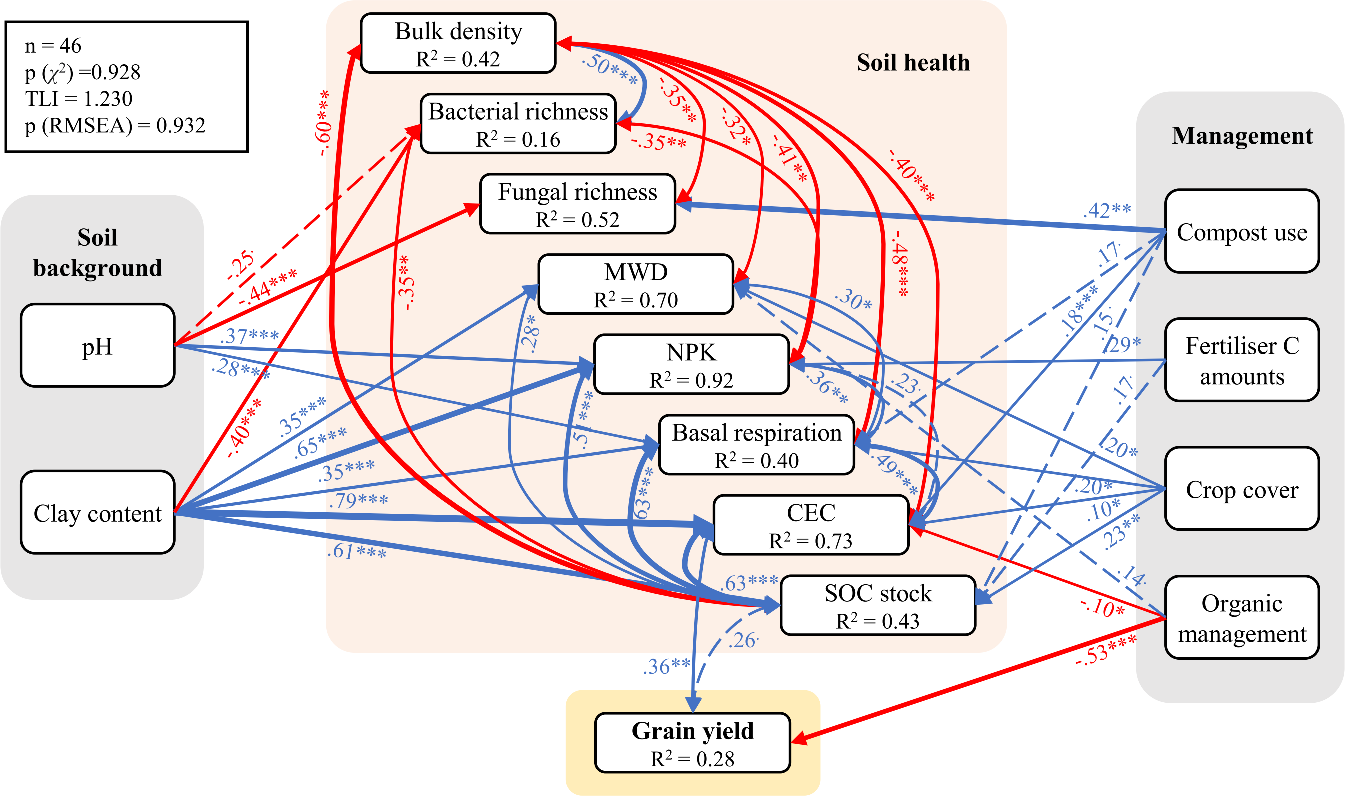


FIGURE 5 | Structural equation model showing the relationships between environmental and management factors on soil health indicators and crop yield. Blue and red lines represent positive and negative correlations, with numbers and line widths indicating the strength of the standardised coefficient. Dashed lines show marginally significant correlations. Only correlations with p-values < 0.10 are shown; ***, **, *, correspond to p-values < 0.001, < 0.01, < 0.05, and < 0.10. TLI = Tucker-Lewis index. Spatial coordinates were considered but not shown. Full model parameters are in Supporting Information S1: Table A6.

regardless of the farming system, even in organic fields that typically employ practices aimed at improving soil health (Mäder et al. 2002). In contrast, solid digestates did not significantly improve soil health, though conclusions are limited by the small sample size ($n = 9$) and apply only to conventional systems, as none of the organic farms in the study applied solid digestates.

Compost's role in enhancing soil health has often been attributed to increased SOC. This study also observed higher C inputs in compost-treated fields, suggesting that compost is used to build SOC rather than replace other fertilisers. However, SOC accumulation and improved soil health may also result from changes in the biotic soil environment. Microbial growth and the accumulation of microbially-derived carbon, which can account for more than half of the SOC in agricultural soils (Wang et al. 2021), may be key mechanisms behind this. The observed sensitivity of microbial respiration to compost aligns with research highlighting its role in sustaining microbial biomass and activity (Diacono and Montemurro 2010). The higher fungal richness in compost-treated fields may be related to an enrichment of specific fungal communities, such as lignin decomposers, which help break down organic matter and release nutrients (Tuomela. 2000).

The strong interconnections between soil health indicators in this study underscore the complexity of soil health as influenced by both biotic and abiotic factors, and how they are mediated by management practices. While compost plays a multifunctional role in improving SOC and related properties (Wiesmeier et al. 2019), further controlled experiments are needed to clarify the specific mechanisms behind these improvements.

4.2 | Other Drivers of Soil Health

Contrary to previous studies showing positive effects of organic management on soil health (Mäder et al. 2002; Walder et al. 2023), the management system was not a key predictor in this study. This may be because both organic and conventional farms in the study region had diverse crop rotations and applied farmyard manure. As such, soil health appears to be shaped by environmental factors and specific management practices rather than the farming system itself (Walder et al. 2023).

Organic fields in this study received fewer C inputs than conventional ones, which may explain the lower SOC stocks and CEC. However, this result cannot be generalised, as a comparable study reported higher soil health in organic systems when C inputs were comparable across systems (Walder et al. 2023). Interestingly, organic fields in this study still exhibited better soil structure and higher bacterial richness, indicating that avoiding mineral fertilisers and synthetic pesticides can still benefit soil habitat properties and soil biodiversity.

Crop cover was the most significant management predictor for various soil health aspects, including SOC stocks, CEC, basal respiration and aggregate stability, aligning with previous studies (Garland et al. 2021; Edlinger et al. 2023; Keel et al. 2019) and supporting predictions that cover crops reduce SOC losses (Seitz et al. 2023). Surprisingly, average management intensity (including nutrient inputs, tillage, and pesticide use) had no significant effect. This may be due to the fact that detailed data were only available for the year before sampling, and practices in previous years likely varied based on crop rotations across the fields.

Clay content was the strongest predictor of SOC stocks, CEC, and soil nutrients, surpassing the influence of management practices. Clay's role in stabilising SOC through mineral-organic complexes is crucial (Wiesmeier et al. 2019). Additionally, compost is often applied to clay-rich soils to mitigate compaction, and these soils, with higher SOC storage potential, may have received more compost, which should be considered when interpreting differences between amendment groups. However, clay content alone may not fully account for improved soil health, as stabilised C becomes less available for decomposition (Six et al. 2002), potentially explaining the negative correlation between clay content and bacterial richness. In contrast, SOC and clay were positively correlated with basal respiration, suggesting that microbial activity depends more on SOC availability than microbial diversity.

4.3 | Compost Amendments to Minimise Trade-Offs Between Yield and Soil Health

While it is commonly assumed that healthy soils support crop yields (Walder et al. 2023), other studies have shown a decoupling of wheat yield from soil multifunctionality in high-input systems (Garland et al. 2021), possibly due to practices that prioritise yields over soil health. Similarly, in this study, wheat yield was not correlated with overall soil health. However, we found positive relationships between yield, CEC and SOC stock (marginally significant), suggesting synergies between certain soil health indicators and crop yields.

The management system was the strongest predictor of grain yields, with organic fields yielding 22% less than conventional fields, consistent with the commonly observed yield gap (Herzog et al. 2019; Knapp and van der Heijden 2018). Considerable variation around the means suggests that environmental and management factors also played a role. In organic systems, weed and pest pressure likely influenced yields (Riemens et al. 2010; Bianchi, Booij, and Tscharntke 2006; Rasmussen 2004), while higher management intensity, including greater nutrient inputs, correlated positively with wheat yields (Supporting Information S1: Figure A8). Differing winter wheat varieties may have contributed to this variation as well.

Contrary to studies showing yield benefits from compost (Agegnehu et al. 2016), we observed no significant impact on wheat yield from compost use. In Switzerland, where organic fertilisers are widely used and soils are already rich in SOC, further yield improvements from compost may be limited (Zhao et al. 2022). Compost's role here may primarily lie in enhancing soil health, though variations in compost quality, which influence its effectiveness in disease suppression (Fuchs et al. 2008), require further investigation.

Notably, yields were 10% higher in fields amended with solid digestates compared to reference fields, though this difference was not statistically significant, likely due to the small sample size. These results are in line with findings by Grillo et al (Grillo et al. 2021)., who showed that solid and liquid digestates can achieve yields comparable to mineral fertilisers. Further research is needed to evaluate the potential of digestates to increase crop yields, particularly under different agronomic and environmental conditions and using various source materials (e.g., manure, slurry, green cuttings).

5 | Conclusion

This study demonstrated that compost amendments improved soil health by 31% compared to the exclusive use of other (organic) fertilisers in 56 Swiss farmer-managed fields. This finding is significant as it confirms that the known benefits of compost persist, despite the noise introduced by the interplay of various management practices and environmental conditions. In contrast, solid digestates had no decisive effect on soil health. Overall, this study highlights compost as a valuable tool for enhancing soil health and supporting sustainable crop production, even under the complexities of practical farming settings.

Author Contributions

Marcel G. A. van der Heijden and Benjamin Seitz conceived the ideas and designed methodology. Anna Edlinger, Chantal Herzog, Gina Garland, Samiran Banerjee, Sana Romdhane, and Benjamin Seitz collected the data. Sonja G. Keel, Jochen Mayer, Marcus Schiedung, and Chloé Wüst-Galley supported calculations behind the soil and management variables. Anna Edlinger and Chantal Herzog analysed the data with support from Florian Walder. All coauthors contributed to the interpretation of the data. Anna Edlinger and Chantal Herzog led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

Acknowledgements

We are very grateful to the participating farmers. We thank M. Roser, A. Held, A. Bonvicini (†), S. Müller, D. Bürge, M. Zuber, E. Szerencsits, L. Hächler and J. Helfenstein for help with sampling, soil analyses, technical support, discussions and feedback on writing. Funding was provided by the Mercator Foundation Switzerland and the Swiss National Science Foundation (grant 31BD30-1724662 and 31003A_166079), awarded to Marcel G. A. van der Heijden.

Ethics Statement

The authors confirm that they have adhered to the ethical policies of the journal.

Conflicts of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding authors upon request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.