European Journal of Soil Science

WILEY

European Journal of Soil Science

RESEARCH ARTICLE OPEN ACCESS

Soil Health, Crop Yield and Carbon Footprint Trade-Offs Between Conservation and Conventional Farming: A Case Study

Christoph Rosinger[1] | Golo Gotthalmseder[1] | Gernot Bodner[1] | Katharina M. Keiblinger[2] | Stefan J. Forstner[3] | Taru Sandén[4] | Giacomo Ferretti[5] | Moltinë Prebibaj[6] | Reinhard W. Neugschwandtner[1] | Hans-Peter Kaul[1]

[1]Institute of Agronomy, Department of Agricultural Sciences, University of Natural Resources and Life Sciences Vienna (BOKU), Tulln an der Donau, Austria | [2]Institute of Soil Research, Department of Ecosystem Management, Climate and Biodiversity, University of Natural Resources and Life Sciences Vienna (BOKU), Vienna, Austria | [3]Agricultural Soil, Department of Forest Ecology and Soil, Austrian Research Centre for Forests (BFW), Vienna, Austria | [4]Department for Soil Health and Plant Nutrition, Institute for Sustainable Plant Production, Austrian Agency for Health and Food Safety (AGES), Vienna, Austria | [5]Department of Chemical, Pharmaceutical and Agricultural Sciences, University of Ferrara, Ferrara, Italy | [6]Department of Crop Science and Technologies, Faculty of Agriculture and Environment, Agricultural University of Tirana, Tirana, Albania

Correspondence: Christoph Rosinger (christoph.rosinger@boku.ac.at)

Received: 13 February 2025 | **Revised:** 16 August 2025 | **Accepted:** 1 September 2025

Funding: This work was supported by Universität für Bodenkultur Wien, BIOS Science Austria—Verein zur Förderung der Lebenswissenschaften.

Keywords: agriculture | agronomy | cover cropping | crop diversification | crop type effect | greenhouse gas emissions | reduced tillage | soil quality | sustainable management

ABSTRACT

Transitioning towards soil health-oriented farming systems is fundamental to mitigate future challenges such as climate change, soil degradation, and increasing global food demands. In this study, we evaluated soil health, crop yields, and greenhouse gas (GHG) emissions at a long-term experimental site in Central Europe that comprised two cropping systems: a conventional system with regular tillage, low-diversity crop rotation, and minimal cover cropping, and a conservation system with shallow tillage, diverse crop rotation, and extensive cover cropping. We assessed soil health using 13 physico-chemical and biological parameters, calculated field-scale GHG emissions, and analysed yield dynamics over an eight-year period to evaluate potential crop yield penalties under conservation farming. We observed significant soil health advances (+7%) and reductions in GHG emissions (−43%) with conservation farming, while crop yields for all cultivated crops remained stable. Improvements in soil health were particularly pronounced for nitrogen cycling and microbial-driven processes. For several measured soil health parameters, we found a larger effect of crop species compared to farming system. Further, positive management effects on soil were apparent particularly for winter wheat and to a lesser extent for maize and sugar beet, strongly emphasizing the need for standardized soil health assessments that take crop species into account. Our study demonstrates that easily implementable conservation farming measures such as reduced tillage, increased crop diversity, and enhanced cover cropping can substantially improve soil health and long-term agricultural sustainability without compromising crop yields. Conservation farming thus emerges as a viable strategy to support resilient crop production in temperate regions.

Summary

- Comparison of a conservation and conventional cropping system during eight years.
- Evaluation of soil health, crop yields and field-scale carbon footprint.
- Conservation farming increased soil health by 7% without compromising crop yields.
- Conservation farming significantly reduced the overall carbon footprint by 43%.

1 | Introduction

The global population is projected to reach nearly 10 billion by 2050, necessitating a significant increase in food production to meet rising global demands (FAO 2017). This surge in demand poses a challenge for agricultural systems worldwide, which must not only produce more food but also do so sustainably, aligning with climate neutrality targets for agricultural production. Adverse effects of climate change further threaten to decrease agricultural productivity through increased frequency and severity of extreme weather events such as flooding, droughts, and heatwaves (Lobell et al. 2008; Hari et al. 2020).

Soil degradation is another critical issue that undermines the capacity of agricultural systems to meet future food demands. Conventional farming practices including frequent tillage at 20–30 cm soil depth, low crop diversity, or crop residue removal have led to soil organic matter depletion, erosion, and loss of soil fertility (Guo and Gifford 2002; Sanderman et al. 2017). Consequently, these soils exhibit lower water and nutrient retention (Man et al. 2021), making crops more vulnerable to environmental stressors. Moreover, current agricultural systems contribute significantly to greenhouse gas (GHG) emissions, accounting for approximately 25% of global anthropogenic emissions (IPCC 2015). These emissions arise from various sources including land-use change, soil management practices, livestock production, and the use of synthetic fertilizers. Evidently, the high GHG emissions associated with conventional farming practices further exacerbate climate change, creating a negative feedback loop that further threatens resilience, resistance, and hence long-term productivity of agricultural systems (Lobell and Gourdji 2012).

Healthy soils are fundamental for agricultural sustainability, directly influencing crop productivity and environmental quality. They are characterized by high levels of soil organic carbon (SOC), stable soil aggregates, and a vital microbial community (Bodner et al. 2023; Rosinger, Bodner, et al. 2023), all of which contribute to improved soil structure, nutrient cycling, and water retention (Lehmann et al. 2020). These properties enable soils to support high crop yields while maintaining resistance and resilience to environmental stressors such as drought, heavy rainfalls, or extreme temperatures. Improving soil health is therefore essential for enhancing agricultural productivity and sustainability. Practices that increase SOC levels, improve soil structure, and promote microbial diversity and activity can enhance soil fertility, water retention, and resilience to environmental stressors (Amelung et al. 2020).

Conservation farming, which particularly emphasizes minimal soil disturbance, increased soil cover, and diversified crop rotations, has emerged as a promising approach to improve soil health and crop yields (Hobbs et al. 2008; Sae-Tun et al. 2023). Reduced tillage minimizes soil erosion and disturbance (Bogunovic et al. 2018), thus preserving soil structure and reducing soil organic matter decomposition. Increased soil cover through cover cropping and residue retention protects the soil surface from erosion, enhances water infiltration, and reduces evaporation, thereby improving soil moisture retention (Blanco-Canqui and Ruis 2020). Diversified crop rotations—including the use of cover and inter crops—can significantly enhance soil fertility and reduce pest and disease pressures. Leguminous crops—either used as main or cover crop—contribute to soil nitrogen (N) enrichment through atmospheric N fixation, thereby reducing the need for mineral fertilizers (Preissel et al. 2015). Additionally, diverse crop rotations can break pest and disease cycles, which reduces the reliance on chemical pesticides. Numerous (meta-)studies have demonstrated the benefits of conservation farming for soil health (Ghaley et al. 2018; Li et al. 2018; Crystal-Ornelas et al. 2021). These improvements in soil health may lead to higher and more stable crop yields (Knapp and van der Heijden 2018; Sun et al. 2024), particularly under conditions of environmental stress such as drought (Teng et al. 2024).

However, the effects of conservation farming on crop yields are not always consistent. Some studies have reported yield reductions, particularly in the initial years of adoption, as soils transition from conventional to conservation practices (Pittelkow et al. 2015; Ponisio et al. 2015). These yield reductions can be attributed to factors such as changes in soil nutrient availability (e.g., the immobilization of available N into stable soil organic matter) and the time required for soil health improvements to manifest. Despite these challenges, the long-term benefits of conservation farming for soil health and crop yield are evident and make it a valuable strategy to pursue.

While improving soil health and crop yields is crucial for sustainable agriculture, it is equally important to consider the broader environmental impacts of farming practices, particularly on GHG emissions. A farming system that achieves good soil health and high crop yields but relies on carbon (C)-intensive inputs, such as synthetic fertilizers and fossil fuel-based energy, may not be sustainable in the long term. Therefore, evaluating GHG emissions at larger scales in addition to soil health is essential to ensure that efforts to improve soil and crop performance align with climate change mitigation goals.

Conservation farming has the potential to reduce GHG emissions by enhancing C sequestration in soils while simultaneously reducing the reliance on mineral fertilizers and fossil fuel-based energy inputs (Lal et al. 2018). For example, reduced tillage can decrease soil C losses and lower fuel consumption for field operations. The use of leguminous cover crops can reduce the need for mineral N fertilization, potentially reducing nitrous oxide (N_2O) emissions from farming systems (Basche et al. 2014). In contrast, no-tillage practices have been associated with elevated

N_2O emissions relative to conventional tillage systems (Mei et al. 2018). Thus, the overall impact of conservation farming on GHG emissions can vary greatly depending on specific management practices and local pedo-climatic conditions, necessitating a comprehensive assessment of GHG emissions at larger scales to identify potential trade-offs and optimize conservation farming practices for both soil health and climate benefits.

To this end, we compare conventional and conservation farming effects on soil health, crop yields and GHG emissions at a long-term experimental site in a temperate (Peel et al. 2007) environment in Central Europe (North-Eastern Austria). Established in 2015, the experimental site accommodates two farming systems: (i) a conventional system, characterized by conventional tillage to 25 cm soil depth, a simple crop rotation and very little use of cover crops and (ii) a conservation system, characterized by shallow tillage at 5 cm soil depth, a diversified crop rotation and the extensive use of cover and inter crops. Eight years after implementation, we evaluated soil health based on thirteen soil physico-chemical and biological parameters, from which we derive a soil health index (Andrews et al. 2002; Askari and Holden 2015). The CoolFarm (CF)-Tool was used to calculate field-scale GHG emissions (Hillier et al. 2011). These indices were complemented by eight-year (2015–2022) data on crop yield and aboveground biomass to assess conservation farming sustainability advances and potential soil health–crop yield trade-offs. The concurrent cultivation of all crops of a respective crop rotation in each year enables a detailed analysis of yield dynamics over an eight-year period, as well as the assessment of potential crop-type specific effects on soil health. We hypothesize that a shift towards conservation farming has increased soil health, with improvements being independent of the crop species currently cultivated on the field. Further, we hypothesize soil health advances with conservation farming to occur at the expense of crop yields. Finally, we expect conservation farming practices to decrease field-scale GHG emissions. This comprehensive evaluation aims to provide a better estimate of attainable soil health improvements and GHG reduction potentials with conservation farming measures for this important production region in Central Europe.

2 | Materials and Methods

2.1 | Experimental Setup

The study was conducted at a long-term experimental site of BOKU University in Tulln, North-Eastern Austria (48.3117° N, 16.0442° E, 177 m a.s.l.; Figure 1a–c). The site is characterized by a dry-temperate climate with warm summers without a dry season (Peel et al. 2007), with a mean annual temperature of 10.4°C and a mean annual precipitation of 759 mm (Figure 1d). The soil is a Chernozem with a loamy clay texture, a neutral pH (6.3–6.8 in H_2O) and SOC concentrations of about 2.5%.

Established in 2015, the experiment features a conventional and a conservation farming system. The conservation farming system differs from the conventional farming system in three main aspects: (i) shallow tillage at 5 cm soil depth as compared to conventional tillage at 20–25 cm soil depth using a field cultivator (Horsch Terrano FX with spring roller; wing shares for conservation farming system, tines for conventional farming system), (ii) a wider and more diverse crop rotation (sugar beet-winter wheat-maize-soybean-winter wheat-sunflower-faba bean-winter wheat with a total of five cover crop mixtures) as compared to a conventional crop rotation common for this region (sugar beet-winter wheat-maize-winter wheat), and (iii) a greater share of cover and inter crops (five cover crops and one inter crop) as compared to one cover crop in the conventional farming system. Fertilization (mainly CAN and urea) was conducted according to national recommendations (BMLRT 2022), and conventional plant protection was applied as needed; fertilization and plant protection were however always the same in both farming systems. For stubble cultivation and seedbed preparation, an S-tine seedbed cultivator was used (Kongskilde Vibromaster, Type SGC) and—if needed—combined with a prism roller (Lely Power Harrow). Seeding of maize and sunflower was conducted using a six-row pneumatic precision seed drill (Kverneland Optima); all other crops were sown with a disc seed drill (Hirsch Pronto 3–4 DC). For more details on the crop rotation, crop yields, cover crop composition, plant protection and fertilization regime, we refer the reader to Table S1. The experiment is set up in a Complete Randomized Block Design with two real and two pseudo-replicates within each of the individual blocks (see Figure 1). Each block is 20 × 160 m, and every crop of the entire crop rotation (4 and 8 crops in the conventional and conservation farming system, respectively) is cultivated each year on two large plots, resulting in a total of 24 plots.

2.2 | Soil Sampling

Soil samples were taken in June 2024 at two soil depths (0–15 and 15–30 cm) using a steel soil corer (⌀ 3 cm) from those conventional and conservation farming plots where the same main crops were cultivated (i.e., Sbeet, sugar beet; Ww1, winter wheat 1; Maize; Ww2, winter wheat2). Ww2 differs in the pre-crop, with soybean in the conservation farming crop rotation and maize in the conventional crop rotation. Five soil cores taken along a Z-shaped transect were pooled to form a composite sample for each plot and pseudo-replicate. Soil samples were sieved to pass through 2 mm and subsequently air-dried or stored at 4°C until further analysis. Laboratory analyses on fresh soil samples were conducted within 10 days of soil sampling. This resulted in a total of 64 soil samples (two systems × four crops × two depths × [two blocks × two pseudo-replicates per block]) taken. In addition, undisturbed soil cores using steel cylinders with 100 cm^3 were taken from each plot for bulk density determination to calculate SOC and total N (TN) pools.

2.3 | Aboveground Biomass Sampling and Yield Evaluation

Manual harvest of winter wheat and maize was done at physiological maturity by sampling the whole above ground-biomass, and for sugar beet when the beet root had reached the harvestable size. Winter wheat was harvested in July on an area of 1 m^2, maize and sugar beet in autumn on an area of 7.5 m^2. Seeds of winter wheat and maize were dried at 105°C for 24 h before weighing. For sugar beet, fresh weight was recorded after cutting off leaves.

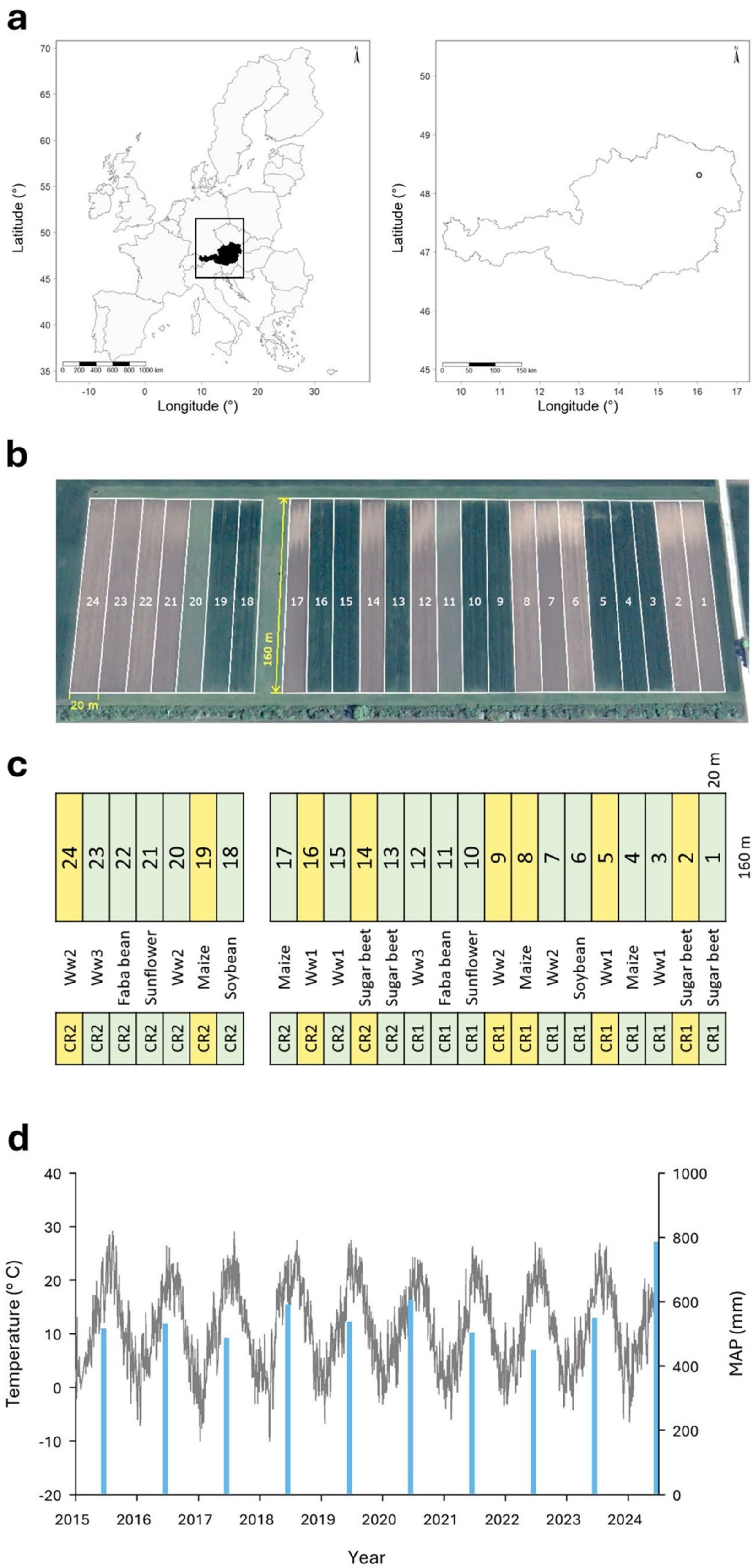


FIGURE 1 | Legend on next page.

FIGURE 1 | (a) Location, (b) aerial photo and (c) setup of the farming management experiment in North-Eastern Austria as well as (d) daily temperatures and mean annual precipitation from 2015 to 2024. For each management system (yellow, conventional farming; green, conservation farming), the crop rotations (CR1 and CR2) are established in duplicate. As such, every crop of the respective crop rotations (conventional rotation: Sbeet-Ww1-Maize-W2; conservation rotation: Sbeet-Ww1-Maize-Soybean-Ww2-Sunflower-Faba bean-Ww3) is cultivated twice each year, resulting in a total of 24 plots (Sbeet, sugar beet; Ww, winter wheat).

2.4 | Laboratory Analyses

Soil pH was measured according to ÖNORM L 1083 in a 10:1 (w/w) suspension of MilliQ-H_2O on air-dried soil using an inoLab Multi 9620 IDS electrode.

Total C and N concentrations were determined using a C/N elemental analyser (Thermo Fisher Scientific, MA, USA) via total combustion of air-dried, ball-milled soil samples and normalized to oven-dry mass. Inorganic C concentrations (calcium carbonate-equivalents) were quantified using the Scheibler method (ÖNORM L 1084). The SOC concentration was subsequently calculated as the difference between total C and inorganic C. SOC and TN pools were calculated using the equivalent soil mass approach (Fowler et al. 2023), and results are given in Mg ha^{-1}.

The relative number of stable aggregates (AS) was assessed using the wet sieving method (ÖNORM L 1082). In this procedure, soil aggregates with diameters ranging from 1 to 2 mm were placed on a 250 µm sieve. A sample of 4 g (EW) of soil was analysed. The mass of stable aggregates remaining after wet sieving (m_K) and the mass of sand following chemical dispersion of the residual aggregates (m_A) were measured, and aggregate stability (in %) was calculated as follows:

$$AS\,(\%) = \frac{mK - mA}{EW - mA} \tag{1}$$

Soil microbial biomass C and N (MB-C and MB-N, respectively) were determined using the chloroform-fumigation-extraction method (Vance et al. 1987). Briefly, 2 g of fresh soil was incubated for 22 h in a chloroform-saturated atmosphere, then extracted with 1 M KCl (1:10 w/v) by overhead shaking for 1 h. The extracts were filtered and stored at −20°C before analysis with a TOC/TN analyser (TOC-V CPHE200V, equipped with a TN-unit TNM −1, Shimadzu Corporation, Kyoto, Japan). Non-fumigated samples were treated identically to determine the background concentration of KCl-extractable organic C (EOC) and total dissolved N (TDN). MB-C and MB-N concentrations were calculated as the difference between fumigated and non-fumigated sample concentrations, with extraction efficiency factors of 0.45 (Vance et al. 1987) and 0.54 (Brookes et al. 1985) used for MB-C and MB-N, respectively. Results are expressed in µg g^{-1} dry soil.

The potential activities of six hydrolytic enzymes were determined using a microplate fluorometric assay following the protocol of Mayer et al. (2022). The enzymes evaluated included β-glucosidase (BG), β-xylosidase (XYL) and cellobiohydrolase (CEL) as proxies for C-acquisition, leucine-aminopeptidase (LAP) and N-acetyl-β-D-glucosaminidase (NAG) as proxies for N-acquisition, and acid phosphatase (AP) as a proxy for phosphorus (P)-acquisition. For the assay, 0.5 g of fresh soil was suspended in 50 mL of 100 mM TRIS buffer (adjusted to pH 6.8) and homogenized in a sonication bath for 1 min. While stirring, 200 µL aliquots were transferred to black 96-well microplates, with four technical replicates per sample. Substrate solutions (50 µL, concentrations of 2 mM for AP and 1 mM for all other enzymes) were added to each well, horizontally shaken for 30 s, and the plates were sealed with a cohesive plastic film. The plates were subsequently incubated in the dark at 20°C for 2 h. Fluorescence was measured using an EnSpire multiplate reader (PerkinElmer, Waltham, MA, USA) at an excitation wavelength of 365 nm and an emission wavelength of 450 nm. Methyl-umbelliferon (MU)-based substrates (BG, XYL, CEL, NAG, AP) were calibrated with standard solutions ranging from 10 to 250 µM, while the amino-methyl-coumarin (AMC)-based substrate (LAP) was used at two standard concentrations (20 and 50 µM). Quenching was accounted for by calculating the slope ratio of standard curves (50 µM) in buffer and soil suspension for both AMC- and MU-based substrates for each sample separately. Potential enzyme activities are expressed as nmol g^{-1} dry soil h^{-1}.

Potassium permanganate ($KMnO_4$)-oxidizable C (from here on referred to as 'Oxidizable C') was determined with a titration of the 0.02 M $KMnO_4$ solution with sodium oxalate ($Na_2C_2O_4$), according to Tatzber et al. (2015). The method was based on Weil et al. (2003) with minor modifications (Culman et al. 2012). Briefly, 2.5 g air-dried soil sample was used and 20 mL of a 0.02 M $KMnO_4$ solution was added. Titration, needed because $KMnO_4$ is not a primary standard, was performed with $Na_2C_2O_4$ according to McBride (1912). Results are expressed in µg g^{-1}.

The anaerobic incubation method according to DeLuca et al. (1992), adapted by Schinner et al. (2012), was used to determine the N mineralization potential (from here on referred to as 'Mineralizable N') on air-dried soils. Briefly, fresh soil samples (5 g) were incubated at 40°C for 7 days in a waterlogged environment in a closed tube with little headspace. The released NH_4^+ was measured using the salicylate-nitroprusside method (Hood-Nowotny et al. 2010). Results are expressed in µg g^{-1} d^{-1}.

2.5 | Calculation of the Soil Health Index (SHI)

As a representative measure of soil health, the Soil Health Index (SHI) provides a numerical assessment of various soil properties (Andrews et al. 2002; Zhou et al. 2020). The calculation of the SHI involves identifying a Minimum Data Set (MDS), comprising selected soil physicochemical and biological soil properties. These indicators are individually scored and summed to produce a final dimensionless value that reflects the overall soil health status (Andrews et al. 2002).

To calculate the SHI, we employed the Principal Component Analysis (PCA) method, as outlined in previous studies (Askari and Holden 2015; Martín-Sanz et al. 2022; Ferretti et al. 2024). PCA reduces dataset complexity while preserving essential information by generating uncorrelated principal components (PCs) that combine contributions from all original variables. These PCs are ranked in descending order of the variance they explain (Armenise et al. 2013). The analysis was conducted using thirteen standardized physicochemical and biological soil parameters (Table S2) to mitigate the influence of differing measurement units among indicators (Yao et al. 2014). The most important PCs were selected based on eigenvalues >1 and an explained variance $>5\%$ criterion (Armenise et al. 2013; Yao et al. 2014). Varimax rotation was applied to maximize correlations between PCs and measured attributes before extracting factor loadings (Shukla et al. 2006; Ferretti et al. 2024).

To construct the MDS, variables with factor loadings within 10% of the highest loading in each PC were selected. When multiple variables met this criterion, Pearson correlation coefficients were used to avoid redundancy. Specifically, if highly weighted variables were uncorrelated, all were retained; otherwise, only the variable with the highest loading was selected (Andrews et al. 2002; Singh et al. 2014). The finalized MDS was then scored using a linear method, assigning values between 0 and 1 based on a 'the more is better' approach (Equation 2) (Martín-Sanz et al. 2022):

$$Ls = \frac{X - Xmin}{Xmax - Xmin} \tag{2}$$

where Ls represents the linear score, X is the measured variable value, and Xmin/Xmax are the minimum and maximum values of the variable, respectively. The SHI was then calculated following Equation (3) (Martín-Sanz et al. 2022):

$$SHI = \sum_{i=1}^{n} WiLs \tag{3}$$

where n is the number of variables selected in the MDS, Ls is the score derived from the linear scoring method, and Wi represents the weight of each indicator, calculated using Equation (4):

$$Wi = \frac{(\%\,VarPCi)}{(\%\,VarTotal)} \Big/ \sum_{i=n}^{n} \frac{\%\,VarPCi}{\%\,VarTotal} \tag{4}$$

Here, %VarPCi is the variance explained by the PC for the indicator i, %VarTotal is the cumulative variance explained by all the selected PCs, and n is the total number of selected PCs.

2.6 | Calculation of the Carbon Footprint

GHG emissions (in kg CO_2-eq ha^{-1}) were calculated using the CoolFarm Tool v2.11.0 (Hillier et al. 2011). This tool combines several empirical models for the estimation of GHG emissions of individual farming management practices such as crop management, livestock management, and direct energy use from on-farm operations or primary processing while taking into account pedo-climatic conditions. In particular, site-specific data about crop yields and crop residue management, cover crop and intercrop cultivation, fertilizer application, plant protection, energy consumption from field operations, and transport of harvested crops from the field were used to drive the model, allowing us to compare the performance (i.e., land-use efficiency and efficiency per unit of product) of the farming systems from a GHG emissions perspective. A detailed description of the input variables can be found in Table S1. As management data are available for all crops and the entire experiment (2015–2022), GHG emissions were calculated for each crop within the respective farming system using the average management practices across the eight-year period.

2.7 | Statistical Analysis

Data were tested for variance homogeneity as well as normal distribution and—in the case of any violation—log-transformed before further analysis. Differences in aboveground biomass and crop yields of maize, sugar beet, winter wheat 1 and winter wheat 2 for each individual year as well as across the whole crop rotation were evaluated using one-way analysis of variance.

For the tested soil parameters, we first used multivariate analysis of variance (MANOVA) to test for a potential block effect. Therefore, we tested the factors management system, crop type, soil depth and block as main effects and interactions between block and all other factors (using a SS type III model) on the following soil health-related parameters: (i) SOC and TN (ii) EOC and oxidizable C, (iii) TDN and mineralizable N, (iv) MB-C and MB-N, (v) potential C-, N- and P-acquiring enzyme activities, and (vi) aggregate stability. Our analysis revealed a significant block effect across the whole dataset (Table S3), yet no significant interactions between block and all the other factors were observed. Subsequently, we used MANOVA to evaluate the effects of management system (with was as such nested within block), crop type and soil depth on our tested soil health-related parameters. To evaluate the statistical significance of the overall model, the Wilks' lambda distributions (λ) and derived F- and p-values for main and interaction effects are stated. Post hoc Tukey tests using a Šidák correction for multiple pairwise comparisons were used to evaluate significant differences between crops. The same MANOVA approach was followed for the evaluation of the SHI. Significant interactions were detected between management and crop type. In this case, we used one-way ANOVA to evaluate management differences within each crop type (i.e., Maize, Sbeet, Ww1 and Ww2). A Mann–Whitney U test was used to test for significant differences in GHG emissions between conventional and conservation farming. All statistical analyses were conducted in SPSS 26. We refer to significant differences at the $p<0.05$ level and marginal differences at the $p<0.1$ level.

3 | Results and Discussion

3.1 | Conservation Farming Effects on Crop Yield and Aboveground Biomass

A key challenge of our time is to feed a growing and increasingly demanding global population while minimizing external inputs and environmental impacts, with the additional pressure of current future climate predictions (Lobell et al. 2008; Godfray and Garnett 2014). Guided by the three main principles of minimizing soil disturbance, increasing soil cover, and diversifying crop rotations (Hobbs et al. 2008), conservation agriculture has received strong support as a potential solution to this challenge.

As for our study, we did not observe such yield losses with conservation farming over the entire experimental period (i.e., 2015–2022; Figure 2), thus contrasting earlier reports of yield penalties ranging from 5% to 20%, which have been cited as a significant barrier to the broader adoption of conservation farming practices (Pittelkow et al. 2015; Ponisio et al. 2015; Knapp and van der Heijden 2018). Significant differences in crop yield between conservation and conventional farming were however evident for specific years. For example, Sbeet yields were significantly higher under conservation farming as compared to conventional farming (Figure 2a,d) in 2017 and 2018, when Central Europe experienced a severe drought period (Hari et al. 2020; Moravec et al. 2021). This suggests that conservation farming practices may have positively affected soil hydraulic properties (i.e., pore size distribution) and the overall soil water balance in our experiment, as commonly reported for conservation farming systems (Parihar et al. 2019; Patra et al. 2019; Bodner et al. 2023). A better resistance of the conservation farming system alongside increased yield levels during years of excessive drought (Knapp and van der Heijden 2018) may therefore particularly benefit shallow-rooting crops with high water demand.

Interestingly, we observed a significantly larger aboveground biomass for Ww2 with conservation farming ($11.9 \pm 0.5\,\mathrm{Mg\,ha^{-1}}$) as compared to conventional farming ($11.4 \pm 0.5\,\mathrm{Mg\,ha^{-1}}$) over the entire experimental period (Figure S1). The conservation and conventional farming systems differ in one main aspect regarding Ww2: while maize is the pre-crop in the conventional farming system, soybean is the pre-crop in the conservation farming system. While the cultivation of grain legumes usually entails smaller economic revenues for farmers (Zander et al. 2016), they are important constituents of sustainable and diverse crop rotations. Aside from soil health benefits such as improved soil structure, P mobilization or N provision, crops yield $0.5–1.6\,\mathrm{Mg\,ha^{-1}}$ more after a grain legume pre-crop (Kaul 2004; Preissel et al. 2015). This grain legume pre-crop benefit may thus explain the elevated Ww2 aboveground biomass ($+0.52\,\mathrm{Mg\,ha^{-1}}$) in the conservation farming system, which did however not translate into significant crop yield increases. We therefore conclude that—contrasting to our first hypothesis—conservation farming did not compromise crop yields; in fact, we evidenced a greater aboveground biomass of a Ww2, likely due to a positive grain legume pre-crop effect.

3.2 | Conservation Farming Effects on Soil Health-Related Indicators

We further evaluated several soil health indicators related to soil structure, soil organic matter, and microbially-driven C-, N-, and P-cycling (de Vries and Caruso 2016; Lehmann et al. 2020). Our results generally reflect the notion of increased soil health in conservation farming systems (Li et al. 2018), albeit not for all indicators. Using a MANOVA, we found no significant change in SOC as a key soil health indicator with conservation farming (Table 1, Figure 3e). This is similar to several studies that report inconsistent trends in SOC with the adoption of conservation farming practices (Govaerts et al. 2009; Crystal-Ornelas et al. 2021), highlighting the importance of specific pedoclimatic conditions and management measures that seem particularly beneficial for SOC accrual (Crystal-Ornelas et al. 2021; Rosinger, Keiblinger, et al. 2023). For example, Page et al. (2020) state that SOC gains with conservation farming mainly occur under favourable pedoclimatic conditions, while a cold and wet climate as well as poorly drained soils negatively affect SOC levels. Moreover, eight years of conversion may still be considered too short to detect management-induced SOC changes on these fine-textured soils (Rosinger, Bodner, et al. 2023).

More sensitive indicators of soil health such as oxidizable C or MB-C on the other hand were affected by a change in management towards conservation farming (Table 1, Figure 3): while oxidizable C decreased with conservation farming from 574 ± 8 to $577 \pm 8\,\mu\mathrm{g\,g^{-1}}$ (Figure 3b), MB-C concentrations increased with conservation farming from 205 ± 7 to $208 \pm 8\,\mu\mathrm{g\,g^{-1}}$ (Figure 3c). While these advances in soil health indicators seem minor compared to literature (Li et al. 2018; Crystal-Ornelas et al. 2021), a shift towards conservation farming on fine-textured soils such as ours can encompass SOC and crop yield declines (Rusinamhodzi et al. 2011; Das et al. 2022)—something we did not observe. Overall, these results support that management-induced changes in C-related soil health indicators are primarily observed in labile C fractions for fine-textured soils (Wieser et al. 2024).

Soil health parameters related to N cycling were for the most part positively affected under conservation farming (Table 1, Figure 3). In particular, TN stocks (+0.9%) as well as labile N fractions such as TDN (+9.1%) or MB-N (+6.0%) were significantly increased with conservation farming (Table 1, Figure 3f,h,j). Higher N contents in the conservation farming system might be related to reduced N losses as a result of reduced topsoil disturbance from soil tillage (Zhang et al. 2020) and/or to the greater share of legume grains and legume-containing cover crops in the crop rotation (Bohoussou et al. 2022). These management measures have a great potential to enhance soil N cycling and accumulation, ultimately facilitating N supply to crops.

While enzymatic indicators of microbial C- and N-acquisition did not differ between farming systems, potential activities of P-acquiring enzymes were significantly lower with conservation farming ($100 \pm 5\,\mathrm{nmol\,g^{-1}\,h^{-1}}$) as compared to conventional farming ($111 \pm 5\,\mathrm{nmol\,g^{-1}\,h^{-1}}$). This contrasts with recent studies (Hallama et al. 2021; Campdelacreu Rocabruna et al. 2024), where increased P-acquisition has been reported with a high share of cover crops and reduced tillage. In conservation farming systems, the greater share of leguminous plants cultivated may have exacerbated rhizosphere acidification, possibly facilitating P mobilization from inorganic (adsorbed, precipitated) pools and reducing the production of P-acquiring enzymes in turn (Haynes 1983; Shen et al. 2011; Muindi 2019). If such shifts indicate management-induced changes in soil (inorganic) P availability or microbial nutrient limitation (Rosinger et al. 2019) remains to be resolved in more targeted research that could include measurements of soil P pools and gross fluxes (Negassa and Leinweber 2009; Wanek et al. 2019).

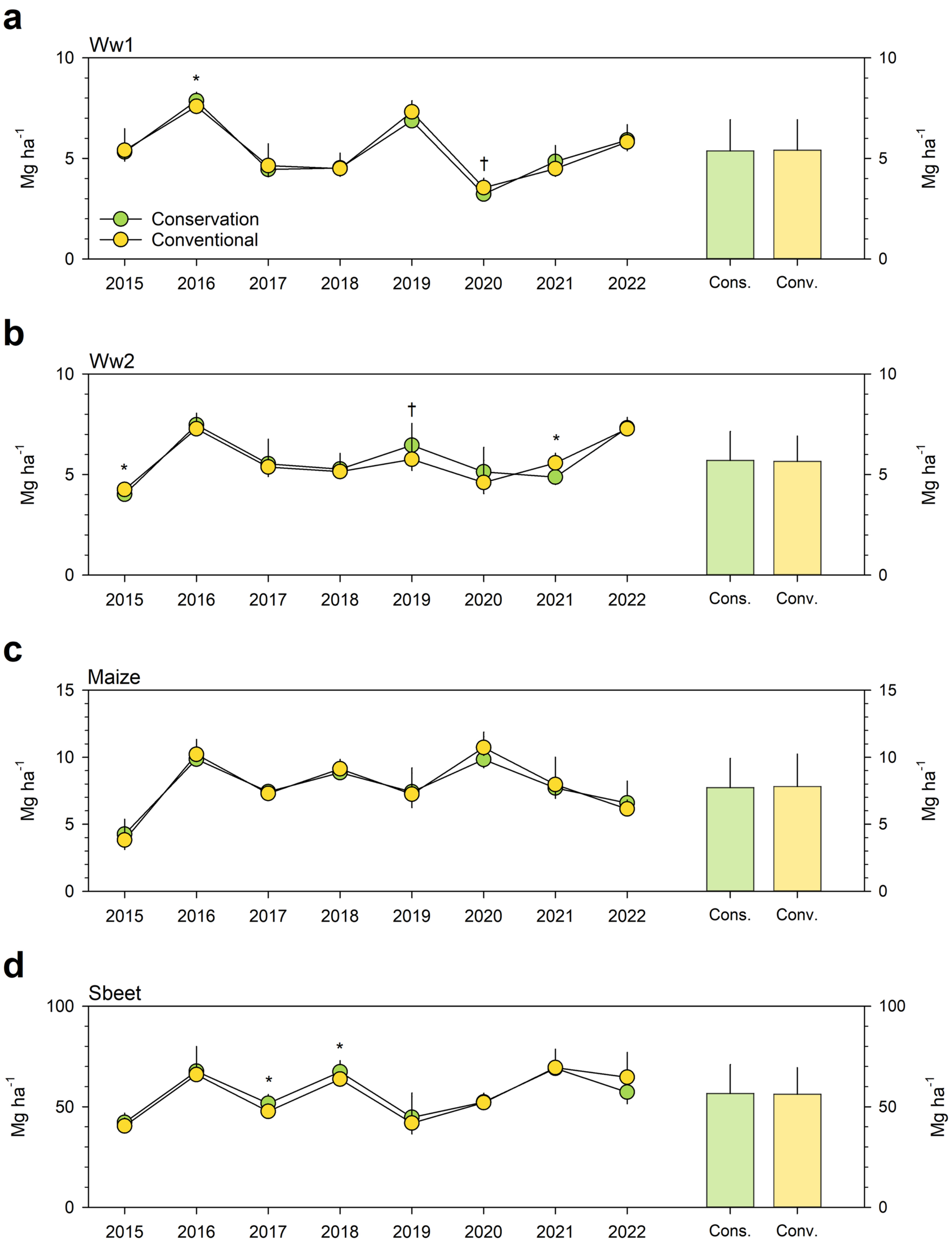


FIGURE 2 | Crop yield (in Mg ha^{-1}) of (a) winter wheat 1 (Ww1), (b) winter wheat 2 (Ww2), (c) Maize and (d) sugar beet (Sbeet) in a conventional (yellow dots and bars) and conservation (green dots and bars) farming system from 2015 to 2022. Standard errors show ± SD, and significant differences between farming systems within each year are indicated (*$p < 0.05$; †$p < 0.1$). Bars on the right-hand side display the average crop yield for all eight cropping seasons.

TABLE 1 | Results of a MANOVA on the effect of management, soil depth and crop type (as well as interactions thereof) on soil health-related parameters.

	Management	Soil depth	Crop type	Management × Crop type	Management × Soil depth	Management × Crop type × Soil depth
Wilk's λ	0.117	0.068	0.010	0.131	0.609	0.126
F-value	5.601	39.711	10.673	2.860	1.872	1.265
p-value	< 0.001	< 0.001	< 0.001	< 0.001	0.074	0.105
SOC	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
TN	***	n.s.	*	n.s.	n.s.	n.s.
MB-C	*	***	***	*	*	n.s.
MB-N	***	**	***	*	n.s.	**
Mineralizable N	n.s.	***	***	n.s.	n.s.	n.s.
Oxidizable C	*	***	***	n.s.	n.s.	n.s.
Aggregate stability	***	n.s.	***	**	n.s.	n.s.
N-acquisition	n.s.	n.s.	***	n.s.	n.s.	n.s.
C-acquisition	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
P-acquisition	***	*	n.s.	*	n.s.	n.s.
EOC	n.s.	n.s.	***	n.s.	n.s.	n.s.
TDN	*	***	***	*	n.s.	n.s.

Note: Wilk's λ, F- as well as *p*-values refer to the overall model performance, and significant effects on single parameters are indicated below (***$p < 0.001$; **$p < 0.01$; *$p < 0.05$; n.s., not significant).
Abbreviations: EOC, extractable organic carbon; MB-C, microbial biomass carbon; MB-N, microbial biomass nitrogen; SOC, soil organic carbon; TDN, total dissolved nitrogen; TN, total nitrogen.

3.3 | Soil Depth and Crop Type Effects on Soil Health Indicators

Beside the commonly observed decreases in soil health indicators with soil depth (Peigné et al. 2018; Rosinger et al. 2025) as evidenced in this study for oxidizable C, MB-C, TDN, mineralizable N as well as MB-N (Table 1, Figure S3), we show here that crop type has a highly significant effect on all evaluated soil health parameters except for C- and P-acquisition as well as SOC stocks (Table 1, Figure S4). The most striking differences appeared between Ww1 + Ww2 on the one hand and Maize + Sbeet on the other hand. For example, MB-C and MB-N contents, N-acquisition and aggregate stability were significantly higher on Ww1 + Ww2 plots as compared to Maize + Sbeet plots, with differences approximating up to 60%–70%, while the opposite trend was found for EOC concentrations (Figure S4a). In addition, we observed significant differences between Ww1 and Ww2 for oxidizable C, MB-C, TDN and mineralizable N, which could be attributed to the different pre-crop (Sbeet vs. soybean) these two crops have experienced. Beside these strong main effects of crop type on soil properties, we also evidenced significant interactions between crop type and management system (Table 1). MB-C concentrations were significantly increased in Ww2 and Maize plots of the conservation farming system, yet significantly decreased in the Sbeet plot (Figure 4a). MB-N concentrations were significantly higher in Ww1 and Ww2 under conservation farming as compared to conventional farming, while no management effect was observed for Maize and Sbeet (Figure 4c). TDN concentrations were higher in Maize plots under conservation farming as compared to conventional farming (Figure 4b). Conversely, P-acquisition tended to be greater in conventional farming systems under winter wheat (Ww1 and Ww2), while the opposite trend was found for Maize and Sbeet (Figure 4d). While such crop-specific effects of conservation farming have been observed for crop yields (Zheng et al. 2014; Sun et al. 2024) as well as soil health parameters (Thierfelder et al. 2013; Larney et al. 2016; Sadiq et al. 2021), this is to our knowledge the first study that allows for a management comparison of different crops within the same vegetation period. While these interactions must be related to crop-specific traits such as root morphology or nutrient demand (Li et al. 2014), they remain after all challenging to interpret. Further studies are required to decipher the specific mechanisms of these crop-specific management effects on particular soil biochemical properties. In addition, these interactions evidently constitute an important finding with major implications for soil health assessment and the evaluation of soil health-oriented farming systems. Given this strong crop effect even on less dynamic soil parameters such as TN (Table 1), we propose that future on-site comparisons of different farming systems must ensure identical crops on the respective fields or plots.

3.4 | Conservation Farming Effects on the Soil Health Index

In the next step, we evaluated conservation farming advances by deriving a soil health index from the measured soil health

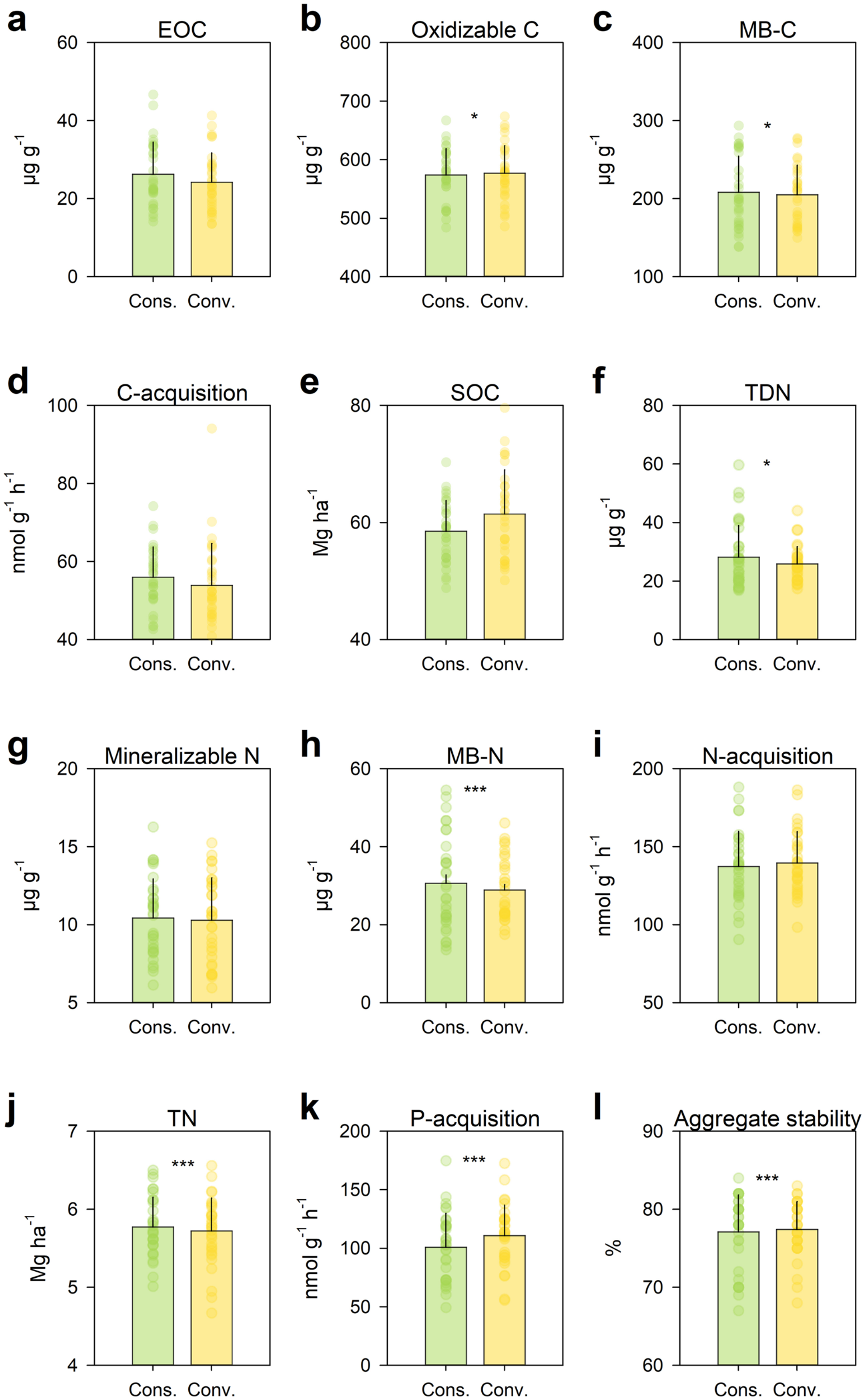


FIGURE 3 | Conservation farming effects on soil health parameters related to (a–e) C cycling, (f–j) N cycling, (k) P cycling and (l) aggregate stability. Given is the mean ± SD, and asterisks above bars indicate significant differences between management systems (*$p<0.05$; **$p<0.01$; ***$p<0.001$) as revealed by multivariate analysis of variance.

indicators (Ferretti et al. 2024). The most important PCs were selected based on eigenvalues > 1. As for our dataset, the first four dimensions of the PCA had eigenvalues > 1 (3.56, 2.42, 1.78 and 1.31) and together explained 69.77% (27.36%, 18.62%, 13.68% and 10.11% for PCs 1–4, respectively) of the total variation within the dataset (Table S2). The most important

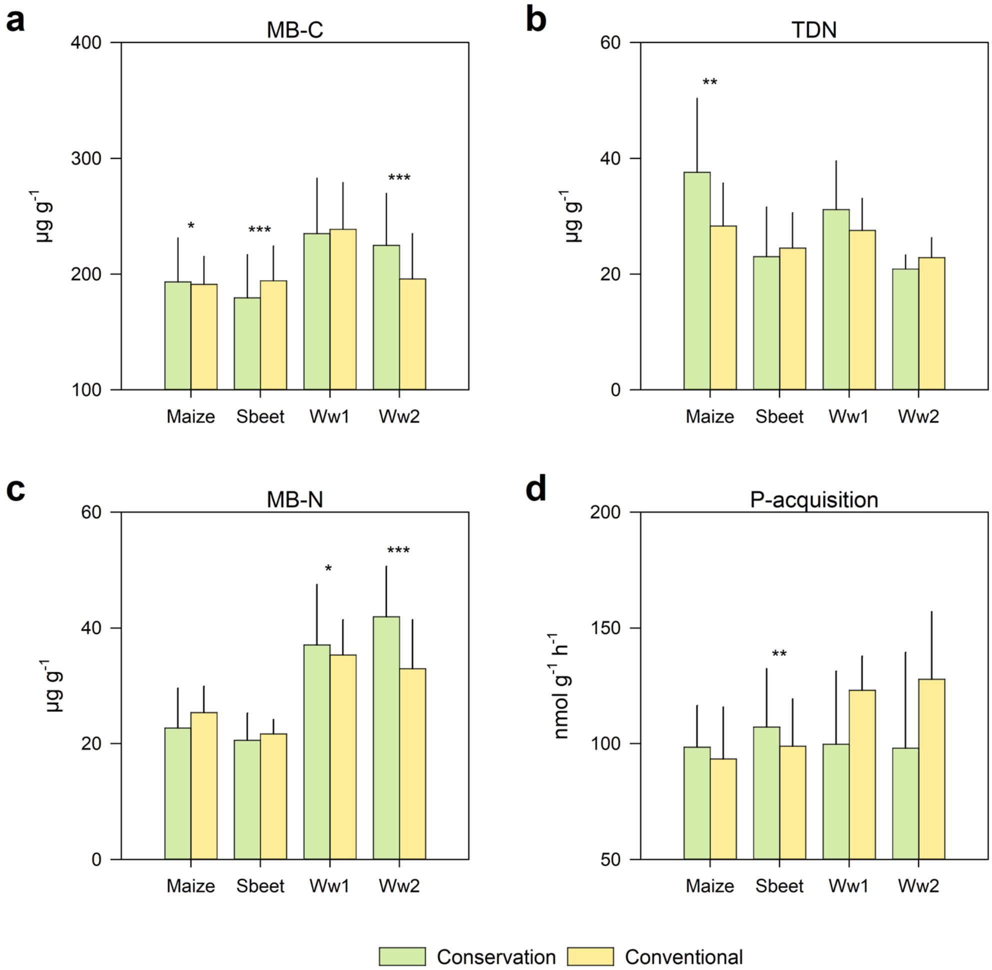
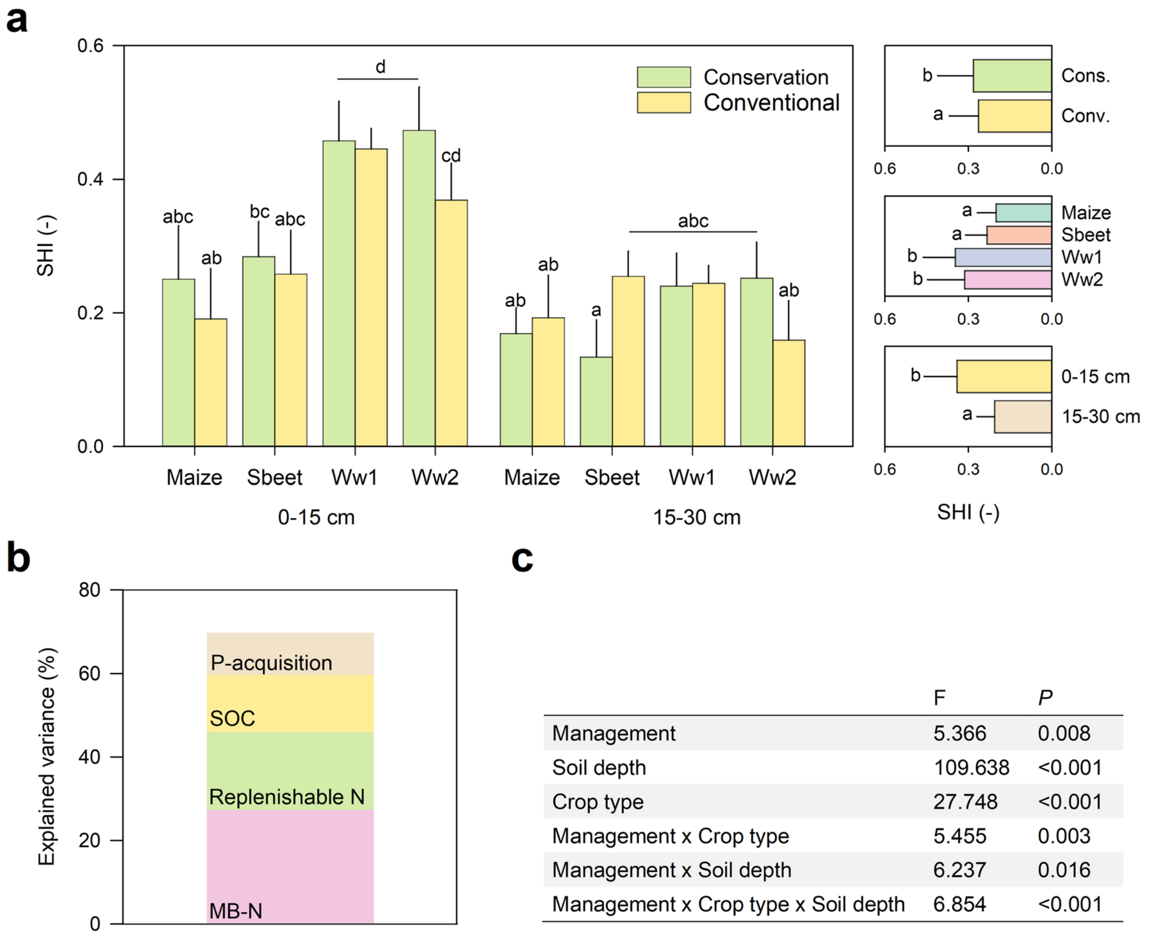


FIGURE 4 | Conservation farming effects on (a) MB-C, (b) TDN, (c) MB-N and (d) P-acquisition within each individual crop type (Maize; Sbeet, sugar beet; Ww1, winter wheat 1; Ww2, winter wheat 2). Given is the mean ± SD, and asterisks above bars indicate significant differences between management systems (* $p<0.05$; ** $p<0.01$; *** $p<0.001$) within each crop as revealed by one-way ANOVA.

variable in each PC by means of loading was MB-N, mineralizable N, SOC and P-acquisition for PCs 1–4, respectively (Table S2), implying that parameters particularly related to soil N-cycling seem to be important indicators for management change (Teng et al. 2024).

For these variables, weights of 0.392, 0.267, 0.196, and 0.145 (for MB-N, mineralizable N, SOC and P-acquisition, respectively; Figure 5b) were used in order to calculate a final SHI for each sample. The ensuing MANOVA revealed significant soil health gains with a shift towards conservation farming (Figure 5a,c). The soil health index increased significantly by 6.84% (from 0.26 ± 0.02 to 0.28 ± 0.02), which is on the lower end of previously reported soil health gains through conservation farming (Das et al. 2021; Roy et al. 2022; Yang et al. 2024). Evidently, more dramatic changes in management, for example, a shift from conventional to no tillage or from monocropping towards highly diverse crop rotations, induce stronger responses in soil health. For example, several studies reported soil health improvements of 30%–50% with no-till (Hussain et al. 1999; Raiesi and Kabiri 2016; Roy et al. 2022) or a diversified crop rotation (Yang et al. 2024). Contrary to previous approaches, our study specifically aimed at testing a viable alternative to conventional farming that can be easily implemented in terms of soil cultivation, cover cropping, and marketing of the cultivated crops (as opposed to more severe management changes such as no-till or organic farming). As such, it is not surprising that the obtained advances in soil health are rather low. Moreover, fine-textured soils are less sensitive to changes in management as compared to coarse-textured soils (Rosinger, Bodner, et al. 2023), thus often exhibiting a lagged response.

Like trends observed for individual soil health-related parameters, the SHI was strongly affected by crop type (Figure 5a,c). Both Ww1 and Ww2 (0.33 ± 0.03 on average) exhibited a significantly higher SHI as compared to Maize (0.20 ± 0.02) and Sbeet (0.23 ± 0.02). While we recognized overall declines in SHI from topsoil to deeper soil layers, these reductions were—upon closer inspection—only observed for Ww1 and Ww2 (Figure 5a) probably owed to differences in root distribution and architecture. This reinforces the importance of crop type as a superior modifier of soil health-related parameters such as MB-C and MB-N, N-acquisition, or aggregate stability (Figure S4) over farming management, an aspect that requires particular consideration for future soil health assessments of farming systems.



	F	P
Management	5.366	0.008
Soil depth	109.638	<0.001
Crop type	27.748	<0.001
Management x Crop type	5.455	0.003
Management x Soil depth	6.237	0.016
Management x Crop type x Soil depth	6.854	<0.001

FIGURE 5 | (a) The effect of agricultural management (conservation vs. conventional), crop type (Maize; Sbeet, sugar beet; Ww1, winter wheat 1; Ww2 winter wheat 2) and soil depth (0–15 and 15–30 cm) on the soil health index. Given is the mean ± SD, and different letters above or beside bars indicate significant differences ($p < 0.05$) revealed by analysis of variance; (b) explained variance of the four parameters used for the soil health assessment as revealed by principal component analysis; (c) results of a multivariate analysis of variance to evaluate the effect of management, soil depth and crop type as well as interactions thereof. Main effects are shown in (a) on the right-hand side.

3.5 | Conservation Farming Effects on GHG Emissions

While soil health and crop yields are key indicators of productivity, assessing GHG emissions at the field scale provides a broader view of environmental impact, assuring that efforts to improve soil and crop performance through conservation farming align with climate change mitigation goals (IPCC 2015). Here, we used the CF Tool to evaluate whether a shift towards conservation farming induced reductions in GHG emissions (Hillier et al. 2011). Along with the realized soil health advances, conservation farming also led to a significant reduction in GHG emissions: while the conventional farming system emitted 1681 ± 72 kg CO_2-eq ha^{-1}, the conservation farming system could reduce GHG emissions to 959 ± 256 kg CO_2-eq ha^{-1} ($p = 0.003$; Figure 6b); this constitutes a GHG reduction potential of 43.4%, which is well in line with potential indicated in corresponding literature (Huang et al. 2018; Shakoor et al. 2022; Yang et al. 2024). The largest savings in GHG emissions could be achieved with reduced soil tillage (−222 kg CO_2-eq ha^{-1} or 33.3%) and reduced expenses for fertilizer production (−121 kg CO_2-eq ha^{-1} or 30%) as a consequence of the diversified crop rotation (Figure 5a). Here, the cultivation of soybean and faba bean in particular reduced the overall use of mineral fertilizer, either directly or indirectly, via the positive pre-crop N effect suggested for leguminous crops (Guinet et al. 2020). On the other hand, the overall greater share of cover and inter crops weighed negatively on GHG emissions of the conservation farming system (Figure 5a); here, emissions increased by 204 kg CO_2-eq ha^{-1} or 84% in the conservation farming system. This increase can be explained by modelled N_2O emissions of legume-based cover crops inherent to the CF Tool (Schipanski et al. 2024). Although the cultivation of cover crops in arable systems has been associated with increased N_2O emissions (Matthews et al. 2025), the assumption that legume-based cover crops invariably increase N_2O emissions has recently been questioned. Several field studies have instead reported negligible or even positive effects of legume cover crops on overall N_2O balances (Basche et al. 2014; Sanz-Cobena et al. 2014; Muhammad et al. 2019). Apparently, mineral N fertilization results in sudden N_2O peaks and was found to outweigh legume-based cover cropping in its N_2O emission potential (Peyrard et al. 2016); thus, substituting N supply from mineral fertilization by legume-based cover cropping may contribute favourably to overall GHG emissions (Tribouillois et al. 2015). Legume-based cover cropping in combination with

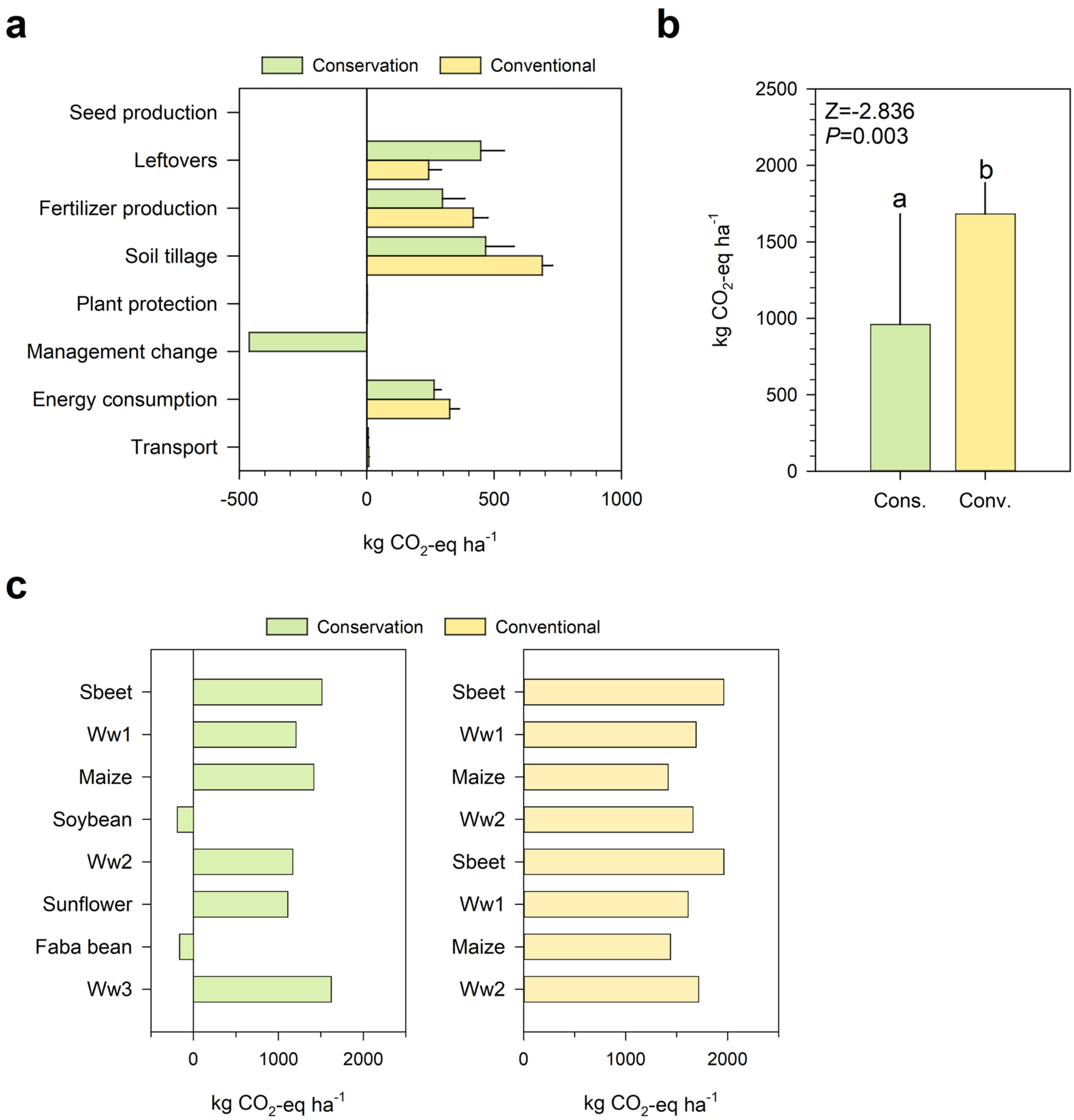


FIGURE 6 | GHG emissions (in kg CO_2-eq ha^{-1}) of a conservation and a conventional farming system for a whole crop rotation period (8 years) for (a) each individual sector, (b) for the whole management system and (c) for each individual crop in the respective farming system (Sbeet, sugar beet; Ww, winter wheat). Given is the mean ± SD, and different letters above bars in (b) indicate significant differences ($p < 0.05$) between management systems as revealed by the Mann–Whitney U test.

other sustainable farming management practices such as crop residue retention or reduced tillage results in N immobilization over autumn and better remobilization in spring for the subsequent crop and may thus further ensure sustainability advances within conservation farming systems (Frimpong and Baggs 2010).

In line with this notion, the incorporation of faba bean and soybean into the crop rotation had a strong positive effect on the conservation farming systems overall GHG emissions, since these legume crops showed a negative net balance on GHG emissions (−163.7 and −190.7 kg CO_2-eq ha^{-1} for faba bean and soybean, respectively; Figure 6c). This renders legume crops not only an important measure for N supply, but also for the overall environmental impact of farming systems as such (Matthews et al. 2025).

When using the CF Tool, certain potential shortcomings and inaccuracies need to be recognized. Model-based plot-scale estimates of GHG emissions may not accurately depict real-world GHG emissions from the field. For example, given our current understanding, the proposed effect of cover cropping on GHG emissions, particularly N_2O emissions, requires reassessment and should be fine-tuned to site- and management-specific characteristics which mainly determine whether cover crops facilitate or mitigate N_2O emissions. According to the methodology outlined by the IPCC's Guidelines for National Greenhouse Gas Inventories in 2006, C dynamics in the applied model are limited to a 20-year timeframe, which results in a sharp increase in calculated GHG emissions after the 20-year period. Although not relevant in our case study, soil texture differences and organic fertilization are inherently important metrics strongly shaping the projected GHG emissions with the CF Tool. To comprehensively evaluate long-term advances in soil health and crop production with conservation farming, future studies should integrate not only the global warming potential via field-level measurements of GHG fluxes but also additional environmental impacts, for example through comprehensive life cycle assessment approaches (Goglio et al. 2015).

In addition, the financial sustainability of conservation systems deserves attention, particularly with respect to the marketability of specific crops within diversified rotations. The cultivation of less commonly grown crops not only faces limited market opportunities but may also involve additional management challenges and—subsequently—an inherent risk of yield reductions. These agronomic and economic factors together represent potential barriers to the long-term adoption of conservation farming (Scopel et al. 2013).

4 | Conclusion

Our comprehensive analysis revealed significant soil health advances and reduced GHG emissions with the adoption of conservation farming measures without compromising crop yields. Yield levels remained virtually unchanged over the initial 8-year experimental period, with higher Sbeet yields in the drought years of 2017 and 2018 indicating a more resilient crop production with conservation farming under drought. The observed soil health improvements with conservation farming were particularly evident for parameters related to soil N rather than C cycling and to dynamic, microbial-related properties such as MB-C or -N as well as P-acquisition. For several commonly measured soil health parameters, we found a larger effect of crop species compared to farming system. This, together with the observed crop type-dependent management effects, implies that soil health assessments must guarantee similar crops on the plots/field to be compared.

Easily implementable measures such as reduced tillage, greater crop diversity and an increased share of cover crops inherit a great potential to advance farming systems in temperate cropping regions, with inherent soil health improvements through conservation farming representing a key adaptation and mitigation strategy against the negative effects of climate change to warrant future crop production.

Author Contributions

Christoph Rosinger: conceptualization, investigation, methodology, data curation, supervision, formal analysis, project administration, resources, writing – original draft, funding acquisition, visualization. **Golo Gotthalmseder:** investigation, formal analysis, data curation, methodology. **Gernot Bodner:** supervision, writing – original draft, conceptualization, validation. **Katharina M. Keiblinger:** writing – original draft, conceptualization, supervision, validation. **Stefan J. Forstner:** conceptualization, data curation, writing – original draft, validation, supervision. **Taru Sandén:** writing – original draft, conceptualization, validation. **Giacomo Ferretti:** methodology, formal analysis, writing – original draft, visualization, data curation. **Moltinë Prebibaj:** writing – original draft, validation. **Reinhard W. Neugschwandtner:** conceptualization, data curation, supervision, resources, writing – original draft, methodology. **Hans-Peter Kaul:** conceptualization, methodology, data curation, supervision, resources, project administration, writing – original draft, funding acquisition.

Acknowledgements

We thank Gerlinde Wieshammer, Elisabeth Ziss, Craig Jackson, Astrid Hobel, Elisabeth Kopecky, and Stefan Hotz for support with laboratory analyses, and Doris Meisinger and Andreas Hans for supporting with the evaluation of aboveground biomass and crop yield. Open Access funding provided by Universitat fur Bodenkultur Wien/KEMÖ.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

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

References

Amelung, W., D. Bossio, W. de Vries, et al. 2020. "Towards a Global-Scale Soil Climate Mitigation Strategy." *Nature Communications* 11: 1–10.

Andrews, S. S., D. Karlen, and J. Mitchell. 2002. "A Comparison of Soil Quality Indexing Methods for Vegetable Production Systems in Northern California." *Agriculture, Ecosystems & Environment* 90: 25–45.

Armenise, E., M. Redmile-Gordon, A. Stellacci, A. Ciccarese, and P. Rubino. 2013. "Developing a Soil Quality Index to Compare Soil Fitness for Agricultural Use Under Different Managements in the Mediterranean Environment." *Soil and Tillage Research* 130: 91–98.

Askari, M. S., and N. M. Holden. 2015. "Quantitative Soil Quality Indexing of Temperate Arable Management Systems." *Soil and Tillage Research* 150: 57–67.

Basche, A. D., F. E. Miguez, T. C. Kaspar, and M. J. Castellano. 2014. "Do Cover Crops Increase or Decrease Nitrous Oxide Emissions? A Meta-Analysis." *Journal of Soil and Water Conservation* 69: 471–482.

Blanco-Canqui, H., and S. J. Ruis. 2020. "Cover Crop Impacts on Soil Physical Properties: A Review." *Soil Science Society of America Journal* 84: 1527–1576.

BMLRT. 2022. *Richtlinie für die sachgerechte Düngung im Ackerbau und Grünland*. Vol. 8. Auflage.

Bodner, G., A. Zeiser, K. Keiblinger, et al. 2023. "Managing the Pore System: Regenerating the Functional Pore Spaces of Natural Soils by Soil-Health Oriented Farming Systems." *Soil and Tillage Research* 234: 105862.

Bogunovic, I., P. Pereira, I. Kisic, K. Sajko, and M. Sraka. 2018. "Tillage Management Impacts on Soil Compaction, Erosion and Crop Yield in Stagnosols (Croatia)." *Catena* 160: 376–384.

Bohoussou, Y. N. D., Y.-H. Kou, W.-B. Yu, et al. 2022. "Impacts of the Components of Conservation Agriculture on Soil Organic Carbon and Total Nitrogen Storage: A Global Meta-Analysis." *Science of the Total Environment* 842: 156822.

Brookes, P., A. Landman, G. Pruden, and D. Jenkinson. 1985. "Chloroform Fumigation and the Release of Soil Nitrogen: A Rapid Direct Extraction Method to Measure Microbial Biomass Nitrogen in Soil." *Soil Biology and Biochemistry* 17: 837–842.

Campdelacreu Rocabruna, P., X. Domene, C. Preece, and J. Peñuelas. 2024. "Relationship Among Soil Biophysicochemical Properties, Agricultural Practices and Climate Factors Influencing Soil Phosphatase Activity in Agricultural Land." *Agriculture* 14: 288.

Crystal-Ornelas, R., R. Thapa, and K. L. Tully. 2021. "Soil Organic Carbon Is Affected by Organic Amendments, Conservation Tillage, and Cover Cropping in Organic Farming Systems: A Meta-Analysis." *Agriculture, Ecosystems & Environment* 312: 107356.

Culman, S. W., S. S. Snapp, M. A. Freeman, et al. 2012. "Permanganate Oxidizable Carbon Reflects a Processed Soil Fraction That Is Sensitive to Management." *Soil Science Society of America Journal* 76: 494–504.

Das, S., R. Bhattacharyya, T. Das, et al. 2021. "Soil Quality Indices in a Conservation Agriculture Based Rice-Mustard Cropping System in North-Western Indo-Gangetic Plains." *Soil and Tillage Research* 208: 104914.

Das, S., S. Chatterjee, and J. Rajbanshi. 2022. "Responses of Soil Organic Carbon to Conservation Practices Including Climate-Smart Agriculture in Tropical and Subtropical Regions: A Meta-Analysis." *Science of the Total Environment* 805: 150428.

de Vries, F. T., and T. Caruso. 2016. "Eating From the Same Plate? Revisiting the Role of Labile Carbon Inputs in the Soil Food Web." *Soil Biology and Biochemistry* 102: 4–9.

DeLuca, T., D. Keeney, and G. McCarty. 1992. "Effect of Freeze-Thaw Events on Mineralization of Soil Nitrogen." *Biology and Fertility of Soils* 14: 116–120.

FAO I. UNICEF WFP WHO. 2017. "The state of food security and nutrition in the world 2017. Building resilience for peace and food security."

Ferretti, G., C. Rosinger, E. Diaz-Pines, B. Faccini, M. Coltorti, and K. M. Keiblinger. 2024. "Soil Quality Increases With Long-Term Chabazite-Zeolite Tuff Amendments in Arable and Perennial Cropping Systems." *Journal of Environmental Management* 354: 120303.

Fowler, A. F., B. Basso, N. Millar, and W. F. Brinton. 2023. "A Simple Soil Mass Correction for a More Accurate Determination of Soil Carbon Stock Changes." *Scientific Reports* 13: 2242.

Frimpong, K. A., and E. Baggs. 2010. "Do Combined Applications of Crop Residues and Inorganic Fertilizer Lower Emission of N_2O From Soil?" *Soil Use and Management* 26: 412–424.

Ghaley, B. B., T. Rusu, T. Sandén, et al. 2018. "Assessment of Benefits of Conservation Agriculture on Soil Functions in Arable Production Systems in Europe." *Sustainability* 10: 794.

Godfray, H. C. J., and T. Garnett. 2014. "Food Security and Sustainable Intensification." *Philosophical Transactions of the Royal Society, B: Biological Sciences* 369: 20120273.

Goglio, P., W. N. Smith, B. B. Grant, et al. 2015. "Accounting for Soil Carbon Changes in Agricultural Life Cycle Assessment (LCA): A Review." *Journal of Cleaner Production* 104: 23–39.

Govaerts, B., N. Verhulst, A. Castellanos-Navarrete, K. D. Sayre, J. Dixon, and L. Dendooven. 2009. "Conservation Agriculture and Soil Carbon Sequestration: Between Myth and Farmer Reality." *Critical Reviews in Plant Sciences* 28: 97–122.

Guinet, M., B. Nicolardot, and A.-S. Voisin. 2020. "Nitrogen Benefits of Ten Legume Pre-Crops for Wheat Assessed by Field Measurements and Modelling." *European Journal of Agronomy* 120: 126151.

Guo, L. B., and R. M. Gifford. 2002. "Soil Carbon Stocks and Land Use Change: A Meta Analysis." *Global Change Biology* 8: 345–360.

Hallama, M., C. Pekrun, S. Pilz, et al. 2021. "Interactions Between Cover Crops and Soil Microorganisms Increase Phosphorus Availability in Conservation Agriculture." *Plant and Soil* 463: 307–328.

Hari, V., O. Rakovec, Y. Markonis, M. Hanel, and R. Kumar. 2020. "Increased Future Occurrences of the Exceptional 2018–2019 Central European Drought Under Global Warming." *Scientific Reports* 10: 12207.

Haynes, R. 1983. "Soil Acidification Induced by Leguminous Crops." *Grass and Forage Science* 38: 1–11.

Hillier, J., C. Walter, D. Malin, T. Garcia-Suarez, L. Mila-i-Canals, and P. Smith. 2011. "A Farm-Focused Calculator for Emissions From Crop and Livestock Production." *Environmental Modelling & Software* 26: 1070–1078.

Hobbs, P. R., K. Sayre, and R. Gupta. 2008. "The Role of Conservation Agriculture in Sustainable Agriculture." *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences* 363: 543–555.

Hood-Nowotny, R., N. H.-N. Umana, E. Inselbacher, P. Oswald-Lachouani, and W. Wanek. 2010. "Alternative Methods for Measuring Inorganic, Organic, and Total Dissolved Nitrogen in Soil." *Soil Science Society of America Journal* 74: 1018–1027.

Huang, Y., W. Ren, L. Wang, et al. 2018. "Greenhouse Gas Emissions and Crop Yield in No-Tillage Systems: A Meta-Analysis." *Agriculture, Ecosystems & Environment* 268: 144–153.

Hussain, I., K. Olson, M. Wander, and D. Karlen. 1999. "Adaptation of Soil Quality Indices and Application to Three Tillage Systems in Southern Illinois." *Soil and Tillage Research* 50: 237–249.

IPCC, R. Pichs-Madruga, Y. Sokona, et al. 2015. *Climate Change 2014: Mitigation of Climate Change*. Cambridge University Press.

Kaul, H. 2004. "Pre-Crop Effects of Grain Legumes and Linseed on Soil Mineral N and Productivity of Subsequent Winter Rape and Winter Wheat Crops." *BODENKULTUR-Wien and MUNCHEN* 55: 95.

Knapp, S., and M. G. van der Heijden. 2018. "A Global Meta-Analysis of Yield Stability in Organic and Conservation Agriculture." *Nature Communications* 9: 3632.

Lal, R., P. Smith, H. F. Jungkunst, et al. 2018. "The Carbon Sequestration Potential of Terrestrial Ecosystems." *Journal of Soil and Water Conservation* 73: 145A–152A.

Larney, F. J., J. J. Nitschelm, P. J. Regitnig, D. C. Pearson, R. E. Blackshaw, and N. Z. Lupwayi. 2016. "Sugar Beet Response to Rotation and Conservation Management in a 12-Year Irrigated Study in Southern Alberta." *Canadian Journal of Plant Science* 96: 776–789.

Lehmann, J., D. A. Bossio, I. Kögel-Knabner, and M. C. Rillig. 2020. "The Concept and Future Prospects of Soil Health." *Nature Reviews Earth and Environment* 1: 544–553.

Li, H., Q. Ma, H. Li, F. Zhang, Z. Rengel, and J. Shen. 2014. "Root Morphological Responses to Localized Nutrient Supply Differ Among Crop Species With Contrasting Root Traits." *Plant and Soil* 376: 151–163.

Li, Y., S. X. Chang, L. Tian, and Q. Zhang. 2018. "Conservation Agriculture Practices Increase Soil Microbial Biomass Carbon and Nitrogen in Agricultural Soils: A Global Meta-Analysis." *Soil Biology and Biochemistry* 121: 50–58.

Lobell, D. B., M. B. Burke, C. Tebaldi, M. D. Mastrandrea, W. P. Falcon, and R. L. Naylor. 2008. "Prioritizing Climate Change Adaptation Needs for Food Security in 2030." *Science* 319: 607–610.

Lobell, D. B., and S. M. Gourdji. 2012. "The Influence of Climate Change on Global Crop Productivity." *Plant Physiology* 160: 1686–1697.

Man, M., C. Wagner-Riddle, K. E. Dunfield, B. Deen, and M. J. Simpson. 2021. "Long-Term Crop Rotation and Different Tillage Practices Alter Soil Organic Matter Composition and Degradation." *Soil and Tillage Research* 209: 104960.

Martín-Sanz, J. P., A. de Santiago-Martín, I. Valverde-Asenjo, J. R. Quintana-Nieto, C. González-Huecas, and A. L. López-Lafuente. 2022. "Comparison of Soil Quality Indexes Calculated by Network and Principal Component Analysis for Carbonated Soils Under Different Uses." *Ecological Indicators* 143: 109374.

Matthews, L., J. A. Strauss, T. Reinsch, et al. 2025. "Legumes and Livestock in No-Till Crop Rotations: Effects on Nitrous Oxide Emissions, Carbon Sequestration, Yield, and Wheat Protein Content." *Agricultural Systems* 224: 104218.

Mayer, M., C. Rosinger, M. Gorfer, et al. 2022. "Surviving Trees and Deadwood Moderate Changes in Soil Fungal Communities and Associated Functioning After Natural Forest Disturbance and Salvage Logging." *Soil Biology and Biochemistry* 166: 108558.

McBride, R. 1912. "The Standardization of Potassium Permanganate Solution by Sodium Oxalate." *Journal of the American Chemical Society* 34: 393–416.

Mei, K., Z. Wang, H. Huang, et al. 2018. "Stimulation of N_2O Emission by Conservation Tillage Management in Agricultural Lands: A Meta-Analysis." *Soil and Tillage Research* 182: 86–93.

Moravec, V., Y. Markonis, O. Rakovec, et al. 2021. "Europe Under Multi-Year Droughts: How Severe Was the 2014–2018 Drought Period?" *Environmental Research Letters* 16: 034062.

Muhammad, I., U. M. Sainju, F. Zhao, et al. 2019. "Regulation of Soil CO2 and N_2O Emissions by Cover Crops: A Meta-Analysis." *Soil and Tillage Research* 192: 103–112.

Muindi, E. D. M. 2019. "Understanding Soil Phosphorus." *International Journal of Plant & Soil Science* 31: 1–18.

Negassa, W., and P. Leinweber. 2009. "How Does the Hedley Sequential Phosphorus Fractionation Reflect Impacts of Land Use and Management on Soil Phosphorus: A Review." *Journal of Plant Nutrition and Soil Science* 172: 305–325.

Page, K. L., Y. P. Dang, and R. C. Dalal. 2020. "The Ability of Conservation Agriculture to Conserve Soil Organic Carbon and the Subsequent Impact on Soil Physical, Chemical, and Biological Properties and Yield." *Frontiers in Sustainable Food Systems* 4: 31.

Parihar, C., H. Nayak, V. Rai, et al. 2019. "Soil Water Dynamics, Water Productivity and Radiation Use Efficiency of Maize Under Multi-Year Conservation Agriculture During Contrasting Rainfall Events." *Field Crops Research* 241: 107570.

Patra, S., S. Julich, K.-H. Feger, et al. 2019. "Soil Hydraulic Response to Conservation Agriculture Under Irrigated Intensive Cereal-Based Cropping Systems in a Semiarid Climate." *Soil and Tillage Research* 192: 151–163.

Peel, M. C., B. L. Finlayson, and T. A. McMahon. 2007. "Updated World Map of the Köppen-Geiger Climate Classification." *Hydrology and Earth System Sciences* 11: 1633–1644.

Peigné, J., J.-F. Vian, V. Payet, and N. P. Saby. 2018. "Soil Fertility After 10 Years of Conservation Tillage in Organic Farming." *Soil and Tillage Research* 175: 194–204.

Peyrard, C., B. Mary, P. Perrin, et al. 2016. "N_2O Emissions of Low Input Cropping Systems as Affected by Legume and Cover Crops Use." *Agriculture, Ecosystems & Environment* 224: 145–156.

Pittelkow, C. M., X. Liang, B. A. Linquist, et al. 2015. "Productivity Limits and Potentials of the Principles of Conservation Agriculture." *Nature* 517: 365–368.

Ponisio, L. C., L. K. M′Gonigle, K. C. Mace, J. Palomino, P. De Valpine, and C. Kremen. 2015. "Diversification Practices Reduce Organic to Conventional Yield Gap." *Proceedings of the Royal Society B: Biological Sciences* 282: 20141396.

Preissel, S., M. Reckling, N. Schläfke, and P. Zander. 2015. "Magnitude and Farm-Economic Value of Grain Legume Pre-Crop Benefits in Europe: A Review." *Field Crops Research* 175: 64–79.

Raiesi, F., and V. Kabiri. 2016. "Identification of Soil Quality Indicators for Assessing the Effect of Different Tillage Practices Through a Soil Quality Index in a Semi-Arid Environment." *Ecological Indicators* 71: 198–207.

Rosinger, C., G. Bodner, L. G. Bernardini, et al. 2023. "Benchmarking Carbon Sequestration Potentials in Arable Soils by on-Farm Research on Innovative Pioneer Farms." *Plant and Soil* 488: 137–156.

Rosinger, C., G. Bodner, V. Forer, et al. 2025. "Changes in Microbial Physiology and Carbon-Use Efficiency Upon Improving Soil Habitat Conditions in Conservation Farming Systems." *Agriculture, Ecosystems & Environment* 377: 109246.

Rosinger, C., K. Keiblinger, M. Bieber, et al. 2023. "On-Farm Soil Organic Carbon Sequestration Potentials Are Dominated by Site Effects, Not by Management Practices." *Geoderma* 433: 116466.

Rosinger, C., J. Rousk, and H. Sandén. 2019. "Can Enzymatic Stoichiometry Be Used to Determine Growth-Limiting Nutrients for Microorganisms?-A Critical Assessment in Two Subtropical Soils." *Soil Biology and Biochemistry* 128: 115–126.

Roy, D., A. Datta, H. S. Jat, et al. 2022. "Impact of Long Term Conservation Agriculture on Soil Quality Under Cereal Based Systems of North West India." *Geoderma* 405: 115391.

Rusinamhodzi, L., M. Corbeels, M. T. Van Wijk, M. C. Rufino, J. Nyamangara, and K. E. Giller. 2011. "A Meta-Analysis of Long-Term Effects of Conservation Agriculture on Maize Grain Yield Under Rain-Fed Conditions." *Agronomy for Sustainable Development* 31: 657–673.

Sadiq, M., G. Li, N. Rahim, and M. M. Tahir. 2021. "Sustainable Conservation Tillage Technique for Improving Soil Health by Enhancing Soil Physicochemical Quality Indicators Under Wheat Mono-Cropping System Conditions." *Sustainability* 13: 8177.

Sae-Tun, O., K. M. Keiblinger, C. Rosinger, A. Mentler, H. Mayer, and G. Bodner. 2023. "Characterization of Aggregate-Stabilized Dissolved Organic Matter Release-A Novel Approach to Determine Soil Health Advances of Conservation Farming Systems." *Plant and Soil* 488: 101–119.

Sanderman, J., T. Hengl, and G. J. Fiske. 2017. "Soil Carbon Debt of 12,000 Years of Human Land Use." *Proceedings of the National Academy of Sciences* 114: 9575–9580.

Sanz-Cobena, A., S. García-Marco, M. Quemada, J. Gabriel, P. Almendros, and A. Vallejo. 2014. "Do Cover Crops Enhance N_2O, CO_2 or CH_4 Emissions From Soil in Mediterranean Arable Systems?" *Science of the Total Environment* 466: 164–174.

Schinner, F., R. Öhlinger, E. Kandeler, and R. Margesin. 2012. *Methods in Soil Biology*. Springer Science & Business Media.

Schipanski, M. E., S. C. McClelland, H. M. Hughes, et al. 2024. "Improving Decision Support Tools for Quantifying GHG Emissions From Organic Production Systems." *Organic Agriculture* 14: 503–512.

Scopel, E., B. Triomphe, F. Affholder, et al. 2013. "Conservation Agriculture Cropping Systems in Temperate and Tropical Conditions, Performances and Impacts. A Review." *Agronomy for Sustainable Development* 33: 113–130.

Shakoor, A., A. A. Dar, M. S. Arif, et al. 2022. "Do Soil Conservation Practices Exceed Their Relevance as a Countermeasure to Greenhouse Gases Emissions and Increase Crop Productivity in Agriculture?" *Science of the Total Environment* 805: 150337.

Shen, J., L. Yuan, J. Zhang, et al. 2011. "Phosphorus Dynamics: From Soil to Plant." *Plant Physiology* 156: 997–1005.

Shukla, M., R. Lal, and M. Ebinger. 2006. "Determining Soil Quality Indicators by Factor Analysis." *Soil and Tillage Research* 87: 194–204.

Singh, A., L. Bordoloi, M. Kumar, S. Hazarika, and B. Parmar. 2014. "Land Use Impact on Soil Quality in Eastern Himalayan Region of India." *Environmental Monitoring and Assessment* 186: 2013–2024.

Sun, J., W. Niu, Y. Du, et al. 2024. "Regionally Adapted Conservation Tillage Reduces the Risk of Crop Yield Losses: A Global Meta-Analysis." *Soil and Tillage Research* 244: 106265.

Tatzber, M., N. Schlatter, A. Baumgarten, et al. 2015. "KMnO4 Determination of Active Carbon for Laboratory Routines: Three Long-Term Field Experiments in Austria." *Soil Research* 53: 190–204.

Teng, J., R. Hou, J. A. Dungait, et al. 2024. "Conservation Agriculture Improves Soil Health and Sustains Crop Yields After Long-Term Warming." *Nature Communications* 15: 8785.

Thierfelder, C., M. Mwila, and L. Rusinamhodzi. 2013. "Conservation Agriculture in Eastern and Southern Provinces of Zambia: Long-Term Effects on Soil Quality and Maize Productivity." *Soil and Tillage Research* 126: 246–258.

Tribouillois, H., P. Cruz, J.-P. Cohan, and É. Justes. 2015. "Modelling Agroecosystem Nitrogen Functions Provided by Cover Crop Species in Bispecific Mixtures Using Functional Traits and Environmental Factors." *Agriculture, Ecosystems & Environment* 207: 218–228.

Vance, E., P. Brookes, and D. Jenkinson. 1987. "Microbial Biomass Measurements in Forest Soils: The Use of the Chloroform Fumigation-Incubation Method in Strongly Acid Soils." *Soil Biology and Biochemistry* 19: 697–702.

Wanek, W., D. Zezula, D. Wasner, M. Mooshammer, and J. Prommer. 2019. "A Novel Isotope Pool Dilution Approach to Quantify Gross Rates of Key Abiotic and Biological Processes in the Soil Phosphorus Cycle." *Biogeosciences* 16: 3047–3068.

Weil, R. R., K. R. Islam, M. A. Stine, J. B. Gruver, and S. E. Samson-Liebig. 2003. "Estimating Active Carbon for Soil Quality Assessment: A Simplified Method for Laboratory and Field Use." *American Journal of Alternative Agriculture* 18: 3–17.

Wieser, S., K. M. Keiblinger, A. Mentler, et al. 2024. "Labile Not Stable SOC Fractions Constitute the Manageable Drivers of Soil Health Advances in Carbon Farming." *Geoderma* 449: 116991.

Yang, X., J. Xiong, T. Du, et al. 2024. "Diversifying Crop Rotation Increases Food Production, Reduces Net Greenhouse Gas Emissions and Improves Soil Health." *Nature Communications* 15: 198.

Yao, R.-J., J.-S. Yang, T.-J. Zhang, et al. 2014. "Determination of Site-Specific Management Zones Using Soil Physico-Chemical Properties and Crop Yields in Coastal Reclaimed Farmland." *Geoderma* 232: 381–393.

Zander, P., T. Amjath-Babu, S. Preissel, et al. 2016. "Grain Legume Decline and Potential Recovery in European Agriculture: A Review." *Agronomy for Sustainable Development* 36: 1–20.

Zhang, Y., D. Xie, J. Ni, and X. Zeng. 2020. "Conservation Tillage Practices Reduce Nitrogen Losses in the Sloping Upland of the Three Gorges Reservoir Area: No-Till Is Better Than Mulch-Till." *Agriculture, Ecosystems & Environment* 300: 107003.

Zheng, C., Y. Jiang, C. Chen, et al. 2014. "The Impacts of Conservation Agriculture on Crop Yield in China Depend on Specific Practices, Crops and Cropping Regions." *Crop Journal* 2: 289–296.

Zhou, Y., H. Ma, Y. Xie, et al. 2020. "Assessment of Soil Quality Indexes for Different Land Use Types in Typical Steppe in the Loess Hilly Area, China." *Ecological Indicators* 118: 106743.

Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Figure S1:** Aboveground biomass (in Mg ha^{-1}) of (a) winter wheat 1 (Ww1), (b) winter wheat 2 (Ww2), (c) maize and (d) sugar beet (Sbeet) in a conventional (yellow dots and bars) and conservation (green dots and bars) farming system from 2015 to 2022. Standard errors show ± SD, and significant differences between farming systems within each year are indicated (*$p < 0.05$; †$p < 0.1$). Bars on the right-hand side display the average aboveground biomass across all eight years, and different letters above bars indicate significant differences ($p < 0.05$) between management systems. **Figure S2:** Aboveground biomass (green dots) and crop yield (red dots) of (a) sunflower (b) soy bean and (c) faba bean (in Mg ha^{-1}) in the conservation farming system from 2015 to 2022. Shown is the mean ± SD. **Figure S3:** Soil health parameters related to (a–e) C cycling, (f–j) N cycling, (k) P cycling and (l) aggregate stability at two soil depths (0–15 and 15–30 cm). Given is the mean ± SD, and asterisks above bars indicate significant differences between soil depths (*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$) as revealed by multivariate analysis of variance. **Figure S4:** Soil health parameters related to (a–e) C cycling, (f–j) N cycling, (k) P cycling and (l) aggregate stability for four different crops (Maize; Sbeet, sugar beet; Ww1, winter wheat 1; Ww2, winter wheat 2) across both management systems and soil depths. Given is the mean ± SD, and different letters above bars indicate significant differences between crop types ($p < 0.05$) as revealed by post hoc Tukey tests within the multivariate analysis of variance. **Table S2:** Variable loadings on the first four rotated principal components (RC) and communalities (h2) extracted from the PCA of the conservation and conventional farming system. Variables selected for the minimum dataset after checking for autocorrelations and redundancy are highlighted in bold. **Table S3:** Test statistics of the MANCOVA analysis to evaluate the effect of management (conservation vs. conventional), crop type (Ww1, Ww2, Maize, Sbeet), soil depth (0–15 cm, 15.30 cm) and block as well as the interactions between block and the other three variables ($n = 64$). Given is the Wilks' lambda as well as F- and p-values. **Table S1:** Management information for the conventional and theconservation farming system from 2015 to 2022. Given are details on crop management (rotation, yield, crop residue management), fertilization (type and amount), plant protection (type and amount), energy consumption for field operations (process, fuel use) and transport of harvested crops.