

Final Report for the Project

„Schafft eine konservierende Wirtschaftsweise in der Landwirtschaft den Spagat zwischen Bodengesundheit und Ertragsstabilität? – eine Fallstudie aus einem Kernagrargebiet in Österreich“

funded by BIOS Science Austria

submitted by

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Tulln an der Donau, December 2025

Introduction

Global agricultural production is currently facing immense pressures. While global food demand is rising, increased frequency and severity of extreme weather events such as flooding, droughts, and heatwaves along critical levels of soil degradation – imposed by agricultural management practices such as intensive tillage, low crop diversity or crop residue removal – pose a significant challenge to meet this demand. Conservation farming practices – including reduced tillage, a diversified crop rotation or the implementation of cover crops – have emerged as promising tools to increase soil health and fertility, thus counteracting degraded soils and the inherent risk of compromising crop production. However, the effects of conservation farming on crop yields are not always consistent, and yield declines have been reported in scientific literature, particularly in the initial years of adoption.

While the sustainability of farming systems is often evaluated based on soil health advances, broader environmental impacts of farming systems are important to consider. For example, a farming system that maintains strong soil health and high yields but depends heavily on carbon-intensive inputs (such as synthetic fertilizers and fossil-fuel energy) cannot be considered sustainable in the long-term. So far, there exist only a few studies that have evaluated crop yields and soil health advances alongside greenhouse gas emissions and the use efficiency of key elements such as nitrogen.

In this project, we compare the effect of conventional and conservation farming practices on soil health, crop yields, greenhouse gas emissions and nutrient-use efficiencies at a long-term experimental site in Tulln, Lower Austria. Established in 2015, the experimental site comprises two distinct farming systems. The first is a conventional system, defined by conventional tillage to a depth of 25 cm, a simplified crop rotation, and minimal incorporation of cover crops. The second is a conservation system, which employs shallow tillage limited to 5 cm, features a more diversified crop rotation, and makes extensive use of both cover crops and intercrops. Eight years after implementation, we calculated (i) a soil health index based on thirteen physicochemical and biological parameters, (ii) field-scale greenhouse gas emissions using the CoolFarm-Tool, and (iii) aboveground biomass as well as grain nitrogen-use efficiency. These calculations were complemented by eight-year data on crop yield and aboveground biomass to assess conservation farming advances and potential soil health–crop yield trade-offs.

Methodology

Experimental Site and Design

The study was conducted at a long-term field experiment established in 2015 in Tulln, North-Eastern Austria. The site features a dry-temperate climate and a Chernozem soil with loamy clay texture and neutral pH. Two farming systems were compared: (i) conventional farming, with tillage to 20–25 cm, a simple four-year crop rotation (sugar beet–winter wheat–maize–winter wheat), and minimal use of cover crops; and (ii) conservation farming, with shallow tillage at 5 cm, an extended eight-year rotation including legumes and oilseeds, and extensive use of cover and intercrops. Both systems received identical fertilization and plant protection according to national guidelines. The experiment followed a randomized block design comprising 24 large plots, in which each crop of the respective rotations was grown every year in duplicate.

Soil Sampling

Soil samples were collected in June 2024 from selected plots where identical main crops were present in both systems (sugar beet, winter wheat 1, maize, winter wheat 2). Samples were taken at 0–15 cm and 15–30 cm using a soil corer. Five subsamples per plot were pooled to create composite samples. After sieving (<2 mm), samples were either air-dried or stored at 4 °C until analysis. Undisturbed cores (100 cm³) were taken for bulk density determination. In total, 64 soil samples were obtained.

Aboveground Biomass and Yield

Aboveground biomass of winter wheat, maize and sugar beet was harvested at physiological maturity on defined sampling areas. Grain or seed samples were dried before weighing, while sugar beet yield was recorded as fresh root mass.

Laboratory Analyses

Soil analyses included pH, total C and N, inorganic C (for SOC calculation), microbial biomass C and N (fumigation–extraction), oxidizable C (KMnO₄ method), mineralizable N (anaerobic incubation), aggregate stability (wet sieving), and potential activities of key hydrolytic enzymes involved in C, N and P cycling (fluorometric microplate assay). SOC and total N pools were calculated using the equivalent soil mass approach.

Soil Health Index

A Soil Health Index was calculated using a Principal Component Analysis (PCA)–based minimum data set approach. Thirteen soil parameters representing physical, chemical, and biological functions were standardized and analyzed by PCA. Indicators with the highest factor loadings were selected, scored on a 0–1 scale, weighted by their contribution to explained variance, and summed to obtain the SHI.

Carbon Footprint Assessment

Greenhouse gas emissions were estimated using the CoolFarm Tool (v2.11.0). Model inputs included crop yields, fertilizer and pesticide use, cover crop management, field operations, and fuel use. Emissions were calculated for each crop based on average management practices across 2015–2022 to compare system-level carbon footprints.

Nitrogen-use efficiency

We further evaluated aboveground biomass and grain nitrogen use efficiency according to Moitzi et al. (2020)¹, where:

- i. $NUE_{\text{Aboveground biomass}} (\text{g g}^{-1}) = \text{Aboveground biomass} (\text{kg ha}^{-1}) / \text{Nitrogen supply} (\text{kg ha}^{-1})$
- i. $NUE_{\text{Grain}} (\text{g g}^{-1}) = \text{Grain yield} (\text{kg ha}^{-1}) / \text{Nitrogen supply} (\text{kg ha}^{-1})$

and

- ii. $\text{Nitrogen supply} (\text{kg ha}^{-1}) = N_{\text{Fertilizer}} (\text{kg ha}^{-1}) + NO_3\text{-N}_{\text{Beginning}} (\text{kg ha}^{-1})$

$N_{\text{Fertilizer}}$ refers to the amount of fertilizer added to the respective crop, whereas $NO_3\text{-N}_{\text{Beginning}}$ refers to the amount of N in the soil at the beginning of the vegetation period. $NO_3\text{-N}$ was extracted with a 1M potassium chloride solution, subsequently colored with Griess reagent and vanadium(III)-chloride solution, and absorption was measured at 540 nm using an EnSpire® Multiplate reader (Perkin Elmer, USA)². Yield, aboveground biomass and mineral nitrogen data for winter wheat (WW) and maize from the years 2015-2019 were used for the evaluation of aboveground biomass and grain nitrogen-use efficiency.

Statistical Analysis

Data were checked for normality and homogeneity of variance and log-transformed when required. Differences in crop yields were assessed using one-way ANOVA. Soil properties and SHI were evaluated using MANOVA with farming system, crop type, and soil depth as factors, followed by Tukey post hoc tests when applicable. GHG emissions between systems were compared using the Mann–Whitney U test.

For both aboveground biomass and grain nitrogen-use efficiency (g g^{-1}), we used a univariate ANOVA with system (conservation, conventional), crop type (winter wheat, maize) and season (2015-2019) as main factors. Significant differences between years were evaluated using post-hoc Duncan tests. Statistical significance was defined as $p < 0.05$.

A detailed description of the methods can be found in the attached publication.

¹Moitzi et al. (2020). Efficiency of mineral nitrogen fertilization in winter wheat under Pannonian climate conditions. Agriculture, 10(11), 541.

²Pai et al. (2021). Determination of nitrate in natural waters by vanadium reduction and the griess assay: reassessment and optimization. ACS ES&T Water, 1(6), 1524-1532.

Results

Across the full experimental period (2015–2022), conservation farming did not result in overall yield losses (Figure 1). Nonetheless, yield differences between the two systems occurred in specific years. Notably, sugar beet yields were significantly higher under conservation farming in 2017 and 2018, coinciding with the severe drought conditions experienced in Central Europe during those years. This suggests that conservation farming systems may be show a higher resistance towards environmental stresses, resulting in higher crop yield levels.

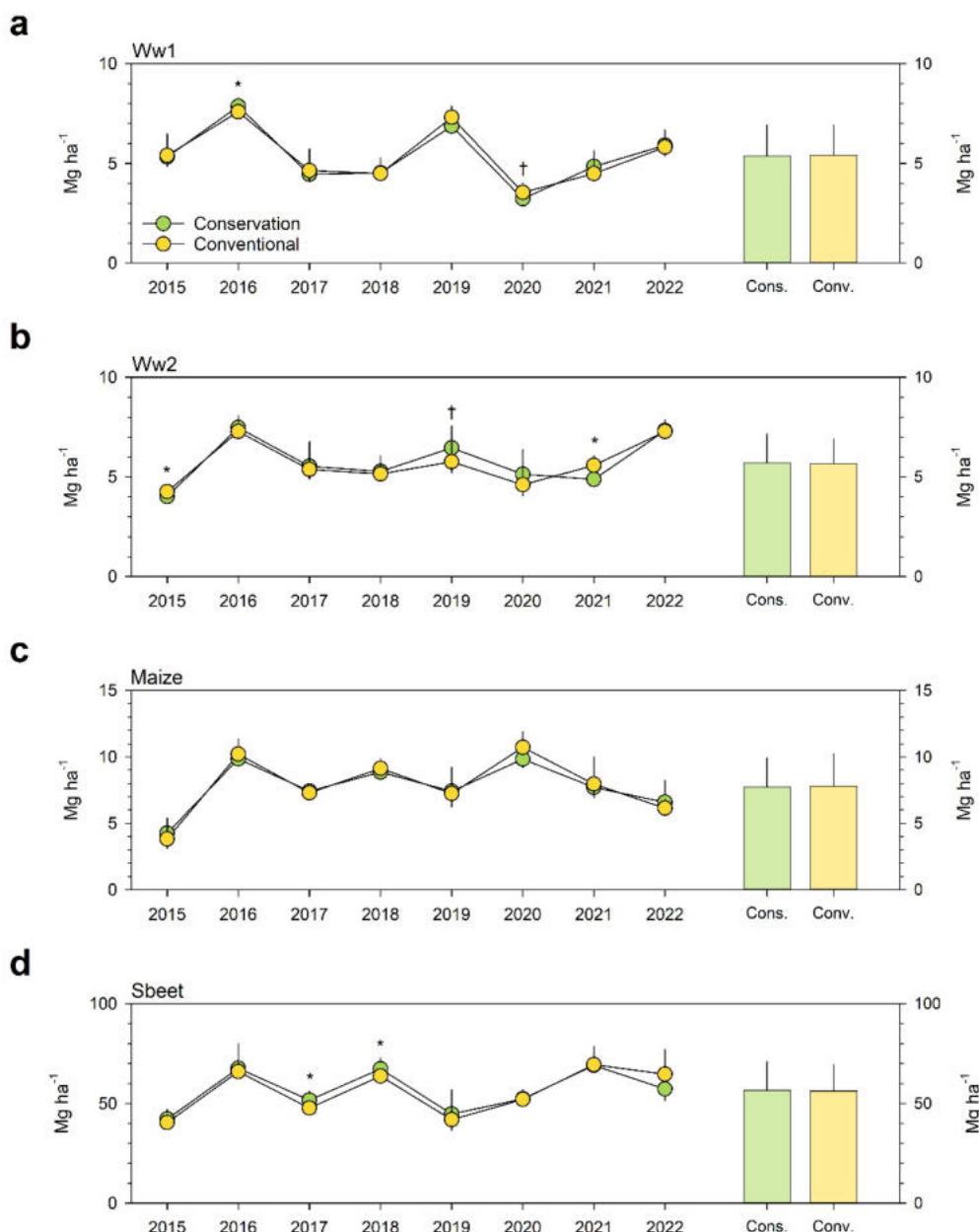


Figure 1. Crop yield (in Mg ha^{-1}) of (a) winter wheat 1 (Ww1), (b) winter wheat 2 (Ww2), (c) Maize and (d) sugar beet (Sbeet) in a conventional (yellow dots and bars) and conservation (green dots and bars) farming system from 2015 to 2022. Standard errors show $\pm \text{SD}$, and significant differences 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.

We also assessed a range of soil health indicators related to soil structure, soil organic matter, and microbial-driven carbon-, nitrogen-, and phosphorus-cycling. The MANOVA analysis showed no significant differences in SOC – a key soil health indicator – between the two farming systems.

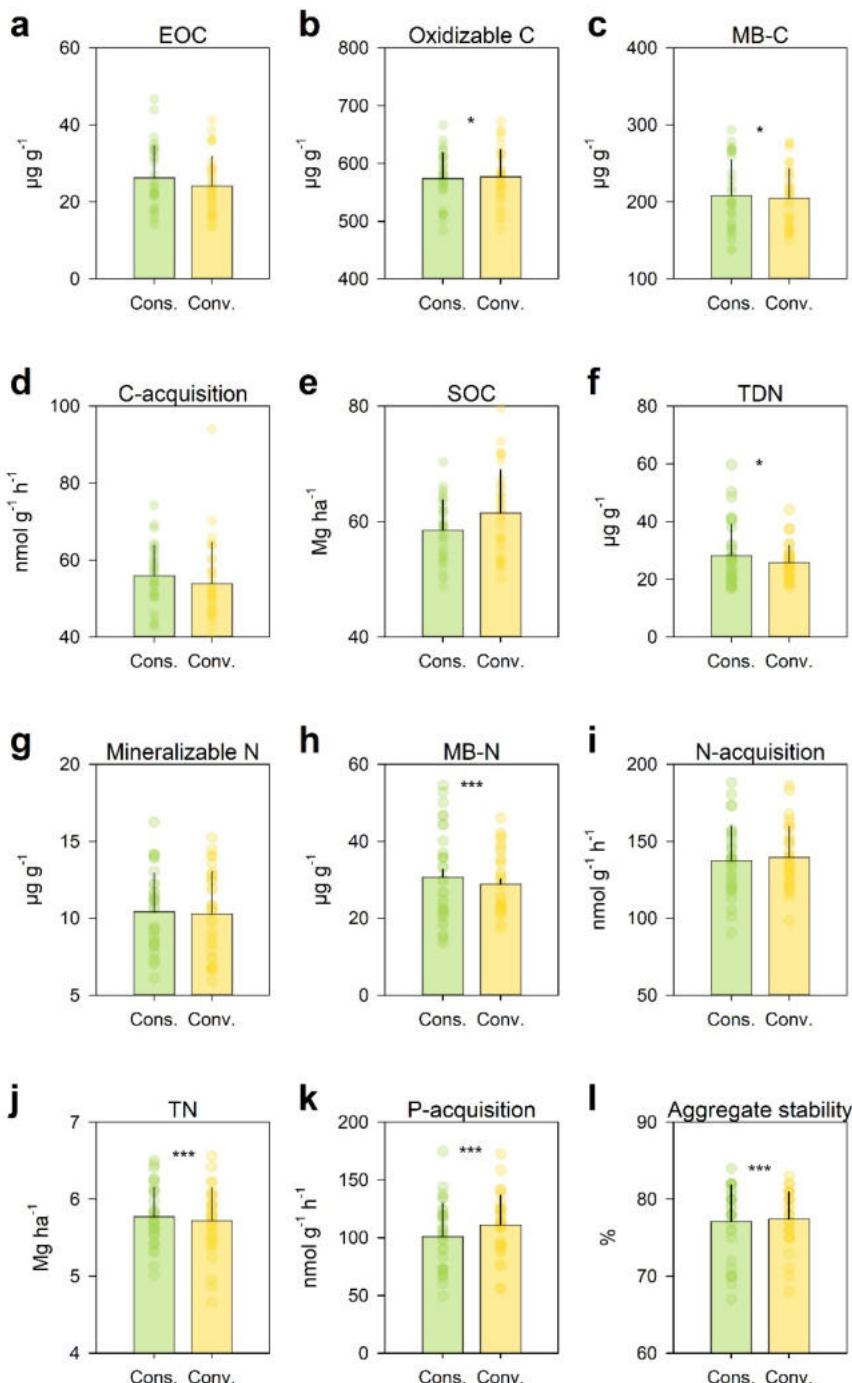


Figure 2. Conservation farming effects on soil health parameters related to (a–e) carbon cycling, (f–j) nitrogen cycling, (k) phosphorus cycling and (l) aggregate stability. Given is the mean \pm SD, and asterisks above bars indicate significant differences between management systems (* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$) as revealed by multivariate analysis of variance. EOC, extractable organic carbon; Oxidizable C, KMnO₄-oxidizable carbon; MB-C, microbial biomass carbon; C-acquisition, potential activity of carbon-acquiring enzymes; SOC, soil organic carbon; TDN, total dissolved nitrogen; Mineralizable N, mineralizable nitrogen from anaerobic incubation; MB-N, microbial biomass nitrogen; N-acquisition, potential activity of nitrogen-acquiring enzymes; TN, total nitrogen; P-acquisition, potential activity of phosphorus-acquiring enzymes.

More sensitive indicators of soil health revealed clearer and more immediate responses to the shift toward conservation farming than soil organic carbon alone (Figure 2). Oxidizable carbon, a widely used indicator of the labile and microbially available carbon pool, decreased under conservation farming. In contrast, microbial biomass carbon increased significantly. These opposing trends suggest that conservation management may stimulate microbial growth and activity, potentially leading to higher biological demand for easily oxidizable carbon.

Soil health parameters related to nitrogen cycling were, for the most part, positively influenced by conservation farming. Total nitrogen stocks were higher under conservation management, and labile nitrogen fractions – including total dissolved nitrogen and microbial biomass nitrogen – showed significant increases. These results indicate an improved capacity for nitrogen retention and biological nitrogen cycling in the conservation system. Carbon- and nitrogen-acquisition did not differ between the two management systems, suggesting that microbial nutrient demand for carbon and nitrogen was relatively stable across treatments. However, potential activities of phosphorus-acquiring enzymes were lower under conservation farming compared with conventional farming, potentially reflecting differences in phosphorus availability, microbial community composition or substrate quality.

In addition to management effects, crop type had a highly significant influence on nearly all evaluated soil health indicators (Figure 3), with the exception of carbon- and phosphorus-acquisition enzyme activities and soil organic carbon stocks. The strongest differences were observed when comparing winter wheat with maize and sugar beet. Winter wheat plots consistently exhibited higher microbial biomass carbon and nitrogen, higher nitrogen-acquisition activity, and markedly improved aggregate stability, reaching differences of up to 60–70% relative to maize and sugar beet plots. Conversely, extractable organic carbon concentrations were higher in maize and sugar beet plots, indicating an accumulation of soluble or partially decomposed organic compounds under these crops.

Overall, these findings highlight that while some soil properties respond slowly to management changes (e.g., soil organic carbon), others – particularly microbial and nitrogen-related indicators – are more sensitive and can detect early transitions in soil functioning under conservation agriculture. They also demonstrate that crop type plays a major role in shaping soil biological and structural properties, sometimes to a greater extent than management system alone.

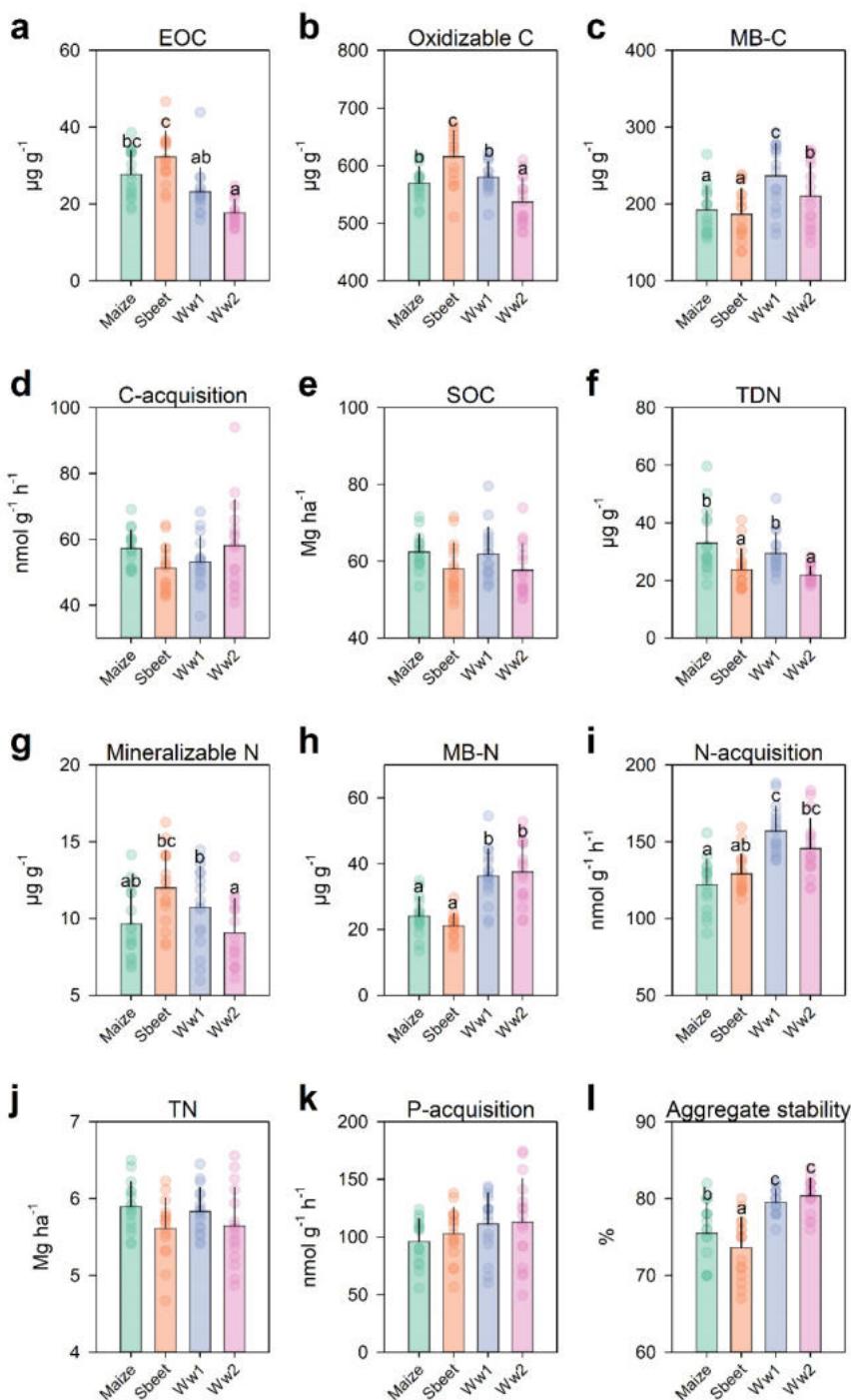


Figure 3. Soil health parameters related to (a-e) carbon cycling, (f-j) nitrogen cycling, (k) phosphorus cycling and (l) aggregate stability for four different crops (Maize; Sbeet, sugar beet; Ww1, winter wheat 1; Ww2, winter wheat 2) across both management systems and soil depths. Given is the mean \pm 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. Abbreviations are similar to Figure 2.

To assess overall progress in soil functioning, we integrated all measured indicators into a soil health index. PCA identified microbial biomass nitrogen, mineralizable nitrogen, soil organic carbon, and phosphorus-acquisition as the key variables driving the first four principal components. Based on these indicators, the subsequent MANOVA showed a significant improvement in soil health under conservation farming. Overall, the soil health index increased by 6.84% compared with conventional management.

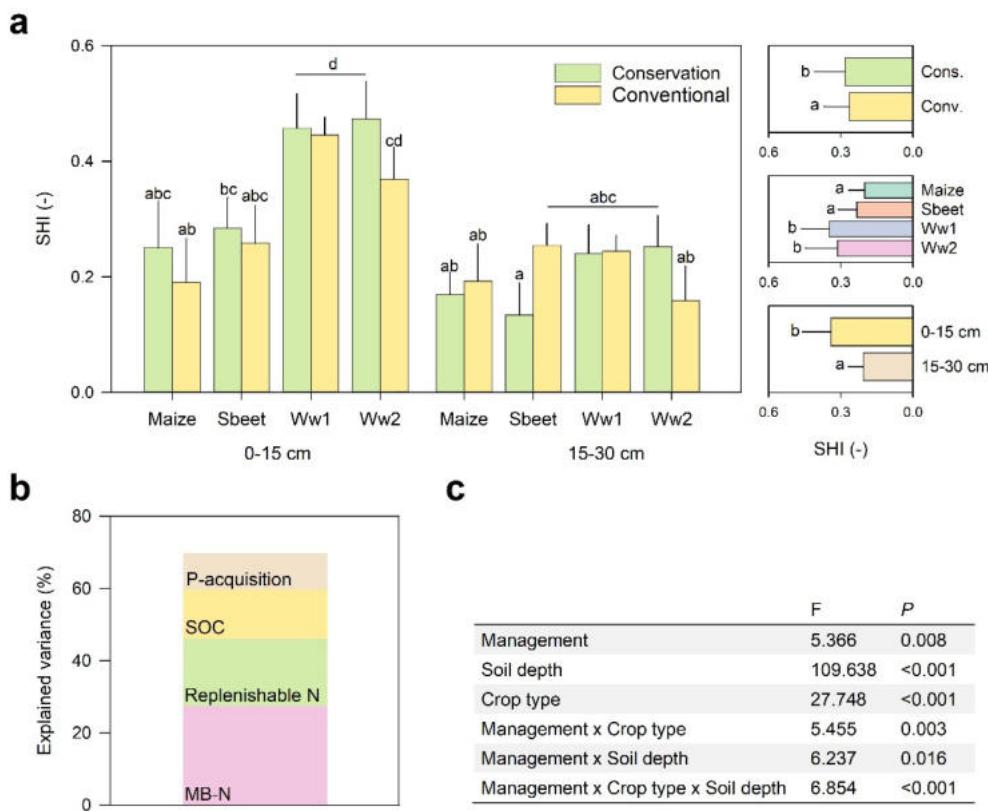


Figure 4. (a) The effect of agricultural management (conservation vs. conventional), crop type (Maize; Sbeet, sugar beet; Ww1, winter wheat 1; Ww2 winter wheat 2) and soil depth (0–15 and 15–30 cm) on the soil health index. Given is the mean \pm SD, and different letters above or beside bars indicate 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. P-acquisition, potential activity of phosphorus-acquiring enzymes; SOC, soil organic carbon, replenishable N, mineralizable nitrogen from anaerobic incubation; MB-N, microbial biomass nitrogen.

The soil health index was also strongly influenced by crop type. Both winter wheat crops (Ww1 and Ww2) showed significantly higher soil health index values than maize and sugar beet. Although the soil health index generally declined from topsoil to deeper layers, this pattern was only evident for the winter wheat plots, likely reflecting differences in root distribution and architecture. These findings highlight crop type as a major driver of soil health – often exerting a stronger influence on indicators such as microbial biomass, nitrogen-acquisition, and aggregate stability than the farming system itself. This underscores the need to account for crop-specific effects when evaluating soil health in agricultural systems.

We applied the CoolFarm-Tool to assess the impact of conservation farming on greenhouse gas emissions. Globally, agriculture contributes ca. 25% to overall emitted greenhouse gas emissions. This is however largely region- and country-specific. According to the climate protection report of the Environmental Agency Austria (2024), agriculture contributes ca. 12.2% (7.8 Mio t CO₂-eq; with emissions trading) or 19.0% (without emissions trading) to Austria's greenhouse gas emissions in 2024. Based on the total area of agricultural land in Austria (i.e., 2.57 Mio. ha), this results in greenhouse gas emissions of ca. 3000 kg CO₂-eq ha⁻¹. Overall, rumen fermentation accounts for the majority of greenhouse gas emissions (ca. 4 Mio t CO₂-eq), fertilization of arable soils (ca. 1.8 Mio t CO₂-eq), organic fertilizer management (ca. 1.3 Mio t CO₂-eq) and direct energy use (ca. 0.9 Mio t CO₂-eq). In addition to improvements in soil health, the conservation farming system showed significantly reduced greenhouse gas emissions. While the conventional system emitted $1,681 \pm 72$ kg CO₂-eq ha⁻¹, conservation farming reduced emissions to 959 ± 256 kg CO₂-eq ha⁻¹, corresponding to a 43.4% reduction.

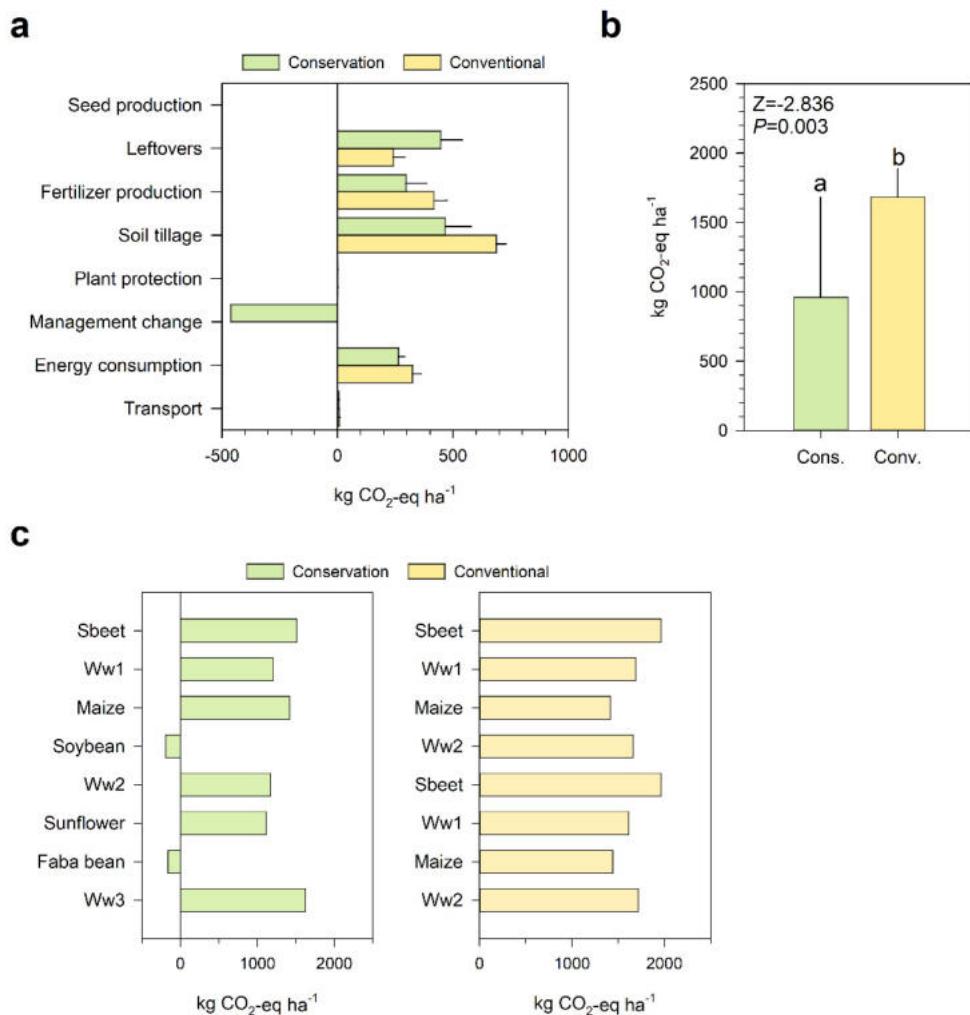


Figure 5. Greenhouse gas emissions (in kg CO₂-eq ha⁻¹) of a conservation and a conventional farming system for a whole crop rotation period (8 years) for (a) each individual sector, (b) for the whole management system and (c) for each individual crop in the respective farming system (Sbeet, sugar beet; Ww, winter wheat). Given is the mean \pm 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.

The largest reductions in greenhouse gas emissions were achieved through reduced soil tillage (-222 kg CO₂-eq ha⁻¹, 33.3%) and decreased fertilizer-related emissions (-121 kg CO₂-eq ha⁻¹, 30%) due to the diversified crop rotation. In particular, the cultivation of soybean and faba bean reduced the need for mineral fertilizers, either directly or via positive pre-crop nitrogen effects typical of legumes. Conversely, the greater share of cover and intercrops in the conservation system increased greenhouse gas emissions by 204 kg CO₂-eq ha⁻¹ (84%). Incorporating legume crops had a strong mitigating effect on overall emissions, with faba bean and soybean contributing -163.7 and -190.7 kg CO₂-eq ha⁻¹, respectively, highlighting their dual role in nitrogen supply and reducing the environmental impact of farming systems.

Finally, nitrogen-use efficiency of aboveground biomass and grain was evaluated. No significant differences were observed between conservation and conventional farming (Figure 6).

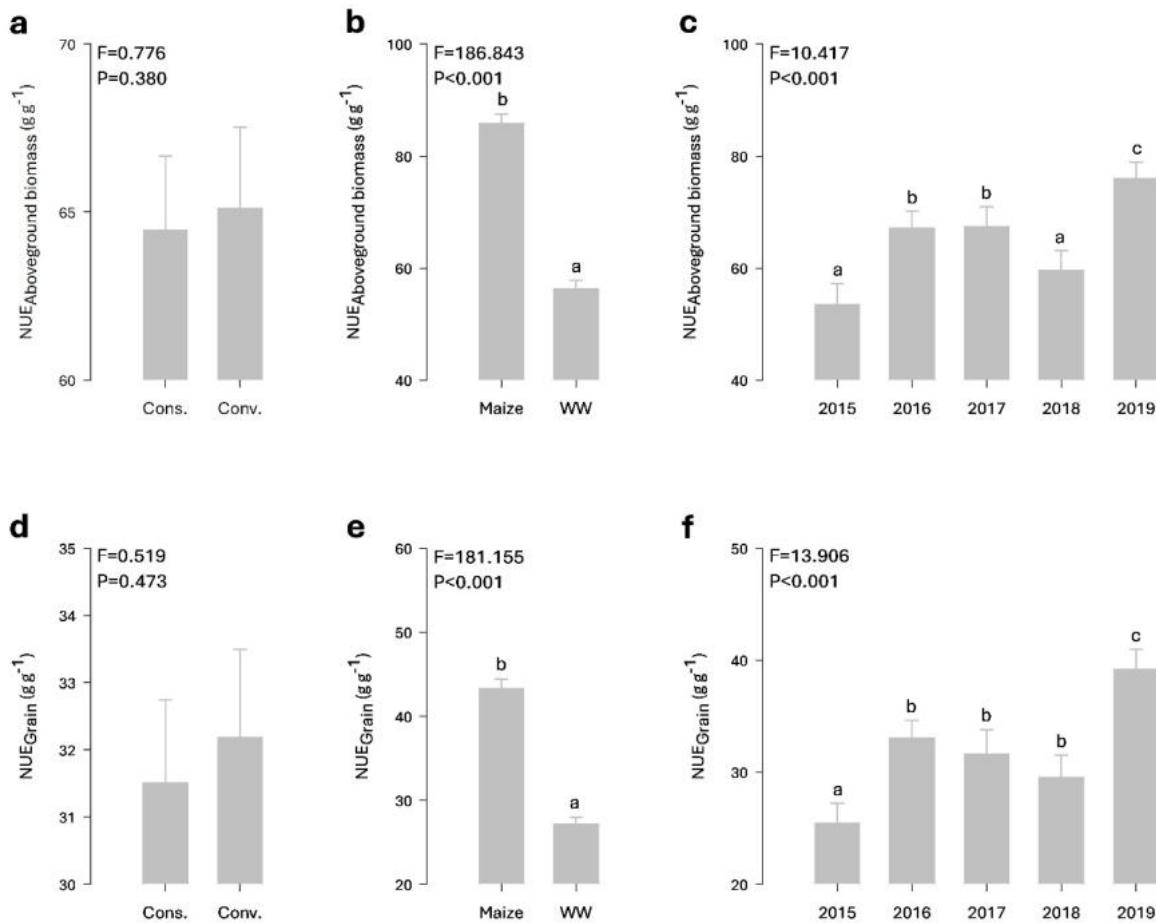


Figure 6. Differences in (a-c) aboveground biomass and grain (d-f) nitrogen-use efficiency (NUE) between farming systems (a, d), crop types (WW, winter wheat) (b, e) and crop year (c, f) for the years 2015-2019. Given is the mean \pm SE, and different letters above bars indicate significant differences between management systems, crop type or year ($P < 0.001$) as revealed by univariate ANOVA and post-hoc Duncan tests.

As with other measured parameters, nitrogen-use efficiency varied strongly between crop types and seasons. Maize showed significantly higher aboveground biomass and grain nitrogen-use efficiency compared with winter wheat. This aligns with known physiological differences between the crops: maize typically has higher nitrogen uptake capacity and greater biomass accumulation efficiency, partly due to its C4 photosynthetic pathway. In contrast, winter wheat exhibited lower NUE, which may reflect greater sensitivity to nitrogen timing or environmental conditions during its longer growth period. Overall, the observed nitrogen-use efficiency for winter wheat corresponded well with global estimates of ca. 30-35%³.

Since nitrogen-use efficiency comparisons between management systems were limited to these two crops, including additional crops from the rotations could influence the results. Interannual differences were largely driven by pedo-climatic conditions. For instance, severe droughts in Europe during 2015, 2017, and 2018 likely contributed to the lower nitrogen-use efficiency observed in 2015 and 2018. Clearly, further research is needed to disentangle the specific pedo-climatic factors affecting nitrogen-use efficiency in temperate arable systems.

Conclusions & Outlook

This project demonstrated that adopting conservation farming can significantly improve soil health and reduce greenhouse gas emissions without compromising crop yields or nitrogen-use efficiency. Yield levels remained largely stable over the 8-year experimental period. Soil health improvements were particularly pronounced for nitrogen-related parameters and dynamic, microbially-driven properties such as microbial biomass carbon and nitrogen and phosphorus-acquiring enzyme activity, whereas soil organic carbon – a widely used soil health indicator – showed little change.

Crop type often had a stronger influence on soil health than farming system, highlighting that crop choice is as important as management measures like reduced tillage or cover/intercropping. Simple, easily implementable measures – such as shallow tillage, diversified rotations, and increased cover crop/intercrop use – offer substantial potential to enhance temperate cropping systems. These practices not only improve soil health but also represent effective adaptation and mitigation strategies under changing climatic conditions, thereby supporting sustainable future crop production in the long-term.

³Omara et al. (2019). World cereal nitrogen use efficiency trends: review and current knowledge. *Agrosystems, Geosciences & Environment*, 2(1), 1-8; Raun & Johnson (1999). Improving nitrogen use efficiency for cereal production. *Agronomy journal*, 91(3), 357-363.

Overall, this project provided valuable insights into the potential of conservation farming in one of the key agricultural zones in Austria. From these results, several research questions arose that require further investigation in the future. One of the most pressing questions is the different development of carbon and nitrogen fractions with conservation farming. While most nitrogen fractions increased significantly under conservation farming, carbon fractions did not correspond. Since soil carbon and nitrogen are stoichiometrically rather constrained, it remains an open question why soil carbon lags behind in its response to management change. Since soil health is mainly driven by microbial-mediated processes, future studies should aim to further evaluate the concept of the soil microbial carbon pump⁴. This would include measurements of microbial growth, microbial necromass and different soil organic carbon fractions.

While this project clearly focused on carbon and nitrogen, covering several fractions of differing availability, investigating soil phosphorus would be another important next step. In this study, we could show that phosphorus acquisition was significantly higher under conventional farming. This could indicate a state of increased relative phosphorus limitation of the residing soil microbial community, which could have consequences for soil microbial biomass formation, and consequently soil organic carbon accrual⁵. However, this requires further verification using direct measurements of growth.

Another aspect that requires further investigation is the strong leverage of crop type for most of the evaluated soil health parameters as compared to management system. This could only be identified due to the unique structure of the experiment, i.e., that all crops of the respective crop rotations are grown in every vegetation period. This has strong implications for soil health. First, farmers have a strong leverage to improve soil health by adjusting their crop rotation. Future studies should thus in-depth evaluations of crop-type effects on soil health. Second, future soil health assessments (as e.g., outlined in the Soil Monitoring Law of the European Commission) have to consider these strong crop-specific effects on soil health when evaluating soil health of a given field, a management system, etc.

Further, while the investigation of a full 8-year crop rotation already gave valuable insights, we require a better understanding of real long-term effects of conservation farming. Therefore, it would be critical to consistently evaluate this experiment over decades.

⁴Liang, C., Schimel, J. P., & Jastrow, J. D. (2017). The importance of anabolism in microbial control over soil carbon storage. *Nature microbiology*, 2(8), 1-6.

⁵Tang et al. (2025). Soil carbon sequestration enhanced by long-term nitrogen and phosphorus fertilization. *Nature Geoscience*, 1-9.

⁵Kirkby et al. (2014). Nutrient availability limits carbon sequestration in arable soils. *Soil Biology and Biochemistry*, 68, 402-409.

Achieved milestones

We have successfully published our manuscript entitled 'Soil Health, Crop Yield and Carbon Footprint Trade-Offs Between Conservation and Conventional Farming: A Case Study' in the *European Journal of Soil Science* (see Appendix). The collaboration and the publication of this manuscript was highly appreciated by all project partners, and several new ideas arose from this research.

Further, our research results were made public to a broader audience with an article published in *Der Pflanzenarzt* (08/2025) entitled 'Langzeitversuch: Die Vorteile konservierender Bewirtschaftung. Verbesserte Bodengesundheit und CO₂-Fussabdruck, Ertrag gleich' (see Appendix). In addition, the project was mentioned in a special issue of the BOKU-managed magazine CAS as an example for high-quality research in the field of sustainable agricultural management conducted at BOKU University (see Appendix).

At the 65th Conference of the Society for Crop Science (September 23-25, 2025) at the University of Halle-Wittenberg, Univ. Prof. Dr. Hans-Peter Kaul presented the results of this project ('Yields, Soil Health and GHG Emissions in a Conventional vs. Conservation Farming System').

Golo Gotthalseder, the Master student who was employed through the project, has continued working in our research group after finishing the laboratory work and is currently in the final stage of his Master thesis.

Appendices

- Scientific publication

Rosinger, C., Gotthalseder, G., Bodner, G., Keiblinger, K.M., Forstner, S. J., Sandén, T., & Ferretti, G., Prebibaj, M., Neugschwandtner, R.W. & Kaul, H.-P. (2025). Soil Health, Crop Yield and Carbon Footprint Trade-Offs Between Conservation and Conventional Farming: A Case Study. *European Journal of Soil Science*, 76(5), e70194.

- Article in a non-scientific journal

Rosinger, C. & Kaul, H.-P. (2025). Langzeitversuch: Die Vorteile konservierender Bewirtschaftung. Verbesserte Bodengesundheit und CO₂-Fussabdruck, Ertrag gleich. *Der Pflanzenarzt*, 08/2025.

- Short Contribution

Boden im Fokus: Forschungsansätze für eine zukunftsfähige Landwirtschaft. *CAS Newsletter*, 16/2025.

- Invoices

- SAP statement

Note: The Rectorate has erroneously taken an overhead from the project, as can be seen in the SAP statement. We are currently clarifying this.

RESEARCH ARTICLE OPEN ACCESS

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

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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.

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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 Gourdjii 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 (ø 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 cm³ 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 m², maize and sugar beet in autumn on an area of 7.5 m². 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.

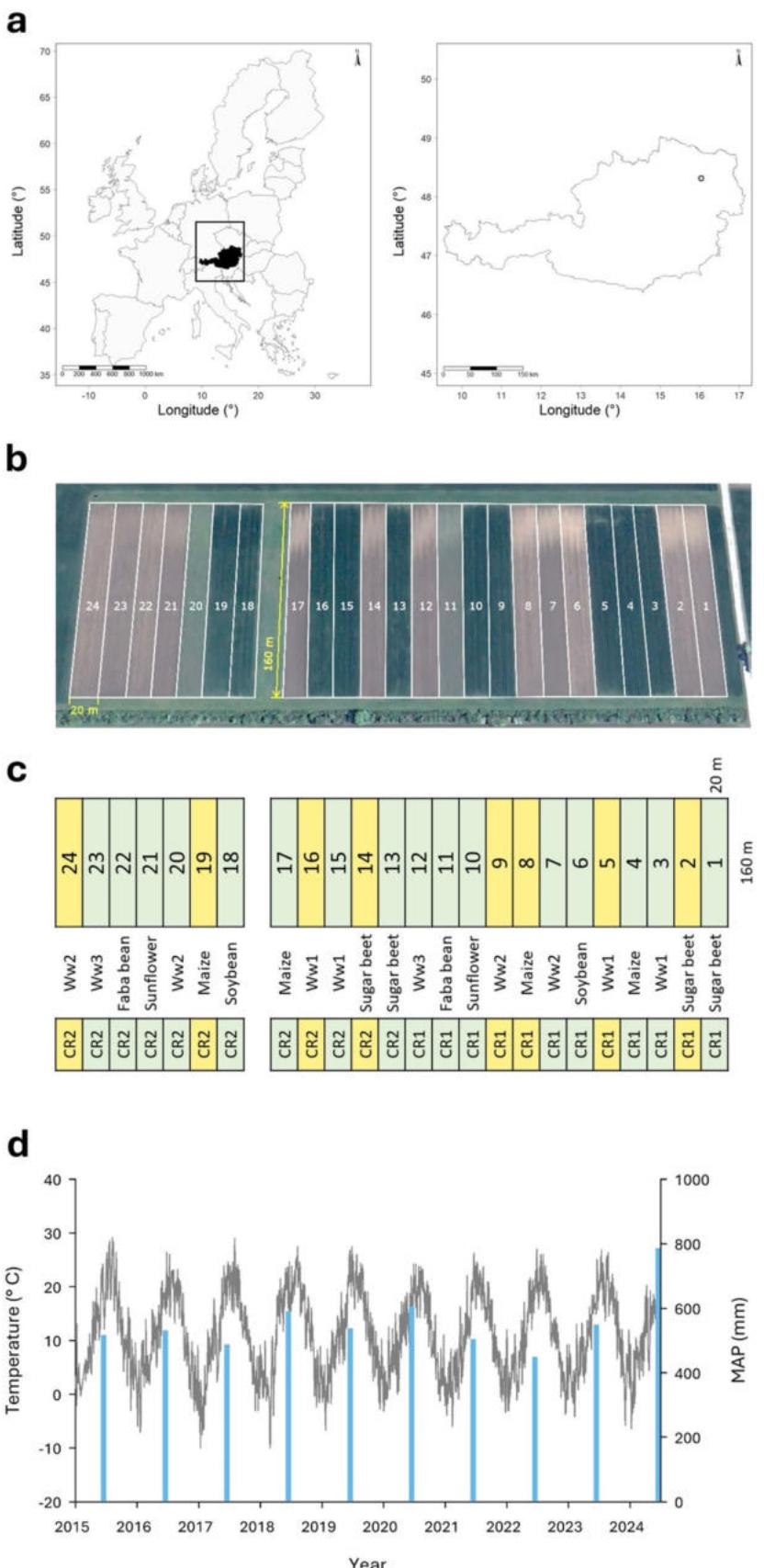


FIGURE 1 | Legend on next page.

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: Beet-Ww1-Maize-W2; conservation rotation: Beet-Ww1-Maize-Soybean-Ww2-Sunflower-Faba bean-Ww3) is cultivated twice each year, resulting in a total of 24 plots (Beet, 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-H₂O 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:

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

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 (KMnO₄)-oxidizable C (from here on referred to as 'Oxidizable C') was determined with a titration of the 0.02 M KMnO₄ solution with sodium oxalate (Na₂C₂O₄), 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 KMnO₄ solution was added. Titration, needed because KMnO₄ is not a primary standard, was performed with Na₂C₂O₄ 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 NH₄⁺ 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):

$$Ls = \frac{X - X_{min}}{X_{max} - X_{min}} \quad (2)$$

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

$$SHI = \sum_{i=1}^n WiLs \quad (3)$$

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):

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

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 CO₂-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 inter-crop 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 ($11.9 \pm 0.5 \text{ Mg ha}^{-1}$) as compared to conventional farming ($11.4 \pm 0.5 \text{ Mg ha}^{-1}$) 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 $0.5\text{--}1.6 \text{ Mg ha}^{-1}$ 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 ($+0.52 \text{ Mg ha}^{-1}$) 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, Keiblanger, 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 $577 \pm 8 \mu\text{gg}^{-1}$ (Figure 3b), MB-C concentrations increased with conservation farming from 205 ± 7 to $208 \pm 8 \mu\text{gg}^{-1}$ (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 ($100 \pm 5 \text{ nmol g}^{-1} \text{ h}^{-1}$) as compared to conventional farming ($111 \pm 5 \text{ nmol g}^{-1} \text{ h}^{-1}$). 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; Mundi 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).

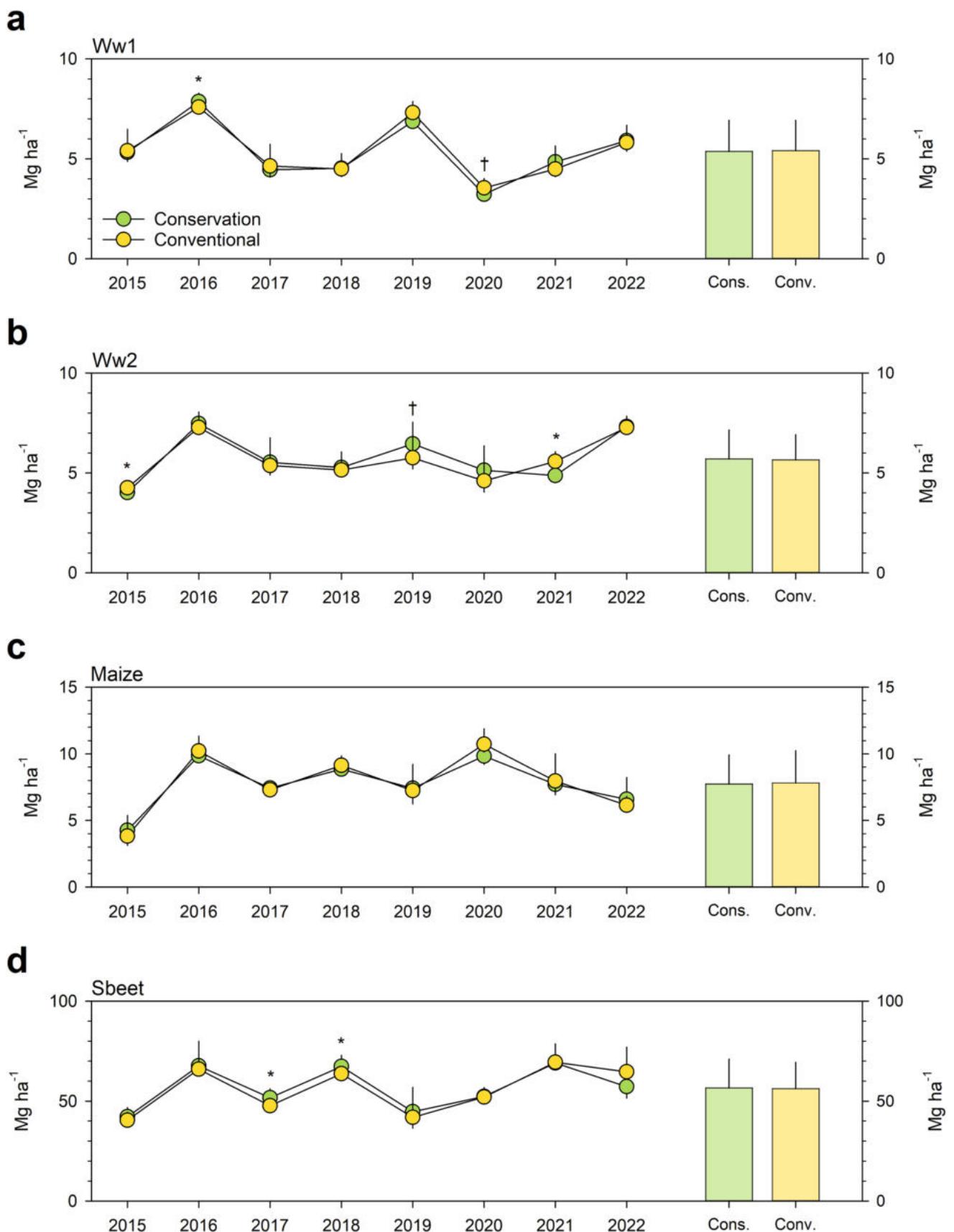


FIGURE 2 | Crop yield (in Mg ha^{-1}) of (a) winter wheat 1 (Ww1), (b) winter wheat 2 (Ww2), (c) Maize and (d) sugar beet (Sbeet) in a conventional (yellow dots and bars) and conservation (green dots and bars) farming system from 2015 to 2022. Standard errors show $\pm \text{SD}$, and significant differences 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 + Sheet 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 + Sheet 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 (Sheet 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 Sheet 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 Sheet (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 Sheet (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

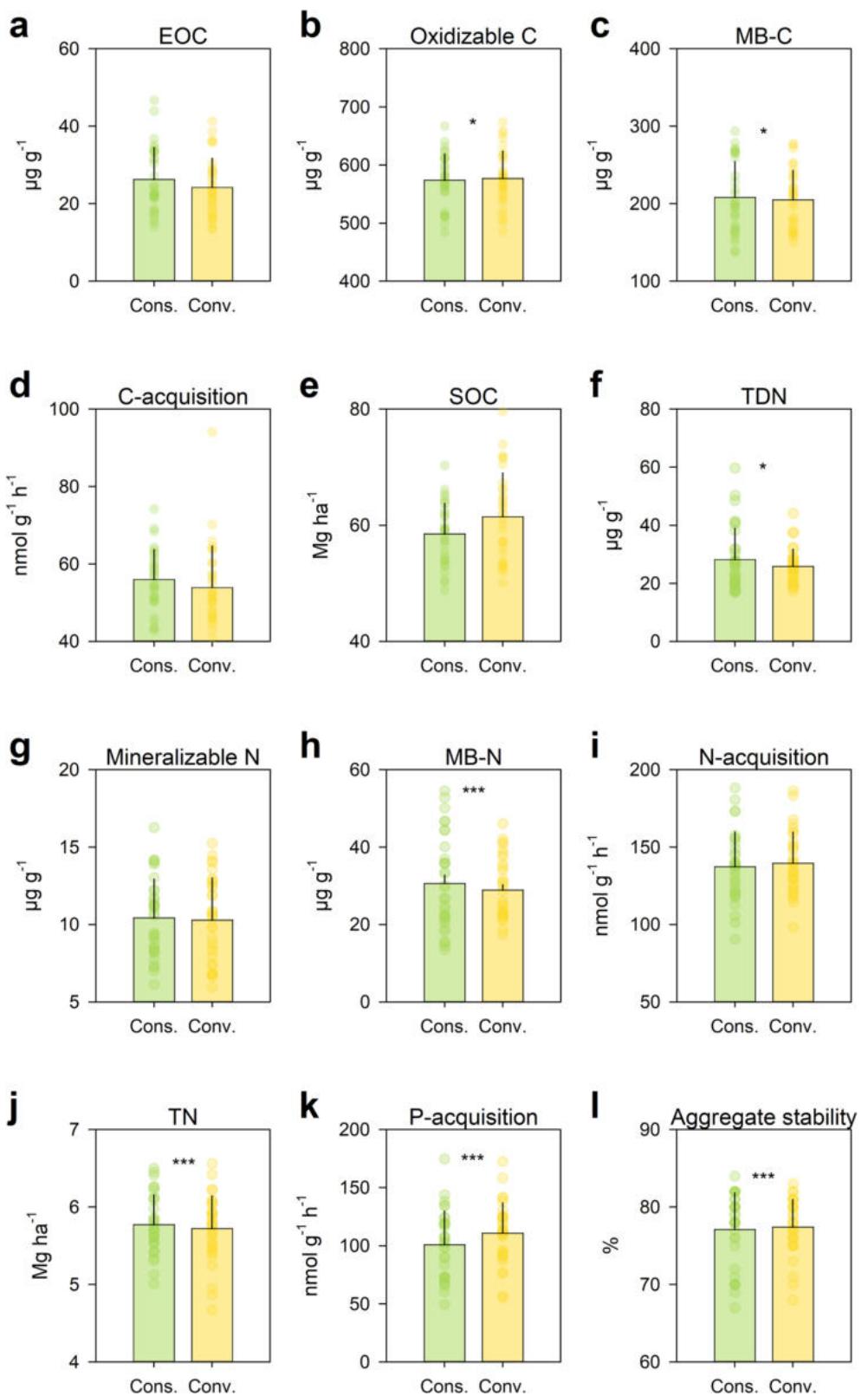


FIGURE 3 | Conservation farming effects on soil health parameters related to (a–e) C cycling, (f–j) N cycling, (k) P cycling and (l) aggregate stability. Given is the mean \pm SD, and asterisks above bars indicate significant differences between management systems ($*p < 0.05$; $**p < 0.01$; $***p <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

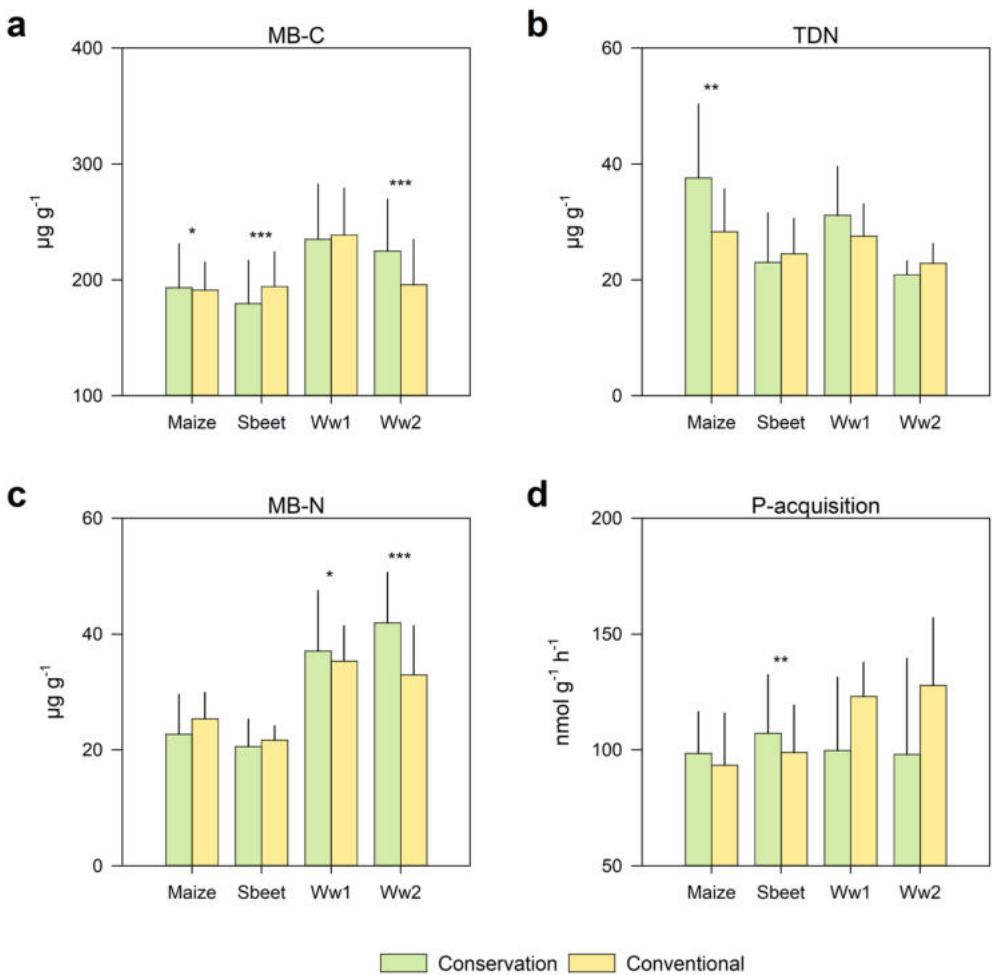


FIGURE 4 | Conservation farming effects on (a) MB-C, (b) TDN, (c) MB-N and (d) P-acquisition within each individual crop type (Maize; Sbeet, sugar beet; Ww1, winter wheat 1; Ww2, winter wheat 2). Given is the mean \pm SD, and asterisks above bars indicate significant differences between management systems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

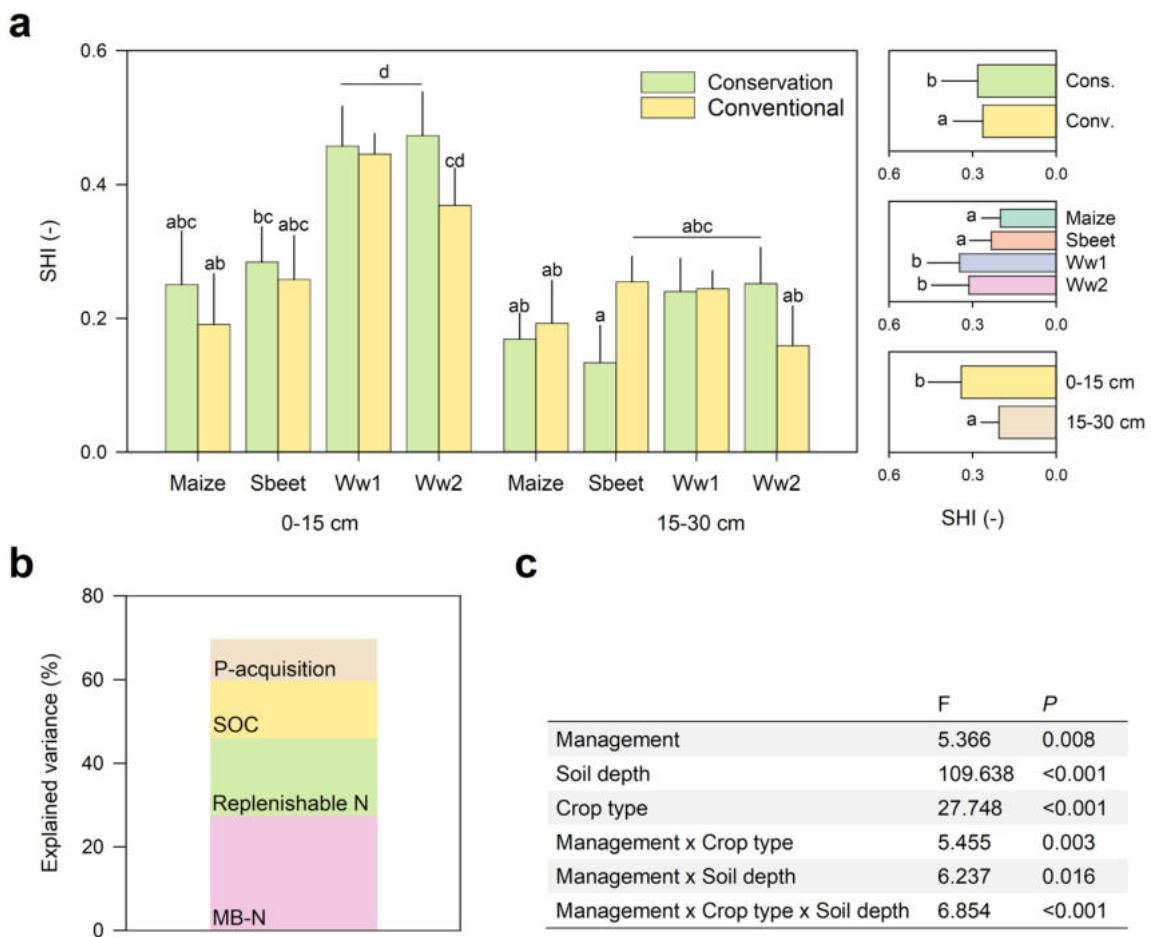


FIGURE 5 | (a) The effect of agricultural management (conservation vs. conventional), crop type (Maize; Sbeet, sugar beet; Ww1, winter wheat 1; Ww2 winter wheat 2) and soil depth (0–15 and 15–30 cm) on the soil health index. Given is the mean \pm SD, and different letters above or beside bars indicate 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 $1681 \pm 72 \text{ kg CO}_2\text{-eq ha}^{-1}$, the conservation farming system could reduce GHG emissions to $959 \pm 256 \text{ kg CO}_2\text{-eq ha}^{-1}$ ($p = 0.003$; 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 ($-222 \text{ kg CO}_2\text{-eq ha}^{-1}$ or 33.3%) and reduced expenses for fertilizer production ($-121 \text{ kg CO}_2\text{-eq ha}^{-1}$ 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 $204 \text{ kg CO}_2\text{-eq ha}^{-1}$ 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

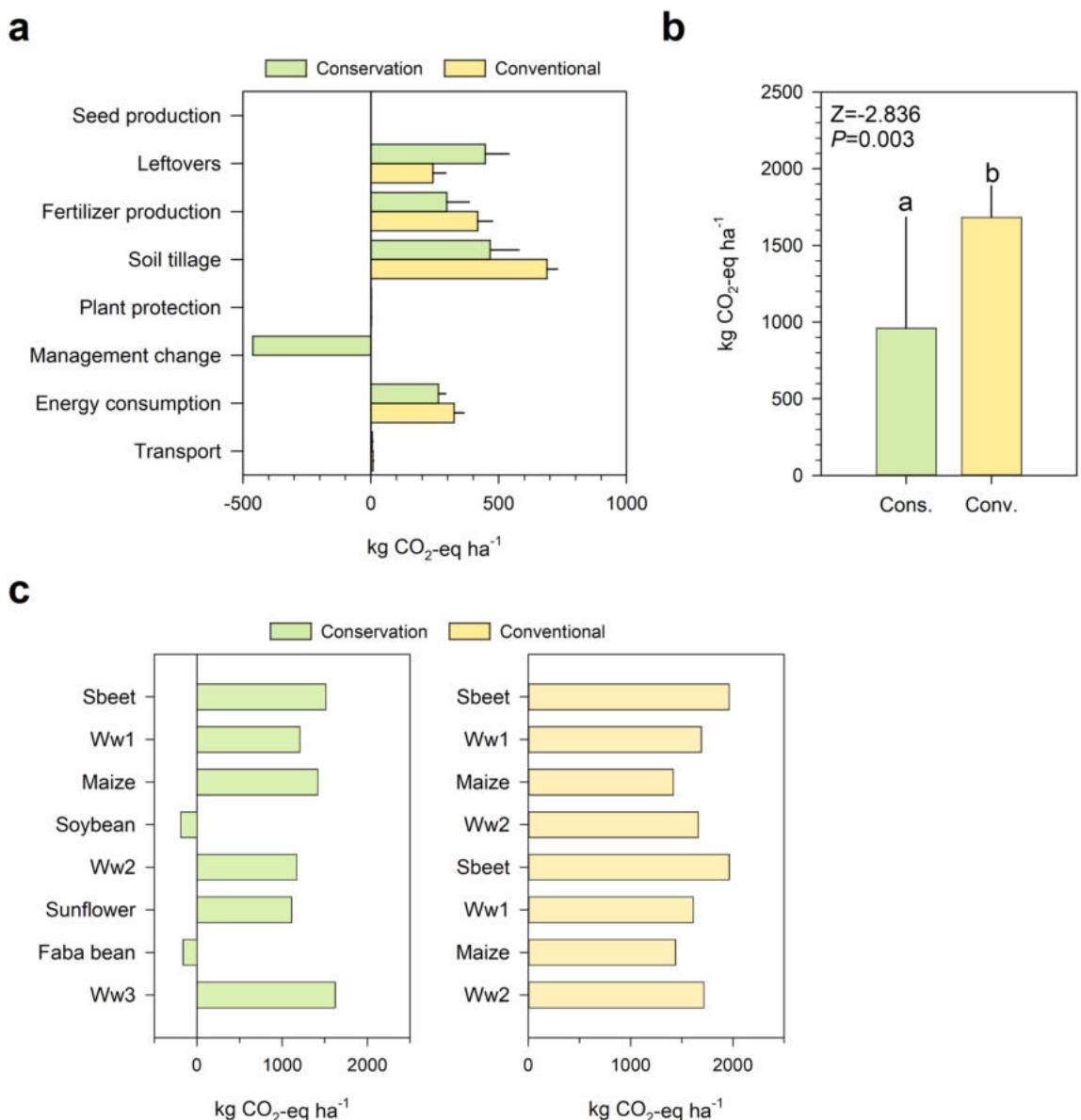


FIGURE 6 | GHG emissions (in kg CO₂-eq ha⁻¹) of a conservation and a conventional farming system for a whole crop rotation period (8 years) for (a) each individual sector, (b) for the whole management system and (c) for each individual crop in the respective farming system (Sbeet, sugar beet; Ww, winter wheat). Given is the mean \pm 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 CO₂-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 N₂O emissions, requires reassessment and should be fine-tuned to site- and management-specific characteristics which mainly determine whether cover crops facilitate or mitigate N₂O 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 beet 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 Gotthalseder:** 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.

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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.

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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 $\pm \text{SD}$, and significant differences between farming systems within each year are indicated ($*p < 0.05$; $\dagger p < 0.1$). 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 $\pm \text{SD}$. **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 $\pm \text{SD}$, 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 $\pm \text{SD}$, 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 (h^2) 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 the conservation 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.



Abb. 1: Zwischenfrüchte können einen wertvollen Beitrag zur Verbesserung der Bodengesundheit leisten

Foto: Oberbannert

Langzeitversuch: Die Vorteile konservierender Bewirtschaftung

VERBESSERTE BODENGESUNDHEIT UND CO₂-FUSSABDRUCK, ERTRAG GLEICH

Wie Langzeitversuche zeigen, verbessern reduzierte Bodenbearbeitung und eine diversifizierte Fruchtfolge die Bodengesundheit, besonders hinsichtlich Stickstoff- und Phosphatkreislauf. Zusätzlich sinkt der CO₂-Fußabdruck deutlich, und es kommt zu keinen Ertragseinbußen bei Winterweizen, Körnermais und Zuckerrübe.

Text & Fotos: C. Rosinger und H.-P. Kaul

Die Weltbevölkerung wird voraussichtlich bis zum Jahr 2050 auf nahezu 10 Milliarden Menschen anwachsen, was eine erhebliche Steigerung der Nahrungsmittelproduktion erforderlich macht. Dieser Nachfrageschub stellt die landwirtschaftlichen Systeme weltweit vor große Herausforderungen: Sie müssen nicht nur mehr Lebensmittel produzieren, sondern dies auch nachhaltig tun – im Einklang mit den Zielen zur Klimaneutralität in der Landwirtschaft. Zusätzlich bedrohen die negativen Auswirkungen des Klimawandels die landwirtschaftliche Produktivität, etwa durch die zunehmende Häufigkeit und Intensität extremer Wetterereignisse wie Überschwemmungen, Dürren und Hitzewellen.

Die Degradierung von Böden ist ein weiteres zentrales Problem, das die Produktionsfähigkeit landwirtschaftlicher Systeme zusätzlich untergräbt. Konventionelle Bewirtschaftungsmethoden, wie häufiges und tiefes Pflügen, eine geringe Fruchtfolgediversität oder das Entfernen von Ernterückständen können zu einem signifikanten Rück-

gang der Bodenfruchtbarkeit führen. Infolgedessen weisen diese Böden eine geringere Wasser- und Nährstoffspeicherfähigkeit auf, was die Anfälligkeit von Pflanzen gegenüber Umweltstress erhöht. Darüber hinaus verursachen heutige landwirtschaftliche Systeme rund 25 % der weltweiten menschengemachten Treibhausgasemissionen (THG). Diese Emissionen stammen aus verschiedenen Quellen, darunter Landnutzungsänderungen, Bodenbewirtschaftung, Tierhaltung und dem Einsatz synthetischer Düngemittel. Offensichtlich verschärfen die hohen THG-Emissionen, die mit konventionellen Anbaumethoden verbunden sind, den Klimawandel weiter – und erzeugen damit eine negative Rückkopplungsschleife, die die Widerstandsfähigkeit, Resilienz und somit die langfristige Produktivität landwirtschaftlicher Systeme zusätzlich gefährdet.

Konservierende Landwirtschaft, die insbesondere auf minimale Bodenbearbeitung, eine erhöhte Bodenbedeckung sowie vielfältige Fruchtfolgen setzt, hat sich als

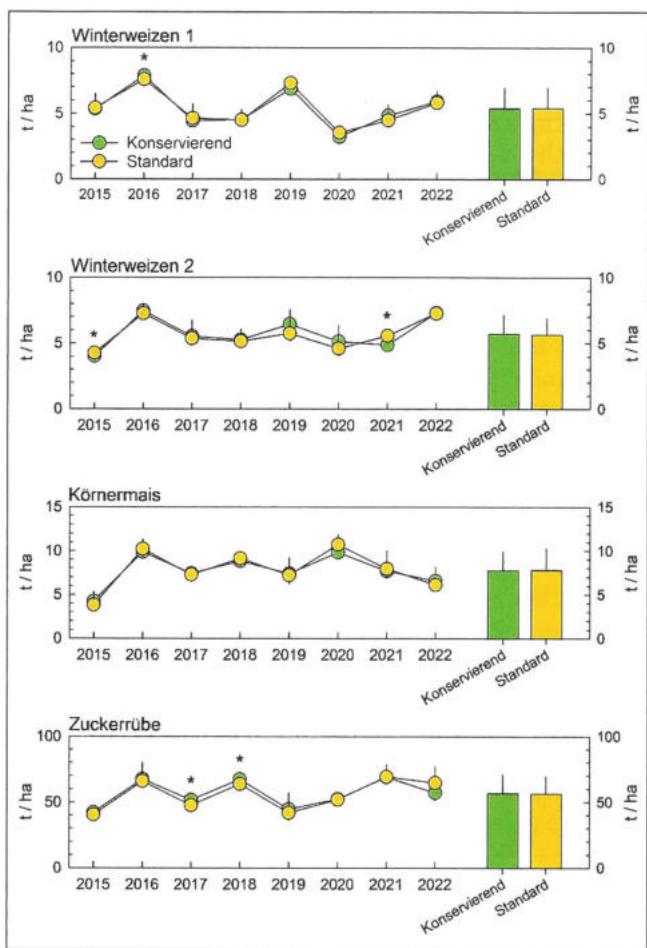


Abb. 2: Durchschnittserträge (in Tonnen pro Hektar) von Winterweizen, Körnermais und Zuckerrübe mit konservierender und Standard-Bewirtschaftung von 2015–2022 und gemittelt über alle Versuchsjahre (rechte Balken). Aufgrund verschiedener Vorfrüchte (Zuckerrübe und Sojabohne) bei Winterweizen in der konservierenden Variante sind zwei Winterweizen (1 und 2) dargestellt. Sternchen über den Symbolen zeigen signifikante Unterschiede zwischen den Bewirtschaftungsvarianten an.

vielversprechender Ansatz zur Verbesserung der Resilienz und Bodengesundheit herausgestellt. Jedoch zeigt sich sehr oft, dass eine Verbesserung von Ökosystemdienstleistungen (wie z. B. Klimaregulation, Nährstoffkreisläufe oder Humusaufbau) auf Kosten der Produktionsfunktion des Bodens stattfindet, sprich: Konservierende Systeme verzeichnen mitunter Ertragsrückgänge, insbesondere in den ersten Jahren der Umstellung von konventionellen hin zu konservierenden Bewirtschaftungspraktiken.

Dies verdeutlicht einen grundlegenden Zielkonflikt, der momentan in der Landwirtschaft vorherrscht und dessen Lösungsmöglichkeit es zu bewerten gilt. Wie sind also eine Reduzierung des CO₂-Fußabdrucks und eine Verbesserung der Bodengesundheit bei gleichbleibenden oder steigenden Erträgen möglich?

Da umfangreiche Langzeitstudien dazu selten sind, wurde im Jahr 2015 am UFT Tulln der Universität für Bodenkultur Wien auf einem schweren, tonreichen Standort ein Versuch etabliert, der zwei Bewirtschaftungssysteme umfasst:

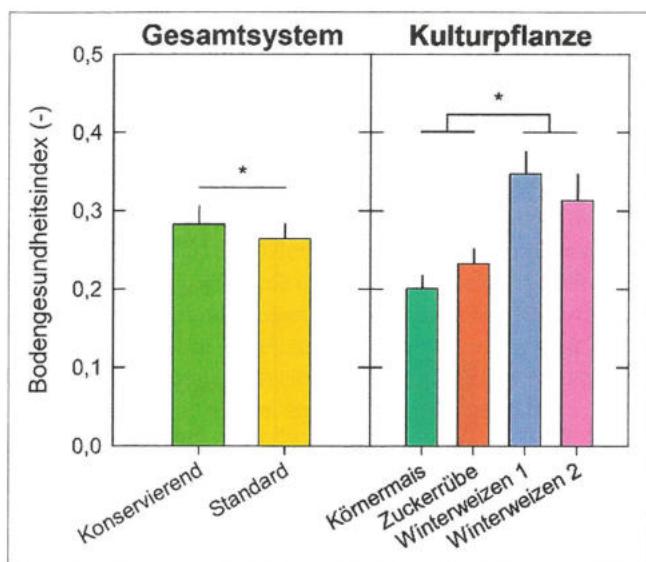


Abb. 3: Veränderung der Bodengesundheit durch konservierende Bewirtschaftung und Unterschiede in der Bodengesundheit zwischen den einzelnen Kulturpflanzen. Die Bodengesundheit wird als Bodengesundheitsindex dargestellt, welcher sich aus den wichtigsten bodenphysikalischen, -chemischen und -biologischen Parametern berechnet. Sternchen über den Symbolen zeigen signifikante Unterschiede zwischen den Bewirtschaftungsvarianten bzw. Kulturpflanzen an.

- ein Standardsystem mit tiefer Grubber-Bodenbearbeitung, einer einfachen ortsüblichen Fruchtfolge (Zuckerrübe – Winterweizen – Körnermais – Winterweizen) und einem sehr geringen Einsatz von Zwischenfrüchten, und
- ein konservierendes System, das sich durch eine flache Grubber-Bodenbearbeitung, eine vielfältige Fruchtfolge (Zuckerrübe – Winterweizen – Körnermais – Sojabohne – Winterweizen – Sonnenblume – Ackerbohne – Winterweizen) sowie den umfassenden Einsatz von Zwischenfrüchten und Untersäaten auszeichnet.

Die Düngung (hauptsächlich Kalkammonalspeter und Harnstoff) erfolgte gemäß den nationalen Richtlinien, und Pflanzenschutz wurde nach Bedarf angewendet, erfolgte in beiden Bewirtschaftungssystemen jedoch stets identisch. Im Gegensatz zu vielen anderen Studien zielte dieser Versuch speziell darauf ab, eine praktikable Alternative zur konventionellen Landwirtschaft zu testen, die in Bezug auf Bodenbearbeitung, Zwischenfruchtanbau und Vermarktung der angebauten Kulturen einfach umsetzbar ist (im Gegensatz zu drastischeren Bewirtschaftungsänderungen wie Direktsaat oder biologischem Landbau).

Nach acht Jahren wurden Bodenproben bis in eine Tiefe von 30 cm gezogen, und zwar aus jenen Parzellen der Standard- und konservierenden Bewirtschaftung, auf denen dieselben Hauptkulturen angebaut wurden (d.h. Zuckerrübe, Winterweizen 1, Körnermais, und Winterweizen 2). Winterweizen 2 unterscheidet sich hinsichtlich der Vorfrucht: im konservierenden System war dies Sojabohne, im Standardsystem hingegen Körnermais.

Daraufhin wurden umfangreiche bodenphysikalische (Aggregatstabilität, Lagerungsdichte), bodenchemische

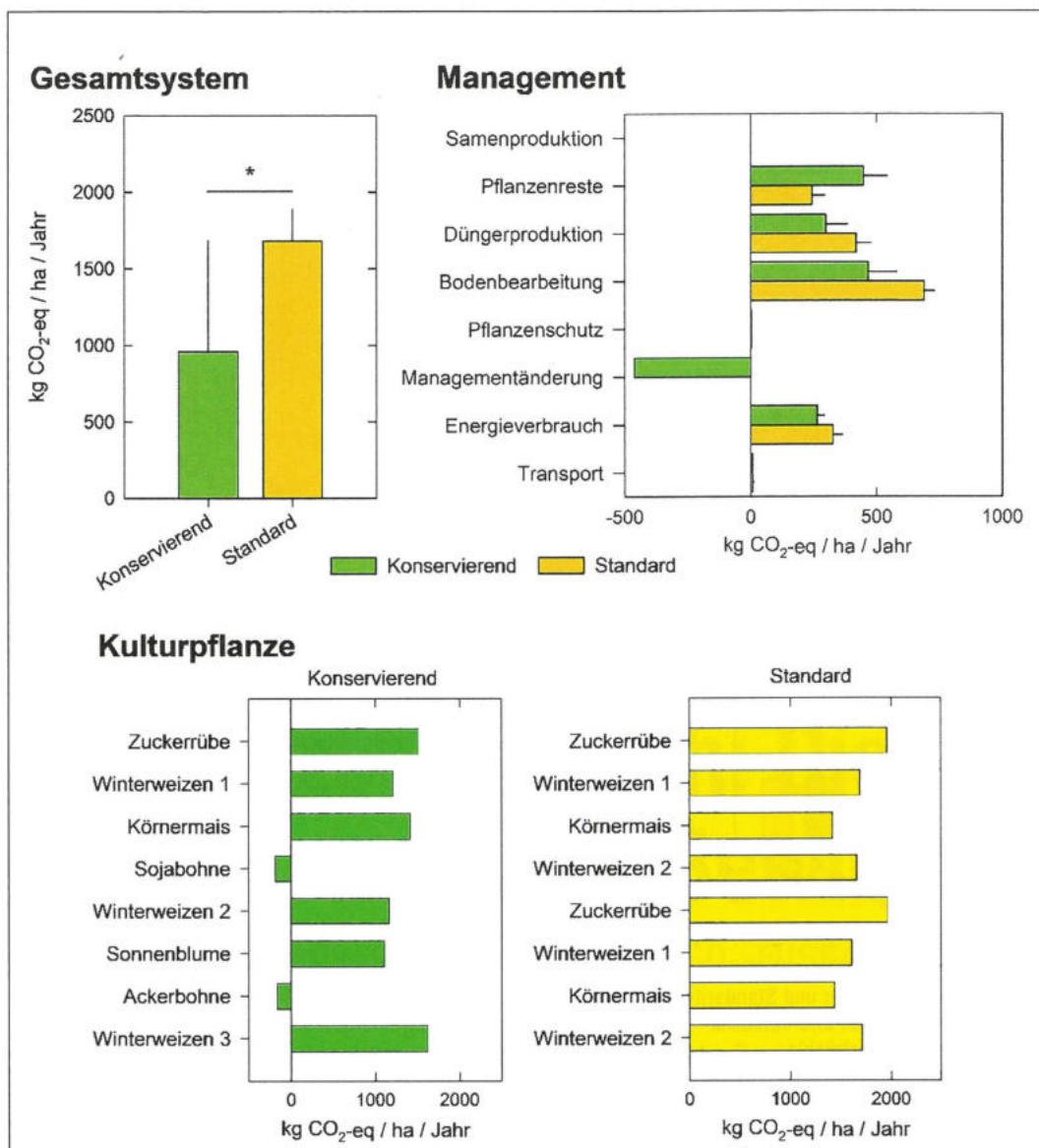


Abb. 4: CO₂-Fußabdruck (als kg CO₂-Äquivalent pro Hektar und Jahr) mit konservierender Bewirtschaftung und im Standardsystem. Die Abbildung zeigt den durchschnittlichen CO₂-Fußabdruck über einen Zeitraum von acht Jahren (oben links), für die einzelnen Managementmaßnahmen (oben rechts) und für jede Kulturpflanze in der vier- bzw. achtgliedrigen Fruchtfolge (unten). Sternchen über den Symbolen zeigen signifikante Unterschiede zwischen den Bewirtschaftungsvarianten an.

(pH-Wert und Leitfähigkeit, verschiedene Kohlenstoff- und Stickstofffraktionen) und bodenbiologische (mikrobielle Biomasse, potenzielle Enzymaktivitäten) Analysen durchgeführt, um die wichtigsten Bodeneigenschaften und Nährstoffkreisläufe abzubilden. Aus diesen Bodenparametern wurde mittels Hauptkomponentenanalyse ein Bodengesundheitsindex errechnet. Der CO₂-Fußabdruck wurde mit dem CoolFarm-Tool (v2.11.0) berechnet. Dieses Tool kombiniert mehrere empirische Modelle zur Abschätzung der THG-Emissionen einzelner landwirtschaftlicher Bewirtschaftungsmaßnahmen in Pflanzenbau und Tierhaltung sowie direktem Energieverbrauch aus betriebsinternen Arbeiten oder der Primärverarbeitung. Dabei werden standortbezogene pedoklimatische Bedingungen berücksichtigt. Insbesondere wurden standortspezifische

Daten zu Erträgen und Ernterückstandsmanagement, Zwischenfrüchten und Untersäaten, Düngung, Pflanzenschutz, Energieverbrauch durch Feldarbeiten sowie Transport der Ernte vom Feld zur Modellierung herangezogen. Dadurch war es möglich, die Leistung der Bewirtschaftungssysteme im Hinblick auf THG-Emissionen zu vergleichen.

ERGEBNISSE

Im Gegensatz zu vielen anderen Studien konnten wir – über den gesamten Versuchszeitraum hinweg – keine Ertragseinbußen mit konservierender Bewirtschaftung feststellen (s. Abb. 2). In einzelnen Jahren hingegen zeigten sich jedoch Unterschiede: Die Erträge von beispielsweise Zuckerrübe waren im konservierenden

Anbausystem in den Jahren 2017 und 2018, als Mitteleuropa von einer Dürreperiode betroffen war, signifikant höher als im Standardsystem. Dies deutet darauf hin, dass konservierende Bewirtschaftung möglicherweise die hydraulischen Eigenschaften des Bodens (z. B. Porengrößenverteilung) sowie die gesamte Bodenwasserbilanz positiv beeinflussen kann. Ein Umstand, über den in der Fachliteratur häufig berichtet wird. Dies spricht für eine potenziell höhere Widerstandsfähigkeit des konservierenden Systems sowie eine gesteigerte Ertragsstabilität in Jahren mit ausgeprägter Dürre.

Bodenparameter im Zusammenhang mit dem Stickstoffkreislauf wurden unter konservierender Bewirtschaftung besonders positiv beeinflusst. Insbesondere die Stickstoffvorräte sowie leicht verfügbare Stickstofffraktionen wie der gesamtgelöste Stickstoff und der mikrobiell gebundene Stickstoff waren im konservierenden System signifikant erhöht. Die höheren Stickstoffgehalte im konservierenden System könnten mit einer Reduktion von Stickstoffverlusten infolge der geringeren Bodenbearbeitungsintensität und mit dem höheren Anteil an Körnerleguminosen und leguminosenreichen Zwischenfrüchten in der Fruchtfolge zusammenhängen. Diese Bewirtschaftungsmaßnahmen

besitzen ein großes Potenzial zur Förderung des Stickstoffkreislaufs und zur Anreicherung von Stickstoff im Boden, was letztlich die Stickstoffversorgung der Kulturpflanzen langfristig verbessern kann; einen signifikanten Humusaufbau konnten wir hingegen während der ersten acht Versuchsjahre nicht feststellen.

Bei mehreren Bodenparametern stellten wir fest, dass der Effekt der Pflanzenart größer war als der des Bewirtschaftungssystems. Dies deutet darauf hin, dass Fruchfolgeentscheidungen (mehr Leguminosen, weniger Hackfrüchte, mehr Zwischenfrüchte und Untersaaten) Nährstoffkreisläufe und Bodenstabilität maßgeblich positiv beeinflussen können. Daraus resultierend ergab sich eine allgemeine Verbesserung der Bodengesundheit um 7 % (s. Abb. 3). Dies mag wenig erscheinen, ist aber angesichts der Bodenschwere (tonreiche Böden reagieren eher träge auf Managementveränderungen) und der sanften Managementveränderungen durchaus beachtlich; deutlichere Veränderungen würde man sich z. B. mit dem Umstieg auf Minimalbodenbearbeitung oder Direktsaat erwarten. Die Ackerkultur stellte sich zudem als ein maßgeblicher Treiber der Bodengesundheit heraus (s. Abb. 3). So zeigten Böden unter Winterweizen eine signifikant höhere Bodengesundheit als Böden unter Körnermais und Zuckerrüben. Das verdeutlicht, dass die Fruchfolgewahl maßgeblich zur Verbesserung der Bodengesundheit beitragen kann.

Neben den erreichten Verbesserungen der Bodengesundheit führte die konservierende Landwirtschaft auch zu einer signifikanten Reduktion des CO₂-Fußabdrucks (s. Abb. 4): Während das konventionelle System 1.681 kg CO₂-Äquivalent pro Hektar und Jahr ausstieß, konnten die Emissionen im konservierenden System auf 959 kg CO₂-Äquivalent pro Hektar und Jahr gesenkt werden. Dies entspricht einem CO₂-Reduktionspotenzial von 43,4 %. Die größten CO₂-Einsparungen konnten durch eine reduzierte Bodenbearbeitung (-222 kg CO₂-Äquivalent pro Hektar und Jahr oder -33,3 %) und geringere Emissionen durch die Düngemittelproduktion (-121 kg CO₂-Äquivalent pro Hektar und Jahr oder -30 %) als Folge der diversifizierten Fruchfolge erzielt werden. Hier reduzierte insbesondere der Anbau von Sojabohne und Ackerbohne den Gesamtverbrauch an Mineraldünger. Andererseits wirkte sich der insgesamt höhere Anteil an Zwischenfrüchten und Untersaaten negativ auf die Treibhausgasemissionen (besonders Lachgas) des konservierenden Anbausystems aus.

Äquivalent pro Hektar und Jahr gesenkt werden. Dies entspricht einem CO₂-Reduktionspotenzial von 43,4 %. Die größten CO₂-Einsparungen konnten durch eine reduzierte Bodenbearbeitung (-222 kg CO₂-Äquivalent pro Hektar und Jahr oder -33,3 %) und geringere Emissionen durch die Düngemittelproduktion (-121 kg CO₂-Äquivalent pro Hektar und Jahr oder -30 %) als Folge der diversifizierten Fruchfolge erzielt werden. Hier reduzierte insbesondere der Anbau von Sojabohne und Ackerbohne den Gesamtverbrauch an Mineraldünger. Andererseits wirkte sich der insgesamt höhere Anteil an Zwischenfrüchten und Untersaaten negativ auf die Treibhausgasemissionen (besonders Lachgas) des konservierenden Anbausystems aus.

FAZIT

Einfach umsetzbare Maßnahmen wie reduzierte Bodenbearbeitung, eine höhere Kulturrartenvielfalt und ein erhöhter Anteil an Zwischenfrüchten besitzen ein großes Potenzial, um landwirtschaftliche Produktionssysteme voranzubringen. Die damit verbundenen Verbesserungen der Bodengesundheit durch konservierende Landwirtschaft stellen eine Schlüsselstrategie zur Anpassung an und Minderung der negativen Auswirkungen des Klimawandels dar, um eine nachhaltige Pflanzenproduktion in Zukunft zu sichern.

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Zwischen Wetterextremen und Zeitdruck: Jetzt ist Augenmaß gefragt

Verein Boden.Leben

Das heurige Wetter stellt uns Bäuerinnen und Bauern einmal mehr auf eine harte Probe. Nach einem außergewöhnlich trockenen Juni kam der Regen genau zur Ernte. Manche Flächen sind schwer befahrbar und die Erntefenster sind kurz. Es zählt jeder trockene Tag, meistens jede Stunde, um Erträge zu sichern und Qualität zu retten. Heuer muss man buchstäblich die Ernte vom Feld stehlen. Andererseits ist der Regen wichtig für unsere Herbstkulturen, Wiesen und Wälder.

Die Reife des Getreides ist nun weit fortgeschritten und deshalb ist es wichtig, die Ernte rasch einzubringen. Den Blick nach vorne dürfen wir aber auch nicht verlieren. Denn auf die Ernte folgt die Bodenbearbeitung und genau hier ist in diesem Jahr besondere Umsicht gefragt. Die jetzige Nässe und eine zu frühe Bearbeitung machen uns bis ins nächste Jahr Probleme. Wer jetzt zu schweres Gerät einsetzt oder bei zu feuchten Bedingungen fährt, riskiert langfristige Schäden an der Bodenstruktur.

Auch der Begrünungsanbau steht unmittelbar bevor. Gerade jetzt braucht der Boden eine Verschnaufpause und die richtige Pflege. Die passende Begrünungsmischung,



zur richtigen Zeit ist kein Luxus, sondern eine Investition in Bodenfruchtbarkeit, Wasserhaltevermögen und Erosionsschutz. Es ist eine Investition in unsere Zukunft: Wir stehen heuer zwischen Erntestress und Bodenverantwortung. Die Kunst liegt darin, beides unter einen Hut zu bringen: Schnelligkeit, wo sie nötig ist aber auch Geduld und Fingerspitzengefühl, wo der Boden es einfordert. Denn

was wir heute im Boden anrichten, wirkt oft noch viele Jahre nach.

In diesem Sinne wünsche ich uns allen jetzt ein Zeitfenster zum Einbringen der noch stehenden Ernte und danach einen wachen Blick auf das, was unter unseren Füßen liegt und uns alle ernährt.

Ing. Lorenz Mayr,
Obmann Verein Boden.Leben



Boden im Fokus: Forschungsansätze für eine zukunftsfähige Landwirtschaft

Böden sind die Grundlage der Landwirtschaft. Sie speichern Wasser und Kohlenstoff, liefern Nährstoffe und sind Lebensraum für unzählige Organismen. Gleichzeitig sind landwirtschaftliche Böden bedroht. Versiegelung, Klimawandel, intensive Nutzung, Erosion sowie der anhaltende Biodiversitätsverlust führen zur Degradierung und zum Verlust von Böden und deren Fruchtbarkeit, mit negativen Folgen für die landwirtschaftliche Produktion. An der BOKU werden Böden, sowie die Möglichkeiten und Herausforderungen deren nachhaltiger Bewirtschaftung, seit jeher intensiv beforscht.

Am Institut für Pflanzenbau wurde 2015 ein *Langzeitexperiment* gestartet, in dem ein konventionelles (25 cm Bodenbearbeitungstiefe, einer viergliedrigen Fruchtfolge, minimaler Einsatz von Zwischenfrüchten) und ein konservierendes Bewirtschaftungssystem (reduzierte Bodenbearbeitungstiefe 10 cm, achtgliedrige Fruchtfolge inkl. Körnerleguminosen, umfassender Zwischenfruchtanbau) hinsichtlich deren Erträge, Klimawirksamkeit und Bodengesundheit verglichen werden. Dün-

gung und Pflanzenschutzmaßnahmen werden in beiden Systemen gleich gestaltet. Daten zu Biomasse, Erträgen und Ertragsstruktur sowie der Stickstoffdynamik werden seit 2015 jährlich erhoben. Seit 2024 werden im Projekt *Trade-Off* für beide Systeme zusätzlich 13 Bodenparameter zu Treibhausgasemissionen und zur Bodengesundheit evaluiert. Die Ergebnisse der Langzeitstudie zeigen Potenziale der konservierenden Bewirtschaftung, zur Sicherung der Bodengesundheit und Produktivität auf.

Im H2020 Projekt *TUdi* forscht ein Team europäischer, chinesischer und neuseeländischer Partner*innen an Möglichkeiten zur Erhaltung und Wiederherstellung landwirtschaftlicher Böden. Um anwendungsorientierte Lösungen zu erzielen, arbeitet das Projekt dabei in allen beteiligten Ländern eng mit insgesamt 42 Interessengruppen zusammen. In Österreich besteht diese Zusammenarbeit aus dem Institut für Bodenphysik und landeskulturelle Wasserwirtschaft der BOKU und dem Bundesamt für Wasserwirtschaft (BAW) sowie dem

Verein Boden.Leben, dem Kompetenzzentrum myhumus und den Landwirtschaftlichen Fachschulen in NÖ. Schwerpunkt der BOKU sind dabei die Forschungsthemen Bodenverdichtung, Humusaufbau und Erosionsschutz. Aus der Kooperation entstanden bislang bereits digitale Werkzeuge (de.v-tudi.web.app) und Schulungsmaterialien, die die Umsetzung in der Praxis unterstützen sollen.

Im Horizon-Europe Projekt *Soil-X-Change* wird das Ziel verfolgt, in Europa bestehende, innovative Praktiken nachhaltiger Bodenbewirtschaftung zu sammeln, zu analysieren und in eine gemeinsame, europaweit zugängliche Datenbank zu integrieren. Damit soll ein umfassender Wissensaustausch, die Umsetzung innovativer, nachhaltiger Lösungsansätze für gesunde landwirtschaftliche Böden auf regionaler und europäischer Ebene ermöglichen und beschleunigen. An der BOKU wird das *Soil-X-Change* Projekt vom Institut für Ökologischen Landbau in Zusammenarbeit mit dem Institut für Geomatik betreut. Fokus des Projekts ist es, ein EU-weites Netzwerk zu schaffen, das sich gemeinsam mit der Weiterentwicklung und Einführung eines neuen, nachhaltigen Boden- und Landwirtschaftsmanagements befasst. Hierfür arbeiten neben den BOKU-Projektpartner*innen aus neun Mitgliedsländern, über 85 operationelle Gruppen (EIP-AGRI OG's) und internationale Projektgruppierungen aus ganz Europa zusammen.

Möchten Sie den CAS-Newsletter auch künftig erhalten? Dann melden Sie sich an unter: www.boku.ac.at/anmeldung-cas-newsletter.html

Rechnungsempfänger:

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UID-Nr.: ATU16285008



zahlen mit Code

Rechnung: 10473497

Betreff: Bodenuntersuchungen

Auftragsnummer: 24108040

Netto	2.112,00
Rabatt	-354,56
Nettobetrag	1.757,44
USt 20 %	351,49
Bruttobetrag in EUR	2.108,93

	--

Leistungszeitraum: 12.08.2024 bis 03.10.2024

Zahlungsfrist: binnen 8 Tagen ohne Abzug zur Zahlung fällig

Bei Überweisung per Telebanking bitte die Nummer der Rechnung in das Feld "Zahlungsreferenz" eingeben!

Es gelten die Allgemeinen Geschäftsbedingungen der Österreichischen Agentur für Gesundheit und Ernährungssicherheit GmbH.

Rechnung: 10473497

Leistungsumfang

Nr.	Anzahl	Bezeichnung	Einzelpreis	Preis	Ust %	Rabatt %
1004540	64,00	NNL-nachlieferbarer Stickstoff	15,20	972,80	20,00	20,00
1004745	64,00	ermäßigte Probenvorbereitung Boden	5,30	339,20	20,00	
1006280	64,00	Bestimmung von Kaliumpermanganat oxidierbarem Kohlenstoff (POXC) von Böden	12,50	800,00	20,00	20,00
Netto				2.112,00		
Rabatt				-354,56		
Betrag				1.757,44		

H951 Institut für Pflanzenbau
 Dr. Christoph Rosinger
 Konrad-Lorenz-Straße 24
 UFT
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 Österreich

IC-Verrechnung 10021443

Rechnungsdatum: 05.12.2024
Kundennummer: 38000013
Bestellnummer: 7951015912
Auftragsnummer: 142925
Leistungszeitraum: 01.07.2024 - 01.10.2024
Sachbearbeiter/in: Nina Holler
Email: nina.holler@boku.ac.at
Interne Projektnummer: 7911004815
Ihre UID-Nummer: ATU16285008

Bezeichnung	Menge	Einheit	USt %	Preis/EH	Betrag/EUR
Karbonatgehalt (á 0,30 €) an 32 Bodenproben	1,000		0	931,20	931,20
Messung von KCl-Extrakten am TOC/TN-Analyser (á 4,30 €) an 128 Bodenproben					
Messung von potentieller Enzymaktivität (á 5,80 €) an 64 Bodenproben					
				Positionssumme	931,20
				Umsatzsteuer	0%
				Rechnungsbetrag EUR	931,20

Zahlungsbedingungen:

sofort zahlbar ohne Abzug



Zahlen mit Code

Die Universität für Bodenkultur Wien leistet im Zusammenhang mit diesem Geschäftsfall nach nationalem österreichischen Recht als hoheitliche Forschungsanstalt des Bundes und weist daher keine Umsatzsteuer aus. Liegt der Leistungsort außerhalb Österreichs, so hat der Empfänger für sein Empfängerland selbst allfällige umsatzsteuerliche Verpflichtungen wahrzunehmen.

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 BIC/SWIFT: RLNWATWW
 UID: ATU16285008
 EORI: ATEOS1000081383
 DVR: 0059234

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Österreich

IC-Verrechnung 10021442

Rechnungsdatum: 05.12.2024
Kundennummer: 38000013
Bestellnummer: 7951015912
Auftragsnummer: 142924
Leistungszeitraum: 01.07.2024 - 01.10.2024
Sachbearbeiter/in: Nina Holler
Email: nina.holler@boku.ac.at
Interne Projektnummer: 2951000003
Ihre UID-Nummer: ATU16285008

Bezeichnung	Menge	Einheit	USt %	Preis/EH	Betrag/EUR
Extraktion von Bodenproben in 1M KCl (á 1,40 €) an 128 Proben	1,000		0	1.017,60	1.017,60
Messung von Gesamtkohlenstoff und -stickstoff (á 13,10 €) an 64 Proben					
				Positionssumme	1.017,60
				Umsatzsteuer	0,00
				Rechnungsbetrag EUR	1.017,60

Zahlungsbedingungen:

sofort zahlbar ohne Abzug



Zahlen mit Code

Die Universität für Bodenkultur Wien leistet im Zusammenhang mit diesem Geschäftsfall nach nationalem österreichischen Recht als hoheitliche Forschungsanstalt des Bundes und weist daher keine Umsatzsteuer aus. Liegt der Leistungsort außerhalb Österreichs, so hat der Empfänger für sein Empfängerland selbst allfällige umsatzsteuerliche Verpflichtungen wahrzunehmen.

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www.boku.ac.at

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IBAN: AT84 3200 0010 0050 0512
BIC/SWIFT: RLNWATWW
UID: ATU16285008
EORI: ATEOS1000081383
DVR: 0059234

Hauptsitz:

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Es gelten unsere AGB.
www.agb.boku.ac.at

Kostenart	Kostenartenbezeichn.	Konto Gegenbuchung	Bezeichnung des Gegenkontos	Kostenartenbeschr.	Personal-nummer	Name des Mitarbeiters	Geschäfts-jahr	Wert/BWähr	Belegdatum
790991	Aufwand IC KoErs §27	38000012	H101 Büro des Rektorats	Aufwand IC Kostenersätze §27	0		2025	974.71	30.09.2025
790911	Aufwand IC B-§27 vv	38000013	H951 Institut für Pflanzenbau	Aufwand IC Bund-§27 (vv)	0		2024	1,017.60	05.12.2024
790970	Aufwand IC §27-§27	38000035	H911 Inst. für Bodenforschung	Aufwand IC §27-§27	0		2024	931.20	05.12.2024
753000	Sonst. Dienstleist.	30005425	Österreichische Agentur für	Sonstige Dienstleistungen	0		2024	2,108.93	21.11.2024
644852	§27 KV DGB MVK wP	367000	VK Auszahlung	Angestellte §27 KV - DGB MVK wissensch.	80017791	Gotthalseder Golo	2024	23.23	15.10.2024
644000	§27 KV Bez. w. Pers.	367000	VK Auszahlung	Angestellte §27 KV - Bezüge wissenschaft	80017791	Gotthalseder Golo	2024	1,518.59	15.10.2024
644837	§27 KV DGB PenK wP	367000	VK Auszahlung	Angestellte §27 KV - DGB Pens.Kass. wiss	80017791	Gotthalseder Golo	2024	46.69	15.10.2024
644805	§27 KV DGB FLAF wP	367000	VK Auszahlung	Angestellte §27 KV - DGB FLAF wissensch.	80017791	Gotthalseder Golo	2024	56.19	15.10.2024
644820	§27 KV DGB SozV wP	367000	VK Auszahlung	Angestellte §27 KV - DGB Soz.Vers. wisse	80017791	Gotthalseder Golo	2024	303.19	15.10.2024
677000	U-Bahnsteuer	367000	VK Auszahlung	U-Bahnsteuer	80017791	Gotthalseder Golo	2024	10.00	15.10.2024
790901	Aufwand IC Fuhrpark	38000014	H173 Facility Services	Aufwand IC Fuhrpark	0		2024	17.52	07.10.2024
644000	§27 KV Bez. w. Pers.	367000	VK Auszahlung	Angestellte §27 KV - Bezüge wissenschaft	80017791	Gotthalseder Golo	2024	1,949.40	15.09.2024
644852	§27 KV DGB MVK wP	367000	VK Auszahlung	Angestellte §27 KV - DGB MVK wissensch.	80017791	Gotthalseder Golo	2024	29.83	15.09.2024
644805	§27 KV DGB FLAF wP	367000	VK Auszahlung	Angestellte §27 KV - DGB FLAF wissensch.	80017791	Gotthalseder Golo	2024	72.13	15.09.2024
644837	§27 KV DGB PenK wP	367000	VK Auszahlung	Angestellte §27 KV - DGB Pens.Kass. wiss	80017791	Gotthalseder Golo	2024	59.94	15.09.2024
677000	U-Bahnsteuer	367000	VK Auszahlung	U-Bahnsteuer	80017791	Gotthalseder Golo	2024	10.00	15.09.2024
644820	§27 KV DGB SozV wP	367000	VK Auszahlung	Angestellte §27 KV - DGB Soz.Vers. wisse	80017791	Gotthalseder Golo	2024	385.63	15.09.2024
677000	U-Bahnsteuer	367000	VK Auszahlung	U-Bahnsteuer	80017791	Gotthalseder Golo	2024	8.00	15.08.2024
644000	§27 KV Bez. w. Pers.	367000	VK Auszahlung	Angestellte §27 KV - Bezüge wissenschaft	80017791	Gotthalseder Golo	2024	1,299.60	15.08.2024
644820	§27 KV DGB SozV wP	367000	VK Auszahlung	Angestellte §27 KV - DGB Soz.Vers. wisse	80017791	Gotthalseder Golo	2024	261.29	15.08.2024
644852	§27 KV DGB MVK wP	367000	VK Auszahlung	Angestellte §27 KV - DGB MVK wissensch.	80017791	Gotthalseder Golo	2024	19.88	15.08.2024
644805	§27 KV DGB FLAF wP	367000	VK Auszahlung	Angestellte §27 KV - DGB FLAF wissensch.	80017791	Gotthalseder Golo	2024	48.09	15.08.2024
644837	§27 KV DGB PenK wP	367000	VK Auszahlung	Angestellte §27 KV - DGB Pens.Kass. wiss	80017791	Gotthalseder Golo	2024	39.96	15.08.2024
644000	§27 KV Bez. w. Pers.	367000	VK Auszahlung	Angestellte §27 KV - Bezüge wissenschaft	80017791	Gotthalseder Golo	2024	1,299.60	15.07.2024
677000	U-Bahnsteuer	367000	VK Auszahlung	U-Bahnsteuer	80017791	Gotthalseder Golo	2024	8.00	15.07.2024
644837	§27 KV DGB PenK wP	367000	VK Auszahlung	Angestellte §27 KV - DGB Pens.Kass. wiss	80017791	Gotthalseder Golo	2024	39.96	15.07.2024
644805	§27 KV DGB FLAF wP	367000	VK Auszahlung	Angestellte §27 KV - DGB FLAF wissensch.	80017791	Gotthalseder Golo	2024	48.09	15.07.2024
644852	§27 KV DGB MVK wP	367000	VK Auszahlung	Angestellte §27 KV - DGB MVK wissensch.	80017791	Gotthalseder Golo	2024	19.88	15.07.2024
644820	§27 KV DGB SozV wP	367000	VK Auszahlung	Angestellte §27 KV - DGB Soz.Vers. wisse	80017791	Gotthalseder Golo	2024	261.29	15.07.2024
644000	§27 KV Bez. w. Pers.	367000	VK Auszahlung	Angestellte §27 KV - Bezüge wissenschaft	80017791	Gotthalseder Golo	2024	1,513.84	15.06.2024
644837	§27 KV DGB PenK wP	367000	VK Auszahlung	Angestellte §27 KV - DGB Pens.Kass. wiss	80017791	Gotthalseder Golo	2024	46.55	15.06.2024
644805	§27 KV DGB FLAF wP	367000	VK Auszahlung	Angestellte §27 KV - DGB FLAF wissensch.	80017791	Gotthalseder Golo	2024	56.01	15.06.2024
644820	§27 KV DGB SozV wP	367000	VK Auszahlung	Angestellte §27 KV - DGB Soz.Vers. wisse	80017791	Gotthalseder Golo	2024	302.28	15.06.2024
677000	U-Bahnsteuer	367000	VK Auszahlung	U-Bahnsteuer	80017791	Gotthalseder Golo	2024	10.00	15.06.2024
430000	Erlöse ForschFörder	30027700	BIOS Science Austria	Erlöse aus Forschungsförderung	0		2024	-16,411.26	08.04.2024
								-1,614.16	

Buchungsdatum	Ausgleichsdatum	Bezeichnung
30.09.2025	30.09.2025	Kostenersatz 2024 7951015912
05.12.2024	10.12.2024	Extraktion von Bodenproben in 1M KCl
05.12.2024	10.12.2024	Karbonatgehalt (á 0,30 €) an 32 Boden-
26.11.2024	28.11.2024	Bodenuntersuchungen IFA Tulln
15.10.2024		D UM UN
07.10.2024	08.10.2024	78332,W-64627C,ROSINGER,02.07.24-02.07.24,6km
15.09.2024		D UM UN
15.08.2024		D UM UN
15.07.2024		D UM UN
15.06.2024		D UM UN
08.04.2024	08.04.2024	1. Rate