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RESEARCH ARTICLE

Synergism between production and soil health through crop diversification, organic amendments and crop protection in wheat-based systems

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Abstract

1. One of the critical challenges in agriculture is enhancing yield without compromising its foundation, a healthy environment and, particularly, soils. Hence, there is an urgent need to identify management practices that simultaneously support soil health and production and help achieve environmentally sound production systems.
2. To investigate how management influences production and soil health under realistic agronomic conditions, we conducted an on-farm study involving 60 wheat fields managed conventionally, under no-till or organically. We assessed 68 variables defining management, production and soil health properties. We examined how management systems and individual practices describing crop diversification, fertiliser inputs, agrochemical use and soil disturbance influenced production—quantity and quality—and soil health focusing on aspects ranging from soil organic matter over soil structure to microbial abundance and diversity.
3. Our on-farm comparison showed marked differences between soil health and production in the current system: organic management resulted in the best overall soil health (+47%) but the most significant yield gap (−34%) compared to conventional management. No-till systems were generally intermediate, exhibiting a smaller yield gap (−17%) and only a marginally improved level of soil health (+5%) compared to conventional management. Yet, the overlap between management systems in production and soil health properties was considerably large.

Florian Walder and Lucie Büchi contributed equally to this work.

4. Our results further highlight the importance of soil health for productivity by revealing positive associations between crop yield and soil health properties, particularly under conventional management, whereas factors such as weed pressure were more dominant in organic systems.
5. None of the three systems showed advantages in supporting production-soil health-based multifunctionality. In contrast, a cross-system analysis suggests that multifunctional agroecosystems could be achieved through a combination of crop diversification and organic amendments with effective crop protection.
6. *Synthesis and applications*: Our on-farm study implies that current trade-offs in managing production and soil health could be overcome through more balanced systems incorporating conventional and alternative approaches. Such multifunctionality supporting systems could unlock synergies between vital ecosystem services and help achieve productive yet environmentally sound agriculture supported by healthy soils.

KEYWORDS
balanced agricultural systems, conservation agriculture, ecosystem multifunctionality, organic farming, productivity, soil improving cropping systems, soil quality, trade-offs

1 | INTRODUCTION

One of the critical steps in meeting the ever-increasing demand for food, feed and fibre while minimising the long-lasting negative impacts of agriculture on the environment is the development of environmentally sound yet productive agricultural systems. Industrial intensification of agriculture tripled global yields (Foley et al., 2011; Godfray et al., 2010) but with profound and lasting consequences for the environment such as decreasing biodiversity, eutrophication and degradation of soils (Godfray & Garnett, 2014; Matson et al., 1997; Tilman et al., 2011). Alternative management systems, such as organic farming and conservation agriculture, aim to reduce such negative influences on the environment by either avoiding synthetic inputs such as synthetic pesticides and inorganic fertilisers (Reganold & Wachter, 2016) or minimising soil disturbance and increasing crop diversification and soil cover (Hobbs et al., 2008). Indeed, both systems have shown promise in reducing the negative impact on the environment, especially on soils (Bengtsson et al., 2005; Birkhofer et al., 2008; Mäder et al., 2002; Wittwer et al., 2021); yet, they often exhibited reduced productivity and yield stability (de Ponti et al., 2012; Knapp & van der Heijden, 2018; Pittelkow et al., 2015). Thus, widely used management systems today fail to reconcile high productivity with moderate environmental impact.

To develop productive yet environmentally sustainable systems, accounting for natural processes that provide various ecosystem functions must become an essential part of management considerations (Power, 2010). Soils supply a set of pivotal functions for agricultural production, such as nutrient and carbon cycling, water infiltration and retention, pest and disease regulation and provision of habitat for roots and soil organisms (Kibblewhite et al., 2008). The multifunctional nature of soils is summarised in the concept of soil health—the soil's continuing capacity to function as a vital ecosystem that sustains plants, animals and humans (Bünemann et al., 2018). Therefore, it is necessary to ensure that management preserves the multifunctionality of soils for future generations (Godfray & Garnett, 2014), for instance, by incorporating soil-conservation practices such as reduced tillage, organic amendments and highly diversified crop rotations (Garland et al., 2021; Lehmann et al., 2020; Mäder et al., 2002).

A critical next step toward refined management regimes is to unlock the potential of widely used management systems (Pretty et al., 2018). Several comparisons of management systems—for example conventional versus organic or conservation agriculture—were carried out, highlighting their benefits for production or soil health (Mäder et al., 2002; Pittelkow et al., 2015; Seufert et al., 2012; Wittwer et al., 2021). However, these studies often focused on field trials implementing standardised agricultural practices (Shennan et al., 2017). On-farm studies offer the advantage of covering a wide range of different practices and management systems within a given management system (Büchi et al., 2022; Kirchmann et al., 2016) and allow screening for their specific ability to maintain soil health and produce sufficient yields. Therefore, we conducted an on-farm study across Switzerland to improve our understanding of the impacts of widely used management systems and individual practices. Moreover, the subtle differences between management systems in Switzerland—for example all systems include measures of crop diversification and organic amendments (Büchi et al., 2019; Garland et al., 2021)—allowed us to investigate the effects of individual practices in both within and between management systems.

Our on-farm study comprised a network of 60 farms covering three management systems—conventional, no-till and organic. We studied one wheat field on each farm. To get a comprehensive view of management's impact on production and soil health, we assessed 68 variables to describe different properties of management, production, soil health and site-specific pedoclimatic conditions (Table 1). Specifically, we addressed the following questions: (i) how do different management systems affect production and soil health? (ii) What role does soil health play in production for each management system? (iii) Finally, we aimed to identify management practices that support production and soil health and best promote a multifunctional agroecosystem.

2 | MATERIALS AND METHODS

2.1 | The farm network

For the farm network, we approached individual farmers and asked if they were interested in participating in the study. We obtained consent from all farmers in this study for sampling on their land and verbal consent for interviews. Participants were free to withdraw at any time. We established a network of 60 farms across Switzerland organised in two hubs (in the northeast and southwest of Switzerland) in 2016 (Figure S1). On each farm, we selected one of the farmer-managed fields based on two criteria:

TABLE 1 Key variables and indices describing management, production and soil health properties.

Management	Production	Soil health
Crop diversification	**Grain yield**	***Soil organic matter***
Leys		Organic carbon
Crop richness	***Yield quality***	Microbial carbon
Legumes	Grain protein content	
Preceding crop	Backing quality	***Soil nutrients***
Soil cover	Grain hardiness	Optimal pH
	Grain nutrient content	Soil nitrogen
Fertiliser input		Soil phosphorus
Inorganic fertiliser	***Crop nutrition***	Soil potassium
Organic amendments	Nitrogen concentration	Soil calcium
	Phosphorus concentration	Soil magnesium
Agrochemical use	Potassium concentration	
Herbicides (TFI)	*Minor nutrient concentration*	***Microbial abundance***
Fungicides (TFI)		Prokaryotic PLFAs
Growth regulator (TFI)	***Weed pressure***	Fungal PLFAs
	Weed biomass	AMF PLFA
Soil disturbance	Weed soil cover	Protozoa PLFAs
Tillage (STIR)		Microbial respiration
Weeding (STIR)	**Leaf damage**	
		Microbial diversity
	Fertiliser use efficiency (PFP)	Bacterial diversity
		Fungal diversity
		Soil structure
		Aggregation
		Water holding capacity
		Soil compaction
		Bulk density
		Penetration resistance

Note: In bold are all key variables and indices used for the primary analysis in the study. Indices are indicated in italic and composed of the variables following beneath. The composition of *the indices grain nutrient content* and *minor nutrient concentration* are given in Table S3. For a brief description of the individual variables and units, see Tables S2–S4.

Abbreviations: PFLA, phospholipid fatty acids; PFP, partial factor productivity; STIR, soil tillage intensity rating; TFI, treatment frequency index.

the crop was winter wheat and the soil type, Cambisol. The fields were managed according to the following three management systems: (i) conventional management with tillage, (ii) conventional management without tillage (no-till practice) and (iii) organic management without agrochemicals but with tillage. The different systems had already been in operation for at least 5 years. Management followed the guidelines of the "Proof of Ecological Performance" (conventional management) or the guidelines of "Bio Suisse" (organic management), both of which include diversified crop rotations, a balanced nutrient budget and only targeted use of pesticides (see Büchi et al., 2019 for details). From here on, we refer to the three different management systems as "conventional", "no-till" and "organic", respectively.

2.2 | Field sampling

We defined the sampling area of 300 m^2 at a distance of at least 20 m from the edge of each field and conducted a comprehensive assessment of production and soil health during three different sampling campaigns within a single growing season (find an overview of dates and measured parameters in Table S1).

In the first sampling campaign in spring, we collected composite soil samples by taking 18–20 soil cores (0–20 cm depth) along two perpendicular transects. We used the composite soil samples to measure physicochemical soil properties, including organic carbon and mineral nutrients according to the Swiss reference methods (Agroscope, 1996); microbial abundance and basal respiration following Vance et al. (1987); microbial diversity as described in Walder et al. (2022); and aggregate stability according to Büchi et al. (2022; see Appendix S1 for details). We obtained additional soil physical information by measuring soil bulk density from undisturbed soil cylinders (100 cm^3) and soil penetration resistance as described in Colombi et al. (2019).

In the second sampling campaign, we sampled flowering wheat plants directly above the ground along 0.5 m length of four rows on four subplots separately to assess biomass and nutrient status (see Appendix S1 for details). We also estimated the percentage of soil covered by weeds and sampled above-ground weed biomass in each subplot. In addition, we estimated wheat leaf damage by scoring the non-green area of the flag leaf of 10 wheat plants per subplot. We also collected a composite soil sample (0–20 cm depth) at ten different positions along both transects at the time of wheat flowering—with presumed most active rhizosphere including symbionts—to extract PLFAs and employed biomarkers for prokaryotes, fungi, arbuscular mycorrhizal fungi and protozoa as described in Banerjee et al. (2019). In the third sampling campaign, we sampled wheat plants directly above the ground along 0.5 m length of four wheat rows on four subplots to assess yield quantity and quality (see Appendix S1 for details). We analysed all plant materials according to the Swiss reference methods (Agroscope, 1996).

2.3 | Selection and composition of indices of management, productivity and soil health

In addition to the variables assessed during the field sampling, we collected information directly from the farmers about the management practices applied to the investigated wheat fields in the last five years before sampling through a questionnaire (for details, see Appendix S2 and Büchi et al., 2019). Given the large number of variables quantified in the study, similar variables describing the same characteristic were combined into a single index to avoid disproportionate weighting of characteristics represented by many variables. These indices were then taken together with some stand-alone key variables (e.g. crop yield) as a set of management, production and soil health properties that were used in the following analysis (see overview in Table 1).

For management, we constructed four indices summarising 12 variables that reflect the management properties: crop diversification, fertiliser inputs, agrochemical use and soil disturbance (Table S2). We used three stand-alone variables and three indices describing the production properties (Table S3). Besides wheat grain yield in 2016, we constructed three indices reflecting the production properties grain quality, crop nutrition and weed pressure. We further included leaf damage and the partial factor productivity, an estimate for fertiliser use efficiency calculated by dividing yield by the total amount of applied nitrogen (Ladha et al., 2005), as production properties. We also assessed the mean relative yield compared to Swiss reference yields of the last 5 years of crop rotation based on the farmer questionnaires (Büchi et al., 2019) to compare the results found in 2016 with the data over a more extended period. For soil health, we summarised 17 variables to six indices that reflect the soil health properties: soil organic matter, soil nutrients, microbial abundance, microbial diversity, soil structure and soil compaction (Table S4).

We constructed the indices using principal component analysis (PCA) following Meyer et al. (2018) to derive a single index reflecting multiple variables simultaneously while avoiding multiple contributions from correlated variables (see Appendix S1 for details).

2.4 | Analyses of management system effects

We first conducted a multivariate analysis of variance (MANOVA) to test if the management systems had any overall effect on specific management, production and soil health properties. We checked for multivariate normality by chi-square quantile-quantile plots. Where the MANOVA rendered significant effects, we assessed the differences between management systems of primary variables and indices by ANOVA. We checked linear model residuals for normality and homoscedasticity by plotting fitted values against residuals, and data were log-transformed where necessary to meet model assumptions. We additionally assessed differences among management systems for all individual variables by ANOVA.

We used a multifunctionality approach to summarise multiple agroecosystem responses, including production and soil health properties (Figure S2). We generated multifunctionality indices by either standardising (mean = 0, SD = 1) and averaging properties (Wagg et al., 2014) or by scoring the number of properties reaching a threshold (>50%) following Allan et al. (2015). We assessed multifunctionality by using five different weightings that form a gradient from prioritising production to prioritising soil health properties (Figure S2). We used the multifunctionality scenario "soil health," where only soil health properties are considered, as a single metric, representing "overall soil health" in the following analyses. We assessed the effect of management systems on the multifunctionality index under all scenarios by ANOVA.

2.5 | Models explaining productivity under different management systems

As we found significant management system effects for most of the parameters, we included 'management system' as a factor in the models of the following analyses or performed the analysis on data subsets by the management system so that the management system effects could not confound the different results. First, we tested the impact of different management and soil health properties on grain yield by applying multivariate linear models with management systems as the first predictor (grain yield ~ management system * property of interest). We employed estimated marginal trends with the *emtrends* function of *emmeans* package (Lenth & Lenth, 2018) to assess different trends depending on management systems.

To compare the importance of soil health for grain yield compared to other biological constraints, we conducted independently for each management system a multivariate linear model with grain yield as the dependent variable and weed pressure, leaf damage and soil health as predictors (grain yield ~ weed pressure + leaf damage + soil health). We then calculated the relative importance of each predictor by variance decomposition (using LMGmetrics, Grömping, 2006).

2.6 | Analysis of management practices' impact on agroecosystem multifunctionality

In the last part of the analysis, we focused on the effect of individual management practices on grain yield, soil health and multifunctionality. We first employed a multimodel comparison using the R package 'glmulti' (Calcagno & de Mazancourt, 2010) to investigate the extent to which management practices and environmental determinants affect yield and soil health for all management systems separately. Besides all 14 management variables, we also used the mean annual temperature (MAT), mean annual precipitation (MAP), field altitude, and clay and silt content as pedoclimatic determinants. We extracted the relative importance of management and environmental predictors (Burnham et al., 2010) and employed multimodel averaging of the "top models" (i.e. models within the lowest two AICc units; R package 'MuMIn' (Barton & Barton, 2015) to obtain the standardised parameter estimates for each top model predictor (see Appendix S1 for details).

Finally, we identified management practices that best support multifunctional agroecosystems across management systems. We first divided the 60 fields into groups of equal size representing 'low' and 'high' multifunctionality performers based on the equal-weight multifunctionality scenario (using the *cut* function in R) to examine the differences in farming practices between the groups. We then performed a linear discriminant analysis (LDA) to infer the management practices associated with 'high' and 'low' multifunctionality (R package 'MASS' Ripley et al., 2013). To test the effect of these presumably multifunctionality supporting practices, we first averaged all practices that were associated with high multifunctionality (discriminator weight >1) into an index (using standardisation [mean = 0, SD = 1] and averaging; Wagg et al., 2014). We then validated the effect of the multifunctionality supporting practices index on the equal-weight multifunctionality scenario by testing their relationships using linear models including clay as a covariate to account for site-specific differences of the primary pedoclimatic determinant of soil health. To capture the relative effect size of the different management variables, we calculated the percentage of the sum of squares to the total sum of squares within each model. We conducted all statistical analyses in R v4.0.2 (R Core Team, 2013).

3 | RESULTS

3.1 | Effect of management system on productivity and soil health

The three management systems varied from each other in multiple aspects. Conventional management was characterised by the lowest crop diversification and the highest overall fertiliser inputs (Figure 1a,b). No-till management stood out with the lowest degree of soil disturbance (Figure 1d). No-till and organic management showed a similar level of crop diversification (Figure 1a). Organic management had the lowest fertiliser input and no agrochemical use but the highest soil disturbance (Figure 1c,d; see Figure S3 and Appendix S1 for details). The systems could clearly be differentiated based on the four management indices (MANOVA: $F_{2,56} = 26.03$, $p < 0.001$).

The difference between systems was also evident across the main variables and indices describing production (MANOVA: $F_{2,56} = 5.85$, $p < 0.001$). Wheat yield varied significantly among the three management systems and was highest with conventional management (5.4 t/ha), intermediate with no-till (4.5 t/ha), and lowest under organic management (3.5 t/ha; Figure 1e). The yield differences were also reflected by the mean relative yield of the last 5 years based on farmer reports (Figure S4A), and the yield measured during this campaign correlated with the yield of the last 5 years (Figure S4C,D). Besides the lowest yields, production under organic management

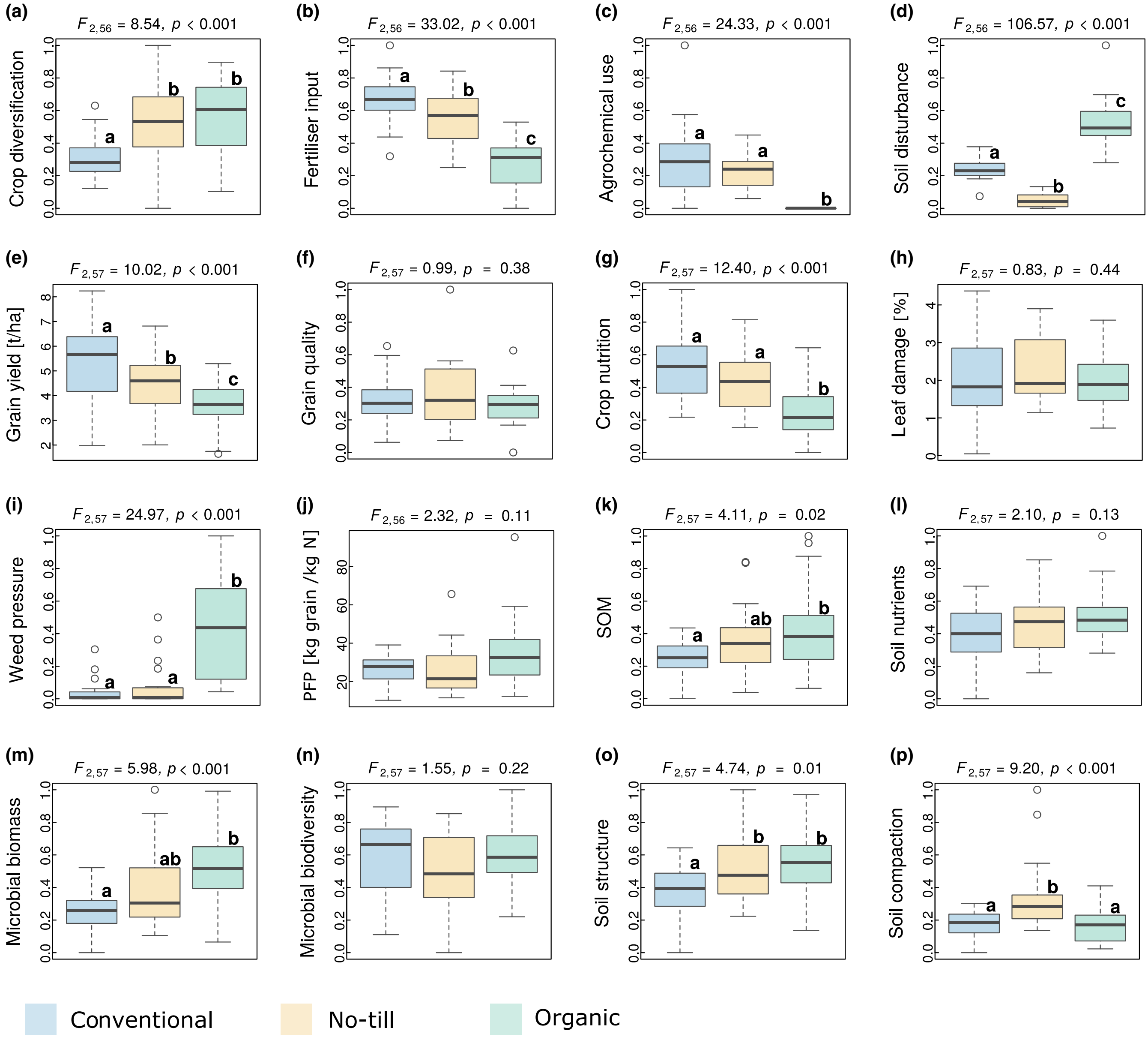

FIGURE 1 Management, production and soil health properties across the different management systems. Influence of management systems on the properties of agricultural management (a–d), production (e–j) and soil health (k–p). The properties are standardised indices combined from several variables (in italics), except for some key variables of production in the original units (e–g). Model performance specifications are given at the top of each plot. Letters indicate a significant difference between the management systems ($p<0.05$). PFP stands for partial factor productivity.

was also characterised by the highest degree of weed pressure (Figure 1h). However, we found no clear differences in grain quality, leaf damage or partial factor productivity between management systems (Figure 1f,h,j; see Appendix S1 for details).

Finally, soil health also differed among the management systems (MANOVA: $F_{2,56}=5.85$, $p<0.001$; Figure 1k–p). Individual properties describing soil health were generally lowest under conventional management and highest under organic management. Organic soils had markedly higher organic matter content and microbial abundance, with no-till management ranging in the middle (Figure 1k,m; see Appendix S1 for details). The soils of no-till systems showed the highest level of soil compaction but, together with the organically managed soils, had a better soil structure than conventional management (Figure 1o,p). We found no difference in soil nutrients and microbial diversity between management systems. On balance, the overall soil health—the soil health only multifunctionality scenario—was significantly higher under organic management than under no-till and conventional management (Figure 2a). Note that pedoclimatic characteristics, such as soil texture and climatic variables, did not vary between management systems and thus did not confound the presented management effects (Figure S5R–W).

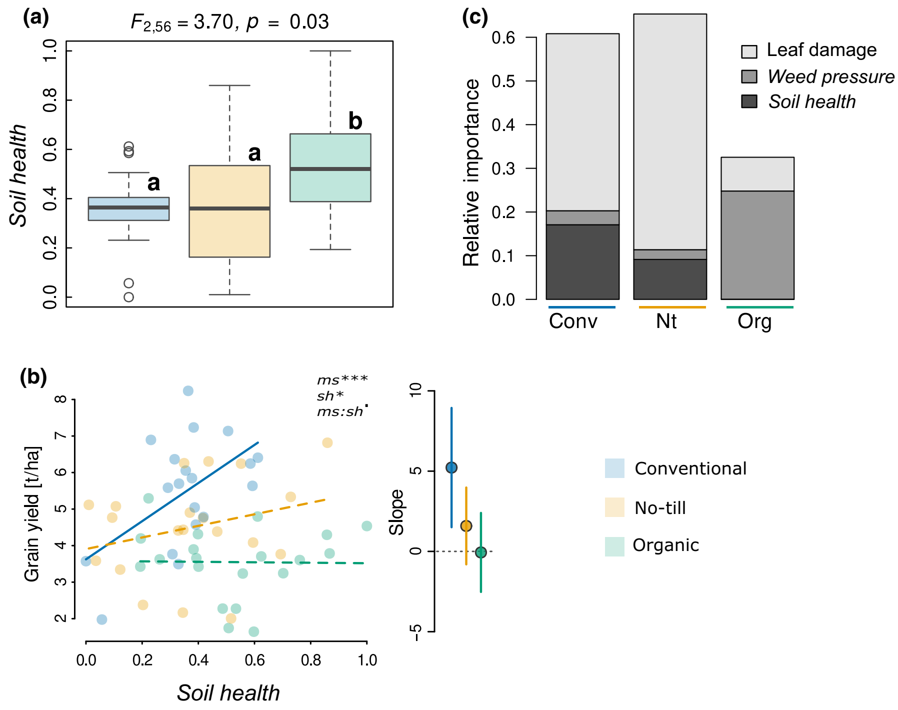

FIGURE 2 Soil health and its influence on production in different management systems. Influence of management systems on overall soil health (a). Model performance specifications are given at the top of the plot. Letters indicate a significant difference between the management systems ($p < 0.05$). Relative importance of overall soil health compared to leaf damage and weed pressure in explaining wheat yields under conventional, no-till and organic management (b). Relative importance was calculated using variation decomposition of multivariate models. The scatter plot presents the relationship between overall soil health and yield (c). Regression lines are shown for individual management systems (coloured depending on the system). Solid lines indicate significant regression relationships ($p < 0.05$). The significance of the main effects of management system (ms) and soil health (sh) and their interactions are shown in the upper edge of the plots. The insets show slope estimates with 95% confidence intervals.

3.2 | Relationships between management, crop yield and soil health

We investigated whether management and soil health properties support crop yield in the next step. None of the management indices showed a clear impact on yield when all management systems were combined (Figure S6). However, crop diversification and overall fertiliser use indices showed an interaction with the management system—both indices were positively related to yield under conventional management only (Tables S5 and S6). The agrochemical use property showed no interaction with the management system but only a positive relationship to grain yield under no-till management (Figure S6C). For the soil health properties, we found clear effects on yield across all management systems for soil organic matter, soil nutrients and overall soil health (Table S7). However, the effect of soil health properties was particularly evident under conventional management (Figures 2b and 3). The properties soil structure, microbial abundance and microbial diversity showed an interaction with management systems and positively related to yield under conventional management (Figure 3b,c,f, Table S7). In addition to the individual soil health properties, overall soil health also showed the most pronounced positive relationship to yield under conventional management (Figure 2b).

We then further compared soil health's overall effect on yield with other biological constraints, namely, weed pressure and leaf damage. Soil health had the highest relative importance for yields in conventional management (17% of explained variance), followed by no-till (9% of explained variance), and it was lowest under organic management (less than 1% of explained variance). Besides soil health, leaf damage was the most important predictor of yield in conventional and no-till systems, while weed pressure was the most important predictor in organic systems (Figure 2b).

3.3 | Management practices supporting yield and soil health

Since soil health can be critical to agricultural production, we wanted to test which individual management practice and pedoclimatic factor best predict wheat yield and soil health. Management factors showed high relative importance for yields in all systems (Figure 4a–c), explaining between 30% and 35% of the total variance. In contrast, pedoclimatic factors were less important for explaining yield (12%–16% of variance explained). We found fungicides and organic amendments to increase grain yield in conventional systems, while herbicides were negatively associated with conventional yields (Figure 4a). Under no-till, the analysis revealed partly opposite

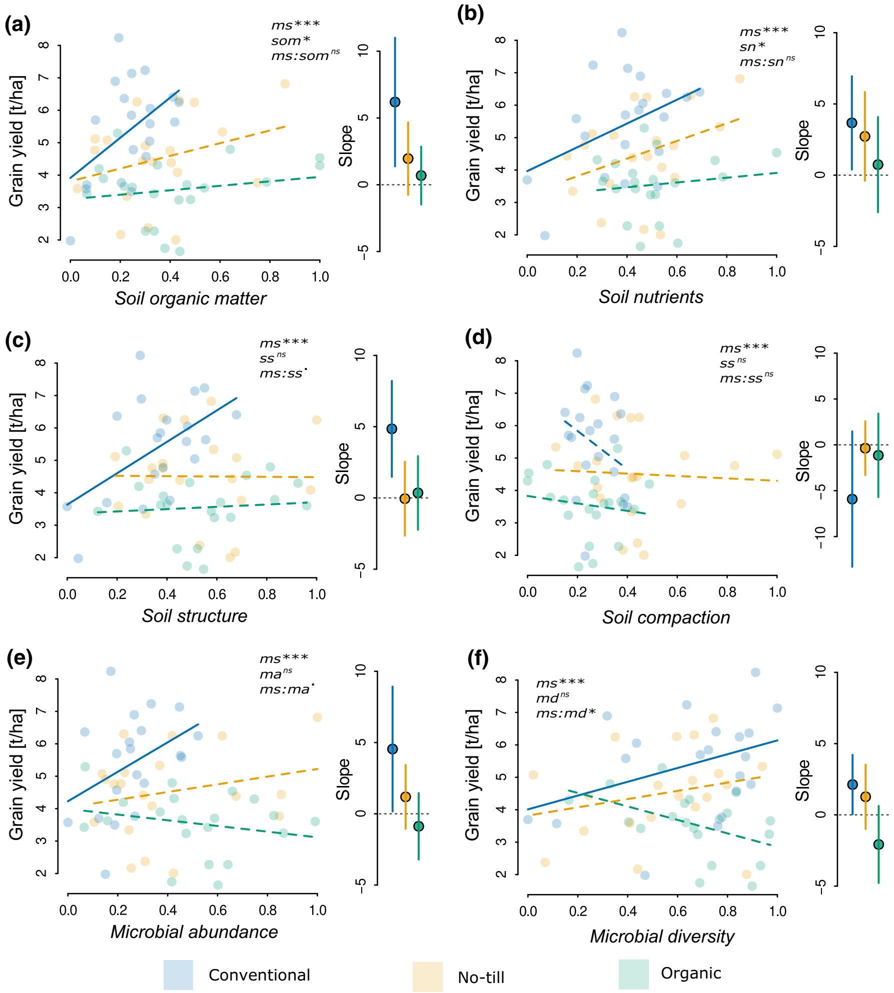

FIGURE 3 Soil health-yield relationships in different management systems. The scatter plots present the relationship between the soil health properties soil organic matter (som, a), soil nutrients (sn, b), soil structure (ss, c), soil compaction (sc, d), microbial abundance (ma, e) and diversity (md, f) to grain yield. Regression lines are shown for individual farming systems (coloured depending on the system). Solid lines indicate significant regression relationships ($p < 0.05$). The significance of the main effects of management system (ms) and soil health indices and their interactions are shown in the upper edge of the plots. The insets show slope estimates with 95% confidence intervals.

effects. While fungicides were also positively associated with wheat yield, under no-till herbicides indicated positive and organic amendments negative effects. Soil cover was negatively associated with yields under no-till and organic management, while other crop diversification measures such as leys and preceding crops were positively associated with organic yields (Figure 4c).

In contrast to yield, overall soil health was best predicted (up to 48% of the total variance) by pedoclimatic factors. Nevertheless, various management factors significantly influenced overall soil health (Figure 4d–f). In particular, crop diversification practices such as the cultivation of leys or legumes and soil cover were positively associated with overall soil health, although legumes were also negatively associated under no-till (Figure 4e). Besides crop diversification, tillage positively affected overall soil health under organic management and mineral fertiliser was negatively related to soil health under conventional management.

3.4 | Agroecosystem multifunctionality and supporting practices

In order to assess the overall performance of the three management systems, we assessed production-soil health-based agroecosystem multifunctionality. We used five multifunctionality scenarios with different weightings to consider all production and soil health properties together (Figure S2). Conventional management was superior in the scenario where only production properties represented multifunctionality, especially compared to organic systems (Figures S8). We found the contrary in the scenario where only soil health properties represented multifunctionality, with organic management showing the highest degree of overall soil health, even more accentuated when assessed by thresholds. Yet, all management systems performed very similarly when the production and soil health properties were considered together under equal weightings (Figure 5a, Figure S8).

To identify the management practices that promote production-soil health-based multifunctionality, we first divided the fields into two distinct groups of low and high equal-weight multifunctionality ($F_{2,57} = 76.9$, $p < 0.001$), followed by a linear discriminant analysis (LDA) that tested the contribution and importance of individual managements practices on low or high multifunctionality. The LDA indicated that leys, crop richness, organic amendments and fungicide use were most associated with the high multifunctionality group, while no variables could be identified that were associated with the low multifunctionality group (Figure 5b). By averaging the four variables that explained high multifunctionality, we calculated an index

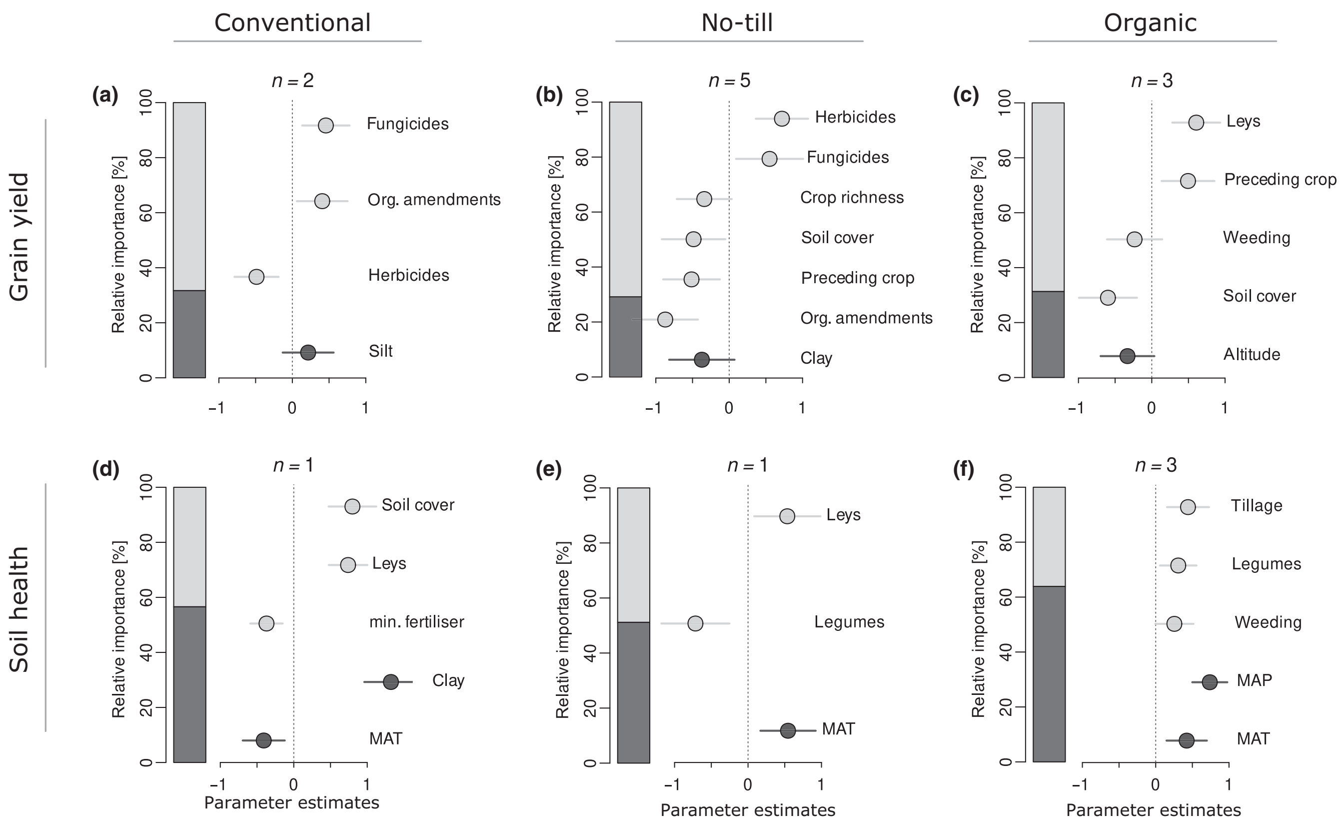

FIGURE 4 Management and environmental drivers of yield and soil health. Influence of management (grey) and pedoclimatic variables (dark) on yield (a-c) and overall soil health (d-f) were calculated separately for each management system using a multimodel comparison. The relative importance of individual management and pedoclimatic factors across all models is shown. For each variable, the average parameter estimates of the top models with 95% confidence intervals are presented. n refers to the number of top models included.

for multifunctionality-supporting practices (Figure S8L). Our model suggests that combining these multifunctionality-supporting practices is positively associated with multifunctionality but reaches a plateau at the highest multifunctionality levels (Figure 5c).

4 | DISCUSSION

Food production is the most prominent function of any agroecosystem but other attributes such as soil health must be carefully considered because they contribute to long-term agroecosystem functioning. By employing a comprehensive study including 68 variables that reflect agroecosystem management and performance across 60 farms, we provide here further evidence that today's widely used management systems lead to critical trade-offs between achieving high yields and maintaining soil health (de Ponti et al., 2012; Godfray & Garnett, 2014; Pittelkow et al., 2015; Tilman et al., 2011). Besides the clear benefits of no-till and especially organic management for several soil health properties, our on-farm comparison also revealed drastic yield gaps to conventional management, indicating that productivity and soil health still need to be better reconciled in agricultural management. Remarkably, however, our results underline clear synergies between production and soil health, highlighting the importance of developing balanced management systems that support multifunctional agroecosystems. A cross-system analysis suggests that by combining crop diversification and organic fertilisation with effective crop protection, such balanced systems sustaining soil health while delivering sufficient yields could be achieved.

Several findings pointed out the importance of soil health for wheat production in our on-farm study. First, we observed that overall soil health, and various specific soil health properties, showed a positive relationship to yields. Second, soil health was an important predictor of yield in conventionally managed fields and to a smaller extent in no-till fields, while other biological constraints (e.g. weed pressure) were much more critical in organically managed fields. The more prominent role of soil health in conventional and no-till fields is in line with the relatively low soil health indices, indicating that soils were partially degraded and could no longer meet their full potential in supporting primary production. Indeed, it is widely accepted that conventionally intensified agricultural management leads to the degradation of soils (Matson et al., 1997; Smith et al., 2016), which ultimately puts productivity at risk.

Further indications that soil degradation played a role in production in our on-farm study can be found when looking at soil organic matter—a sound indicator of the soil's health status (Bünemann et al., 2018; Kibblewhite et al., 2008). Previous studies focus on the role of soil organic carbon concentration—which is also integral to our

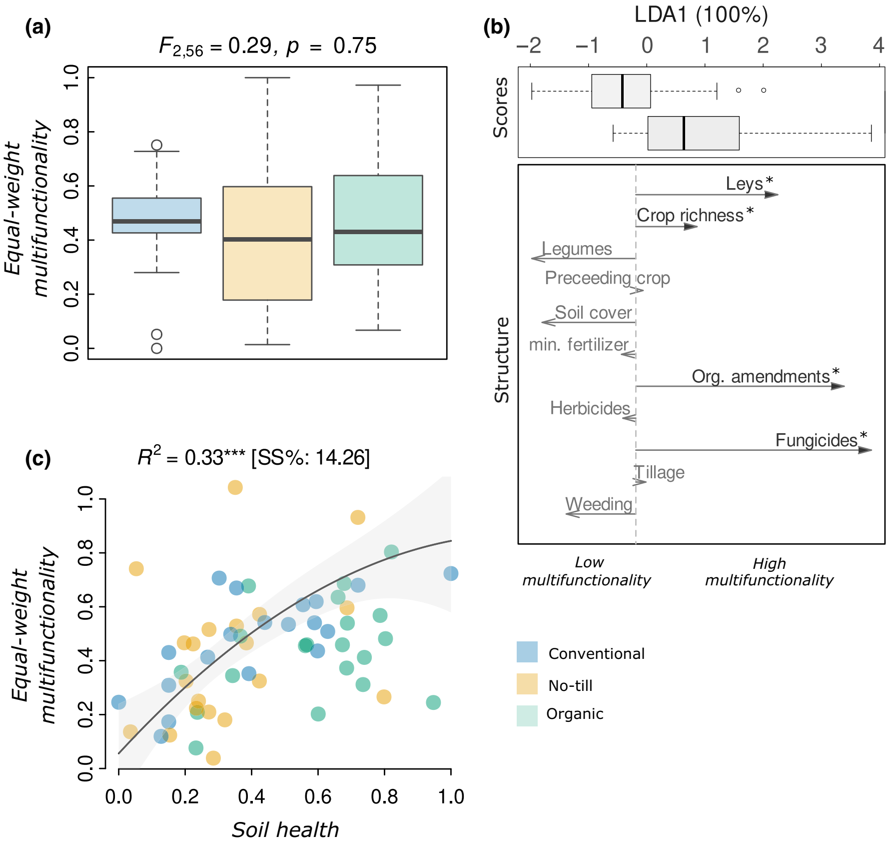

FIGURE 5 Agroecosystem multifunctionality and supporting practices. (a) Production-soil health-based multifunctionality of conventional, no-till and organic management systems. Multifunctionality is calculated by equally averaging production and soil health properties (see Figure S2). Model performance specifications are given at the top of the plot. (b) Linear discriminant analysis highlights management practices associated with low or high multifunctionality performing fields. Stars highlight multifunctionality-supporting practices. (c) Relationships between averaged multifunctionality-supporting practices and equal-weight multifunctionality. The goodness-of-fit statistic (R2) with significance level and the effect size (percentage sum of squares; SS%) of multifunctionality-supporting practices are given at the top of the corresponding graph (*** < 0.001).

soil organic matter property—for productivity (Oldfield et al., 2019, 2020). They indicate that productivity can be affected when soil organic carbon concentration falls below a 2%–4% threshold. With a mean organic carbon concertation of less than 1.4% for conventionally and 1.7% for no-till managed soils, they largely lay below this threshold, and the resulting limitation could have contributed to the positive correlations with yields. Our results suggest similar relationships for soil nutrients, soil structure and microbial abundance, which are also critical for primary production (Lehmann et al., 2020).

The influence of soil health on wheat yield became weaker the higher the level of overall soil health. The relationships between soil health properties and wheat yield, for instance, were less evident in the no-till and almost absent under organic management. The relatively small effect may be since soil health was generally higher—not falling below a critical threshold—in these systems, yet the overlap between the systems was huge for the overall soil health and specific properties. An alternative explanation for the different responses of the systems is that the effects of soil health were overruled by other biological constraints, such as weeds, pathogens and pests, as they often exert higher pressures in more extensive systems (de Ponti et al., 2012; Lobell et al., 2009). It is also possible that we have not addressed soil health holistically enough to reveal the limiting soil health properties in the organic system, as soil health is very complex and challenging to assess (Janzen et al., 2021). For instance, the concept of soil health presented here does not adequately cover soil properties related to water regulation and pest and disease regulation (Kibblewhite et al., 2008). We further measured soil health properties at a single point in time, hence not considering seasonal dynamics, which may be significant under temperate climatic conditions such as in Switzerland (García-Ruiz et al., 2009). However, we took all soil samples at the beginning of the year, which provides a valuable baseline for monitoring long-term effects on soil health and avoids short-term effects due to management and crop demand (Carter & Gregorich, 2007). Even though it was not possible with the present design to depict soil health in its entirety, our results exemplify that soil health can be a prominent factor limiting crop yields in wheat-based systems.

Given the importance of healthy soils for production, management should be designed to promote both. However, none of the investigated management systems appeared to be advantageous in simultaneously promoting crop yield and maintaining soil health. Conventional management highlighted its known advantages in production properties—exhibiting substantially higher wheat yields. The yield gap between fields under conventional and no-till or organic management in our study was 17% and 34%, respectively, which is high compared to previous reports, yet the differences are generally more pronounced for wheat (Mäder et al., 2002; Pittelkow et al., 2015; Seufert et al., 2012; Wittwer et al., 2021). One reason for the particularly marked differences could be that we compared the systems on-farm and not in optimised long-term trials with elaborate alternative systems (Kirchmann et al., 2016). In addition, unlike most comparisons on field trials, our on-farm study included 25 wheat varieties, which differed between the management systems (Banerjee et al., 2019) and may contributed to the observed yield gap. In any case, the comparison to the relative yields over the last 5 years suggests that the observed differences are of general relevance for the surveyed fields and that the no-till and organic management lagged significantly behind in terms of productivity on the farm.

On the other hand, conventional management experienced clear disadvantages in the soil's status with lower soil health properties, especially when compared to organic management. This deficiency is consistent with previous reports where conventionally managed soils exhibited lower soil organic matter, poorer soil structure and less diverse and abundant soil life (Bengtsson et al., 2005; Loaiza Puerta et al., 2018; Mäder et al., 2002; Wittwer et al., 2021). The organically managed soils showed exceptionally high levels of soil organic matter, and earlier in-depth analyses of the same fields indicated that this might foster soil aeration and thereby root growth and carbon allocation (Colombi et al., 2019; Hirte et al., 2021). Soils under organic management also showed higher microbial abundance but no difference in diversity. However, we have shown in an earlier analysis that fungal communities under organic management were far more complex, even if they did not exhibit higher diversity (Banerjee et al., 2019). For no-till management, we revealed mainly positive effects on soil structure. Our earlier work highlighted that those no-till systems also had higher soil carbon stocks in the topsoil layer (Büchi et al., 2022). It should be noted that no-till systems were applied for a shorter time on average compared to organic systems, so the soil health of no-till systems could represent a transitional status that would become more pronounced over time.

To overcome such trade-offs between production and soil health, we must understand which practices drive the conflicts under current management. In our on-farm study, conventional management was characterised by relatively high synthetic mineral fertiliser use, which was negatively associated with overall soil health. The use of mineral fertiliser instead of organic amendments has been attributed to decreased soil organic matter and soil life (Bünemann et al., 2006; Ladha et al., 2011; Mäder et al., 2002) and thus could have contributed to the lower soil health properties in conventional fields. Our work indicates, in contrast, that crop diversification measures provide promising soil health support. The frequent cultivation of leys—as in organic—and a high level of soil cover—as in no-till—promoted overall soil health in our study, which has also been linked to improved soil health earlier (Garland et al., 2021; Loaiza Puerta et al., 2018). Consequently, our work indicates that appropriate management can improve soil health, although the importance of the pedoclimatic conditions on soil was much greater than on yield. Soil management, unlike crop yield, is thus less about maximising and more about optimising within the limits of site-specific conditions (Zwetsloot et al., 2020).

Our work further suggests that crop diversification has also supported crop yield, particularly under conventional management, where the level of crop diversification was relatively low. Low crop diversification has already been identified to put yields at risk in conventionally intensified systems (Bennett et al., 2012). Based on the positive interactions between crop diversification, soil health and crop yield, our work suggests that an essential effect of crop diversification on yield is soil health restoration. The reported role of crop diversification in conventionally intensified systems could be even more critical in other regions than Switzerland, as conventional agriculture in Switzerland is relatively diversified compared with other European countries (Garland et al., 2021). However, our work indicates that crop diversification can also create challenges for production, as we observed a negative effect of soil cover on crop yields under no-till and organic management. Hence, integrating such measures needs to be balanced.

Agricultural management offers clear possibilities to promote simultaneously soil health and productivity, fostering multifunctional agroecosystems. Our models suggest combining crop diversification measures and organic amendments with fungicide use as the most promising set of practices to develop agricultural systems that produce sufficient yields and maintain healthy soils. Similar to crop diversification, fertilisation with organic amendments is well known to hold great potential to support yields—as an integral part of efficient fertiliser systems (Tamburini et al., 2020)—as well as soil health in agricultural systems (Lehmann et al., 2020).

While the importance of crop diversification and organic amendments for balanced management systems seems intuitive, fungicides are somewhat surprisingly part of our multifunctionality-supporting models. However, fungicide use was markedly linked to increased yields in our models and are an effective tool for protecting crops from pathogens and securing yields (Savary et al., 2019). Plant protection may play a particularly critical role in the current study as it was conducted in a very wet year where fungal pathogen pressure is usually high. Thus, the appearance of fungicides in the multifunctionality-supporting practices may symbolise the importance of effective crop protection for agricultural production. However, it is crucial to consider that fungicides and other pesticides have also been linked to decreasing beneficial soil life (Pelosi et al., 2021; Riedo et al., 2021) and thus potentially suppress the natural ability of soils to support primary production (Edlinger et al., 2022). Therefore, it is critical to carefully evaluate such adverse effects before recommending fungicide use as a tool to promote multifunctionality. Balanced farming systems strive for practices that jointly optimise yield, crop quality and environmental sustainability. Therefore, effective crop protection in balanced systems should be achieved primarily through selecting suitable crop varieties and using integrated pest management methods and agro-ecological principles such as push and pull.

Our work highlights the potential to reconcile productivity and soil health through balanced management systems combining conventional and alternative practices. Bringing together different management approaches, detached from current system boundaries, could be an effective way to promote the much-needed change in current management systems (Godfray & Garnett, 2014; Pretty et al., 2018).

AUTHOR CONTRIBUTIONS

Lucie Büchi, Florian Walder, Jochen Mayer, Johan Six, Thomas Keller, Marcel G. A. van der Heijden, and Raphaël Charles conceived and designed the study. Lucie Büchi and Florian Walder collected the data. Florian Walder and Cameron Wagg performed statistical analyses. Florian Walder, Lucie Büchi, Cameron Wagg, Tino Colombi, Samiran Banerjee, Juliane Hirte, Jochen Mayer, Johan Six, Thomas Keller, Raphaël Charles and Marcel G. A. van der Heijden provided substantial contributions to the interpretation of data. Florian Walder wrote the manuscript with substantial contributions from all authors.

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CONFLICT OF INTEREST STATEMENT

The authors declare no competing interests.

DATA AVAILABILITY STATEMENT

Data available via the Dryad Digital Repository https://doi.org/10.5061/dryad.12jm63z3n (Walder et al., 2023).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Appendix S1. Supporting information: Synergism between production and soil health through crop diversification, organic amendments and crop protection in wheat-based systems.

Figure S1. On-farm network across Switzerland, consisting of conventional, no-till and organic farms.

Figure S2. Agroecosystem multifunctionality scenarios.

Figure S3. Original variables describing agricultural management across the 60 field sites.

Figure S4. Original variables describing production properties across the 60 field sites.

Figure S5. Original variables describing soil health properties and pedo-climatic conditions across the 60 field sites.

Figure S6. Management-yield relationships in different management systems.

Figure S7. Production-soil health based agroecosystem multifunctionality.

Figure S8. Composition of the indices for management, crop performance and soil health properties.

Table S1. Overview of sampling efforts for the assessment of production and soil health.

Table S2. Variables related to agricultural management. Composite variables related to sub-sets of particular aspects are shown in italics and are comprised of the variables that follow beneath the next line.

Table S3. Variables related to crop performance. Composite variables related to sub-sets of particular aspects are shown in italics and are comprised of the variables that follow beneath the next line. All main variables are shown in bold.

Table S4. Variables related to soil health. Composite variables related to sub-sets of particular aspects are shown in italics and are comprised of the variables that follow beneath the next line. All main variables are shown in bold.

Table S5. Analysis of variance table for the effect of management properties on grain yield.

Table S6. Marginal trends between management properties and grain yield in different management systems.

Table S7. Analysis of variance table for the effect of soil health properties on grain yield.

Table S8. Marginal trends between soil health properties and grain yield in different management systems.

Appendix S2. Questionnarie to assess farmers' management data.

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