SOIL ECOLOGY LETTERS

SEL RESEARCH ARTICLE
Volume 7 / Issue 1 / 240278 / 2025
https://doi.org/10.1007/s42832-024-0278-7

The dissimilarity between multiple management practices drives the impact on soil properties and functions

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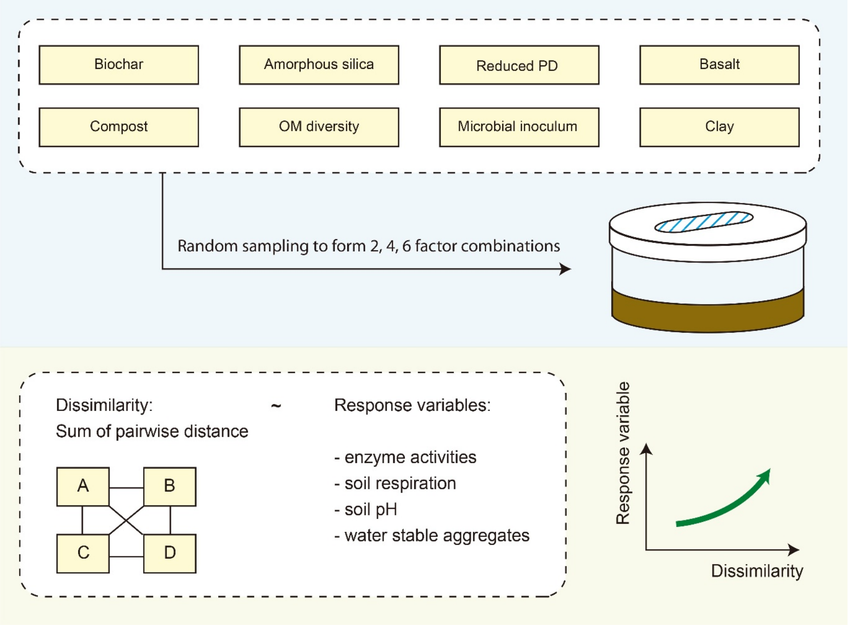
Received September 6, 2024; Revised November 16, 2024; Accepted November 27, 2024

ABSTRACT



- Higher dissimilarity between restoration factors boosted soil microbial activities when multiple factors jointly applied.

- More diverse management practices enhanced soil aggregate stability and improved soil pH.

- Increasing restoration factors up to 8 factors only influenced soil properties (water stable aggregates and soil pH) but not soil microbial activities.

A range of land management practices are available to achieve better soil quality, but their combined effects remain understudied. We hypothesize that more diverse management practices, meaning higher dissimilarity, lead to stronger effects on soil functions and properties. Eight practices (biochar, compost, clay, amorphous silica, basalt, microbial inoculum, reduced physical disturbance and organic matter diversity) were selected with 20 replicates for treatments involving 2, 4, or 6 factors and 10 replicates for 8 factor treatments. We investigated the impact of individual factors, factor number, factor dissimilarity and factor composition on soil respiration, soil enzymatic activities (β-glucosidase, β-D-cellobiosidase, β-N-acetylglucosaminidase and phosphatase), soil pH, water stable aggregates and permanganate oxidizable carbon fraction. By including dissimilarity in addition to factor number, variance explained for soil respiration and enzymatic activities increased up to 54.21%. For soil pH and water-stable aggregates, explained variability increased to 65.57% and 57.38%, respectively. More diverse management practices boosted soil microbial activities, enhanced soil aggregate stability, improved soil pH while reducing labile carbon, whereas factor number only influenced water stable aggregates and soil pH. Our study highlights the importance of management practices diversity in soil functions and properties and calls for further research on synergistic combinations of diverse interventions.

Keywords management practices, soil functions, soil pH, water stable aggregates, multiple factors interactions, factor dissimilarity

1 Introduction

Soil quality and health are key factors for sustainability, biodiversity protection and climate change mitigation (Urra et al., 2019; Lehmann et al., 2020a). A wide range of management practices have been explored and assessed for their potential to improve soil health, with a focus on soil functions (Bai et al., 2022). Implementation of management practices is guided by different contexts. For example, in grasslands, restoration practices are applied with the scope of mitigating climate change, restoring soil health and promoting biodiversity. Examples of grassland restoration

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Cite this: Soil Ecol. Lett., 2025, 7(1): 240278

practices include controlled grazing and control of invasive species. In contrast, the scope of management practices in an agricultural context is to increase crop yield and sustainability. The common agricultural practices include crop rotation, conservation tillage and the application of organic amendments, such as compost. However, the fundamental objective underlying management practices application in both agricultural systems and grassland systems is to modify soil properties as an initial step.

Numerous studies have investigated the impact of different types of management practices with the aim to increase soil carbon stocks and soil fertility, and potentially boost crop yield or increase biodiversity (Wei et al., 2006; Akhtar et al., 2014; Sánchez-Monedero et al., 2019; Schaller et al., 2020; Hannet et al., 2021; Bai et al., 2022). A few management practices including biochar and no-tillage systems are quite common, while some management practices, such as amorphous silica addition, are relatively novel. Amorphous silica, a fine-texture industry by-product, has been applied in a field experiment in Brandenburg, Germany, achieving pronounced effects on plant available water in soil, whereas the joint application of silica and other land management practices remains untested (Schaller et al., 2020,2021). Widely studied land management practices have been investigated in both single implementation and joint application. Biochar has been shown to be successful in combination with nutrient additions, such as from compost and inorganic fertilizers. For example, the joint application of biochar and compost or inorganic fertilizer can enhance the efficiency of co-applied fertilizer and increase crop yield (Hannet et al., 2021; Bai et al., 2022). Therefore, the co-application of management practices could be critical in improving soil properties. However, most prior experimental studies on joint management practice applications have only addressed one or two management practices, and three at the most, meaning that effects of co-applying a greater number of factors are unknown (Rillig and Lehmann, 2019; Hannet et al., 2021; Rillig et al., 2024). This leaves a substantial research gap of how jointly applying a greater number of management practices influences soil properties and functions. Consequently, with the unknown joint effects of more complex, multiple factor combinations, our ability to optimize soil management strategies is limited.

Examining a large number of interacting factors in experiments is challenging, because the number of experimental units increases rapidly with increasing factor number in a classical factorial experiment design. With the goal of revealing joint effects of a large number of treatments, Rillig et al. (2019) developed an experimental design to address multiple global change factors using a random selection approach from a pool of factors, which creates a gradient in the number of factors, offering an opportunity to study effects of combining a greater number of factors, while deemphasizing their identity. Therefore, we applied this approach in multiple management practices research to address the challenge of a large number of experimental units that would come with the classical fully factorial design.

While studying the effects of factor number is important for phenomenologically exploring effects, it is also beneficial to uncover the mechanisms underpinning such joint effects. We conducted an experiment using 'random sampling from a factor pool' to examine effects of an increasing number of management practices and examined the contribution of factor dissimilarity to potential changes in soil functions and properties.

To explore this question, we used soil microcosms to test eight management practices. We hypothesized that (1) the dimensionality of management practices plays an important role for both soil structure and function; and (2) more diverse management practices may provide more strongly positive effects on both soil structure and functions.

2 Materials and methods

2.1 Experimental design

We tested eight land management practices: biochar, compost, organic matter diversity, clay, amorphous silica, decreased physical disturbance, basalt and microbial inoculum. We list the general information of the selected land management practices in Table 1, and below we present the rationale behind the treatments.

1) Biochar. Biochar is the product of pyrolysis of organic material, such as woody materials or crop residues, under oxygen limited environments. It can improve soil properties and mitigate the impacts from global change factors, such as drought and salinity (Akhtar et al., 2014; Liang et al., 2014; Lehmann and Joseph, 2015; Dugdug et al., 2018; Semida et al., 2019). We applied 0.5% (dry mass, w:w) high temperature wood biochar in our experiment.

2) Compost. Compost refers to processed organic waste materials, such as wood chips, manure or a mixture. It can enhance soil quality and includes a wide range of magnitudes (Cogger, 2005; Bonilla et al., 2012). We selected a commercially available compost and applied 0.5% (dry mass, w:w) as our compost treatment.

3) Organic matter diversity treatment. The diversity of carbon source may influence the carbon persistence in the soil (Lehmann et al., 2020b). Therefore, we selected 7 native German plant species (*Festuca pratense*, *Stellaria media*, *Trifolium pratense*, *Cichorium intybus*, *Plantago lanceolata*, *Medicago lupulina*, Hemp stems), dried them at 60 °C, milled and mixed them with wheat straw to form a litter mixture. For the treatment without 'organic matter diversity', we added wheat straw alone as a contrast. We calcu-

Table 1 Tested management practices and concentrations.

Management practice	Product information or source	Concentration (w:w)
Biochar	Carboverte, Eibenstock, Germany Total carbon content 85.20%, sieved through 4 mm	0.5%
Compost	COMPO BIO Gärtnerkompost torffrei, Compo, Münster, Germany Total carbon content 13.32%, sieved through 4 mm	2.5%
Organic matter diversity	Collected from Albrecht-Thaer-Weg, Berlin, Germany Total carbon content 42.45%, sieved through 4 mm	0.8%
Clay	Natur-Bentonit, EGoS GmbH, Bottrop, Germany, grain size 50 µm	1.0%
Amorphous silica	Aerosil 300, Evonik Industries, Essen, Germany Amorphous Si, 0 g (Si-C), 10 g (Si-10), and 100 g silica (Si-100), specific surface area 300 m^2 g^{-1}	1.0%
Basalt	<4 mm $CaSiO_3$	1.0%
Microbial inoculum	Zwillenberg-Tietz Foundation land	200 g fresh soil in 600 mL sterilised distilled water; 5 mL of this suspension added per experimental unit
Decreased physical disturbance	(Not applicable)	Applied after 3 weeks

We used 8 management practices of which 6 were applied as solids. The products used and their concentration (w:w) are presented. Explanations on the application of the other two factors (physical disturbance and microbial inoculum) are given in the text.

lated an equal carbon portion in comparison with compost and biochar and applied 0.8% (dry mass, w:w).

4) Clay. Clay addition has been investigated experimentally to increase the soil biochemical properties, especially for sandy-texture soil (Ismail and Ozawa, 2007; Mi et al., 2021). Therefore, we expect to observe beneficial effects on our sandy loamy soil. We chose bentonite, a natural clay mineral, following the tested application rate, added at 1% (Mi et al., 2020).

5) Amorphous silica. Amorphous silica has been shown to increase soil water holding capacity, mitigating drought stress and reduce phosphorus fertilizer dependency in a field experiment near Berlin (Schaller et al., 2020, 2021). Therefore, we used the same product and the same application rate (1%, dry mass, w:w) as in the field experiment.

6) Basalt. Using basalt for enhanced weathering has a pronounced effect to increase soil pH, accompanied by an increase of K and Mg that is supplied in the Basalt (Gillman et al., 2002). Moreover, by binding the carbon dioxide as HCO_3^-, basalt can increase the inorganic carbon stock in soil (Beerling et al., 2020). Therefore, we selected 1% (dry mass, w:w) finely ground basalt as our basalt treatment.

7) Microbial inoculum. Microbial communities play an essential role in soil functions and inoculating microbes to soil is a common soil restoration strategy (Coban et al., 2022). Therefore, we inoculated microbes from a fungal rich grassland soil (Zwillenberg-Tietz Foundation land, 52°33′9.01" N 12°40′7.73" E) in the form of a microbial wash to our experiment soil. For the units that do not receive microbial inoculum treatment, we applied an equivalent volume of autoclaved inoculum to maintain equal necromass.

8) Reduced physical disturbance. Tillage can increase soil aeration, but it also breaks soil aggregates and reduces aggregate stability, thereby exposing the physically protected organic matter to mineralization (Six et al., 2002; Wei et al., 2006). In our experiment, we implemented physical disturbance to all treatments in exclusion of 'reduced physical disturbance' after three weeks to simulate tillage and non-tillage conditions.

We considered the eight management practices as a factor pool and set a gradient of factor numbers (2, 4, and 6 factor numbers), from which we randomly selected 20 replicates for each level. Control, single factors and 8 factors combination had 10 replicates each because of the assumed lower variability. To assure the same initial carbon level in all units, we calculated all carbon-containing amendments and total soil carbon and added 1–4 portions of wheat straw to all units, in which the carbon content in one portion of wheat straw was equal to the carbon content in a carbon-containing amendment, such as biochar or compost. Therefore, all units have the same initial total organic carbon. The control group was set without any amendments. In total, 160 experimental units were included in this experiment (Fig. 1).

2.2 Soil collection and incubation

The soil was collected in April 2022 from local grassland land at an experimental site of Freie Universität Berlin, Germany (52°28′ N, 13°18′ E). The soil has a sandy loamy texture, 2.29% total C, 0.18% total N, 1.79% soil organic carbon, and a water holding capacity of 37.5%. The freshly collected soil was air dried for two days then sieved (2 mm). Soil for microbial inoculum was freshly collected from a protected grassland area outside of Berlin, Zwillenberg-Tietz Foundation land (52°33′9.01″ N, 12°40′7.73″ E) at a depth of 5 cm–15 cm (previous work in our lab has shown that this grassland site has about 10 times more fungal biodiversity than the soil from the experimental site) (Yang et al., 2022). The collected soil was stored at 4 °C for two weeks before use.

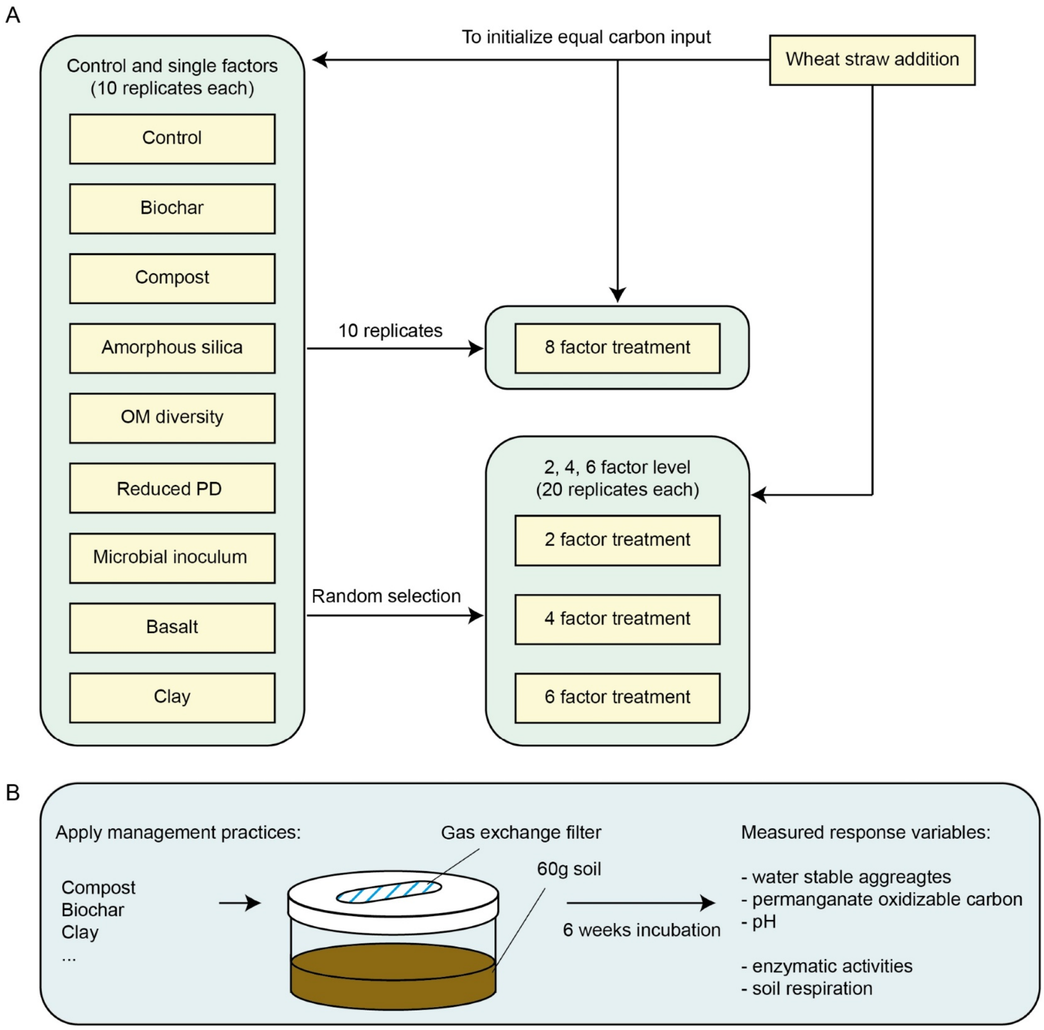


Fig. 1 Experimental design and workflow. Panel A: Experiment design. The factor pool includes a total of 8 factors. 20 replicates were selected randomly for 2, 4, and 6 factor treatments from all possible combinations within the pool. Wheat straws were supplemented to each treatment to standardize the same initial carbon content. Panel B: Workflow of the experiment.

In the experimental set up, 6 (biochar, compost, organic matter, clay, silica, basalt) of the 8 management practice treatments were added as solids. We added their respective dry mass to 60 g of the prepared, dry soil. The soil and the treatment product were mixed on a vertical shaker for 30 min at 200 rpm at room temperature to ensure homogenous distribution in the soil sample. Afterwards the soil mixture was transferred to the test system, for which we chose plastic containers (Product Nr: O95/40+OD95, SacO2, Belgium) with a filter in the lid (#40 green filter, SacO2, Belgium) for gas exchange. For the management practice “microbial inoculum”, we produced a microbial wash using 200 g fresh soil and 600 mL sterilized distilled water. The soil was thoroughly mixed in the water, let rest for 10 min and the supernatant was passed through a 0.125 mm sieve to produce the microbial inoculum suspension. Subsequently, we added 5 mL microbial inoculum suspension to the respective experimental units. For the experimental units that did not receive the “microbial inoculum” treatment, we sterilized (at 120 °C, three times, 20 min each time) the microbial inoculum solution and pipetted 5 mL of the sterilized suspension into the experimental units to keep the amount of organic material and nutrients added with this addition equal among all units. After treatment application, the containers were incubated in the dark at 25 °C for 42 days. Water was added weekly to keep soil moisture at 60% of water holding capacity. Further, we measured soil respiration on the 6th, 13th, 20th, 27th and 45th day to observe the decomposition of the added organic amendments or soil organic matter (we included the respiration results in the supplementary information Fig. S1). We implemented soil disturbance across all treatments after three weeks, with the exception of the ‘decreased physical disturbance’ treatment. To do this, we gently mixed the soil within each pot for 3 minutes using a sterile needle.

We harvested the experiment after 6 weeks. We first mixed the soil for 3 minutes, then collected 20 g fresh soil for respiration measurement and 5 g fresh soil for enzyme activity measurement in 50 mL mini bioreactors (Product Nr: 431720, Corning®, USA). All 50 mL mini bioreactors were stored at 4 °C, soil respiration was measured on the 45th day and enzyme activity was tested within one week after harvest. The remaining soil was air dried at room temperature (20 °C) for five days, and then used for measurement of water stable aggregate, permanganate-oxidizable carbon (POXC) and pH.

2.3 Response variables

We measured eight response variables to investigate the effects of our treatments on the tested soil: pH, water stable aggregates, four enzymatic activities (β-glucosidase, β-D-cellobiosidase, β-N-acetylglucosaminidase and phosphatase), POXC, and soil respiration.

For soil pH, we added 12.5 mL calcium chloride solution to 5.0 g dry soil, mixed homogeneously, centrifuged for 5 min and then placed a pH probe in the supernatant (pH meter: Hanna Instrument, Smithfield, USA). For soil aggregation we used a modified protocol from (Kemper and Rosenau, 1986). For this, we capillarily rewet 4.0 g dry soil in water, and then sieved for 3 mins using a sieving machine (Eijkelkamp, Netherlands), then oven dried the sieved soil at 60 °C overnight to obtain the dry fraction. Then we gently washed the dried soil through a 0.25 mm sieve and dried at 60 °C overnight to obtain the coarse matter fraction. We calculated the water stable aggregates (WSA) as %WSA = (water stable aggregates−coarse matter)/(4.0 g−coarse matter). For enzymatic activities, we measured four enzymatic activities: β-glucosidase, β-D-cellobiosidase, β-N-acetylglucosaminidase and phosphatase. B-glucosidase and β-D-cellobiosidase indicate cellulose degradation, β-N-acetylglucosaminidase indicates chitin degradation and phosphatase indicates phosphorus mineralization (Delgado-Baquerizo et al., 2017). The enzymatic activities were measured by absorbance using a microplate reader (BioRad, Benchmark Plus, Japan) at a wavelength of 410 nm. To measure POXC, we used the protocol from Weil et al. (2003). We added 2 mL 0.2 M $KMnO_4$ solution to 2.5 g dry soil and measured the absorbance through a microplate reader (BioRad, Benchmark Plus, Japan) at a wavelength of 550 nm. We measured soil respiration by collecting 1 mL gas to a gas analyzer (LI-6400XT, LI-COR Biosciences GmbH, Germany). We describe the details on the applied methods in the supplementary information (Notes S1).

2.4 Statistics

All statistical analyses were conducted in R 4.2.1 (R Core Team, 2022). We aimed to investigate the mechanism for joint effects in multiple factors combinations. Therefore, we first investigated the performance of control and single factor treatments. Significance tests between each single factor and blank control, factor numbers and blank control were conducted using anova and p values were adjusted by Tukey's post hoc method. We list all *p* values for each response variable in the supplementary information (Supplementary information Table S1 to Table S9).

Second, we analyzed the impact of the supplemented wheat straw portion on each response variable. Subsequently, we calculated a dissimilarity index with the 'vegan' package (Oksanen et al., 2013). To do this, we first calculated the pairwise dissimilarity based on Euclidean distance for the eight standardized response variables. Then we summed all pairwise distances in the multiple practice combination treatments at each factor level for each treatment. Subsequently we used the 'caret' package and normalized the distance with the preProcess function 'range' method, which generated a normalized dissimilarity index that has the range from 0 to 1 (Kuhn, 2008),

$$D_{\text{sum}} = \sum\nolimits_{i,j \in N} D_{i,j}$$

where D_{sum} is the average Euclidean distance for a certain treatment unit N, $D_{i,j}$ is the distance between practice i and practice j, i and j are the practices within the treatment unit N.

Finally, we applied a machine learning approach to disentangle the effects of factor numbers, factor dissimilarity and factor composition in their contribution to each response variable. To do this, we used random forest models. First, we tested the factor number as an explanatory variable, namely "factor number". Then, we added the normalized calculated dissimilarity index as a second explanatory variable. Finally, we included the factor composition that indicated the feature of factor combinations and was represented by a binary matrix indicating absence and presence of each factor. We illustrated the contribution of adding each explanatory variable with the value of explained variance, where an increase in explained variance implies an increased contribution of the added explanatory variable. We used 'ggplot2' for illustration (Wickham, 2016).

To further demonstrate the effect size for all response variables, we used standard deviation normalization/ Z-score normalization on all single factor treatments, 2, 4, 6 and 8 factor treatments and compared the normalized mean effect sizes in each response variable. We used 'pheatmap' for illustration (Kolde, 2019).

3 Results

3.1 Enzyme activity

All treatments positively affected enzyme activity of the β-N-acetylglucosaminidase and phosphatase after six weeks incubation, while the carbon related enzymes were reduced under most treatments (Fig. 2). Organic matter diversity solely had positive effect size for both β-glucosidase and β-D-cellobiosidase. At multiple factor combination levels, factor dissimilarity significantly influences all four enzymatic activities ($p < 0.01$), but the wheat straw addition did not contribute to the explanation of any enzymatic activity. In the three random forest models, the factor numbers, which we used as a baseline, did not contribute any explained variability in all four enzymatic activities. When we added dissimilarity index as a predictor in addition to factor number, the explained variance by the model was strongly increased for β-N-acetylglucosaminidase, β-glucosidase, β-D-cellobiosidase and phosphatase enzyme activities by 45.21%, 15.63%, 24.62% and 11.74%, respectively (Fig. 2d, 2h, 2l and 2p). Subsequently, we included the factorial composition binary matrix (absence/presence matrix), but only found a limited increase in the explained variability. The explained variability for β-N-acetylglucosaminidase and phosphatase increased by 10.24% and 9.99% respectively, while for β-glucosidase and β-D-cellobiosidase it increased by 22.73% and 21.44%, respectively.

3.2 Soil respiration

Soil respiration was positively affected by all treatments (Fig. 3e). For multiple factor combinations, factor dissimilarity strongly promotes soil respiration while the straw addition does not contribute to the explanation of the soil respiration result (Fig. 3f and 3g). The factor numbers only contribute 8.62% of explained variance, while by including the dissimilarity index the explanatory rate increased to 54.90% (95%-CI: 24.85% to 75.34%) (Fig. 3h). The incorporation of factor composition resulted in an enhancement of the explanatory rate, leading to an increase of 15.74%.

3.3 Water stable aggregates

The percentage of water stable aggregates showed great improvements after applying the management practices

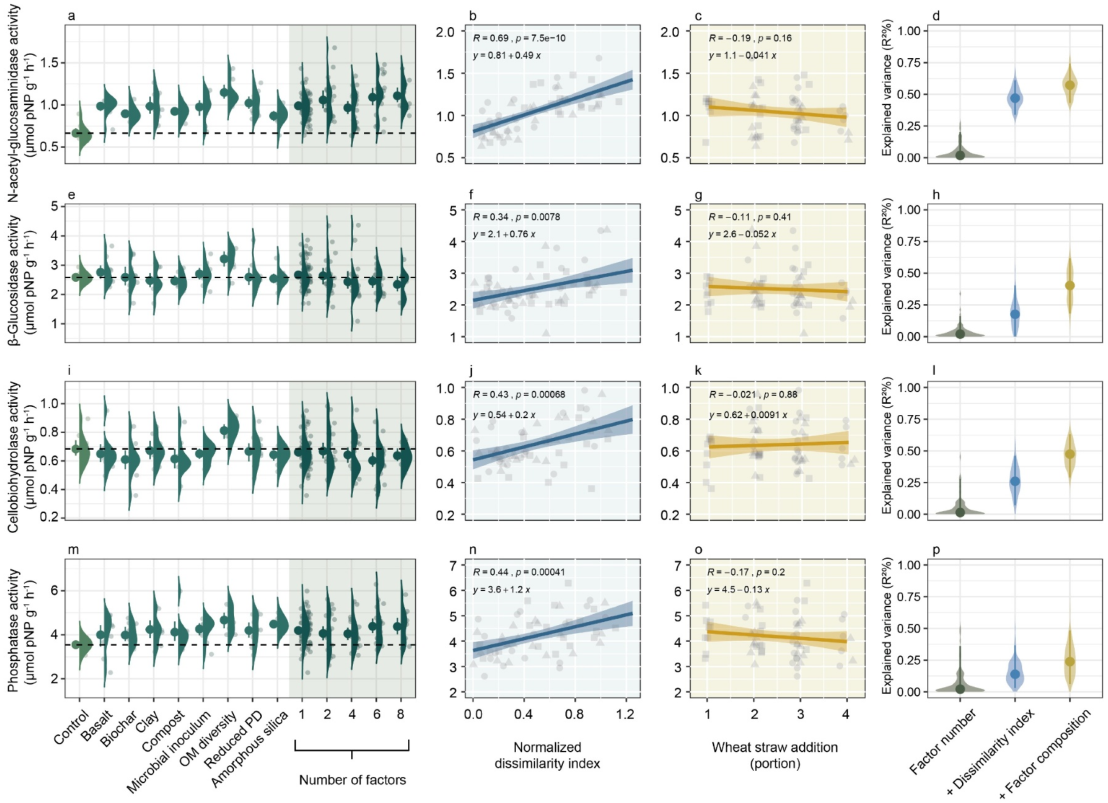


Fig. 2 Effects of 8 different management practices on enzymatic activity of β-glucosidase, β-D-cellobiosidase, β-N-acetylglucosaminidase and phosphatase. [a, e, i and m] effect of management practices tested singly or in combination (2, 4, 6 or 8 factors combined) on the activity of four enzymes. Data are presented as mean and 95% confidence interval and gray raw data cloud in the background with aligned data distribution curve. The dashed line represents the mean of the control group. [b, f, j and n] effect of dissimilarity index of factor combination levels 2, 4 and 6 factor on the four enzymes. [c, g, k and o] impact of the straw addition in each treatment at 2, 4 and 6 factor numbers. For both regression plots, regression line formulas, Spearman correlation coefficient *R* and *p*-values are presented. Raw data are shown in gray in the background. [d, h, l and p] violin plots of explained variability of random forest models with added explanatory variables (factor numbers, factor numbers and dissimilarity index, factor numbers and dissimilarity index and factor composition).

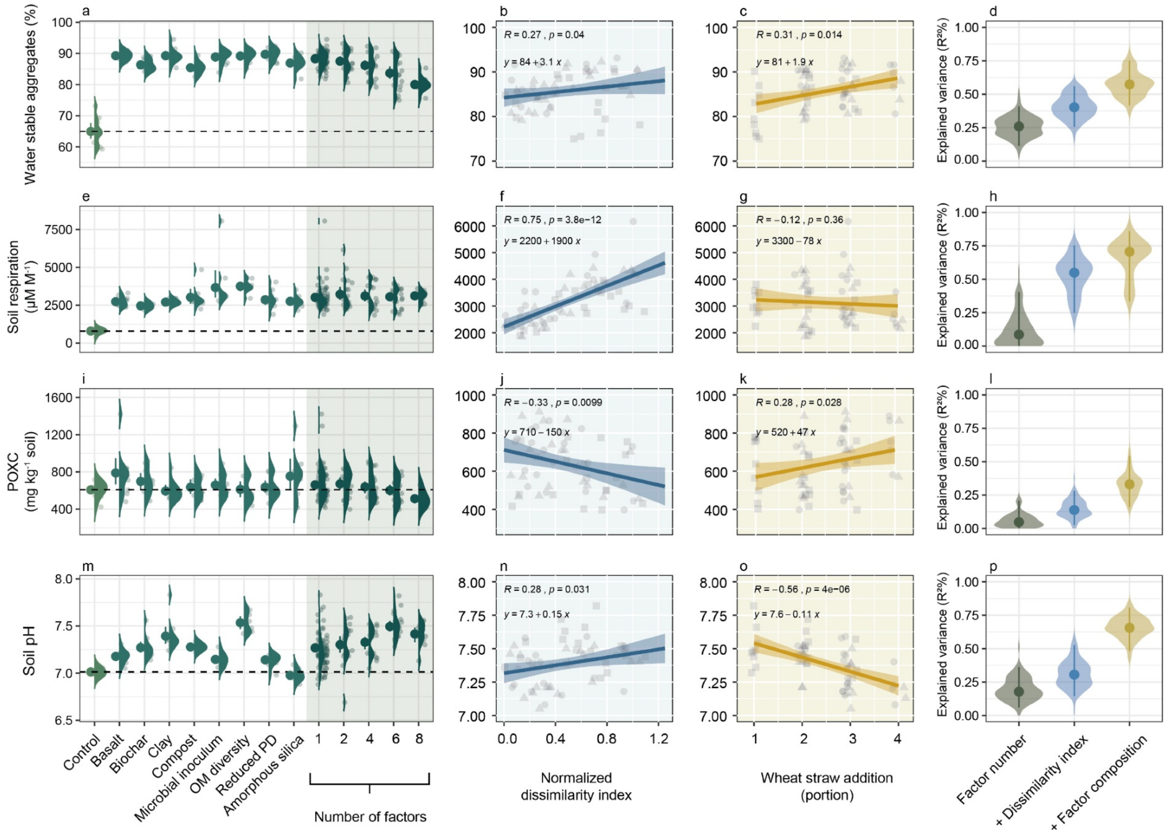


Fig. 3 Effects of 8 different management practices on water stable aggregates, soil respiration, permanganate oxidizable carbon (POXC) and soil pH. [a, e, i and m] effect of management practices tested singly or in combination (2, 4, 6 or 8 factors combined) on water stable aggregates, soil respiration, permanganate oxidizable carbon (POXC) and soil pH. Data are presented as mean and 95% confidence interval and gray raw data cloud in the background with aligned data distribution curve. The dashed line represents the mean of the control group. [b, f, j and n] effect of dissimilarity index of factor combination levels 2, 4 and 6 factor on water stable aggregates, soil respiration, permanganate oxidizable carbon (POXC) and soil pH. [c, g, k and o] impact of the straw addition in each treatment at 2, 4 and 6 factor numbers. For both regression plots, regression line formulas, Spearman correlation coefficient *R* and *p*-values are presented. Raw data are shown in gray in the background. [d, h, l and p] violin plots of explained variability of random forest models with added explanatory variables (factor numbers, factor numbers and dissimilarity index, factor numbers and dissimilarity index and factor composition).

(Fig. 3a). However, the stability of aggregates declined significantly with an increase in factor number ($p< 0.01$). The straw amendments strongly enhanced aggregate stability, and there was a positive correlation with the amount of straw (Fig. 3c). On the other hand, the dissimilarity between management practices can significantly promote aggregate stability (Fig. 3b). In the context of explained variance, the sole consideration of factor number achieves an explanatory rate of 25.97% (95%-CI: 11.36% to 40.89%), whereas including factor dissimilarity and subsequently, factor composition, results in explained variance of 40.27% (95%-CI: 25.54% to 56.01%) and 57.38% (95%-CI: 41.56% to 75.08%), respectively (Fig. 3 d).

3.4 Permanganate-oxidizable carbon (POXC)

Figure 3i illustrated the permanganate-oxidizable carbon measurement. With the exception of clay application, all single factors show positive effects in comparison to control. However, an increase in factor number strongly reduced the POXC ($p < 0.01$), meaning that the active fraction of carbon was reduced. We found a negative effect at the 8 factor number. Dissimilarity demonstrated a negative correlation with POXC for multiple factor treatments, while straw supplementation showed a positive correlation with POXC (p=0.01 and 0.028, respectively) (Fig. 3j and 3k). The highest explained variability, at 33.12% (95%-CI: 15.97% to 54.44%), was obtained by including all three parameters: factor number, dissimilarity and factor composition. The factor number alone explained a mere 4.82% (95%-CI: 0.14% to 20.96%) and with the incorporation of factor dissimilarity it increased to 13.82% (95%-CI: 2.66% to 28.09%) (Fig. 3l).

3.5 Soil pH

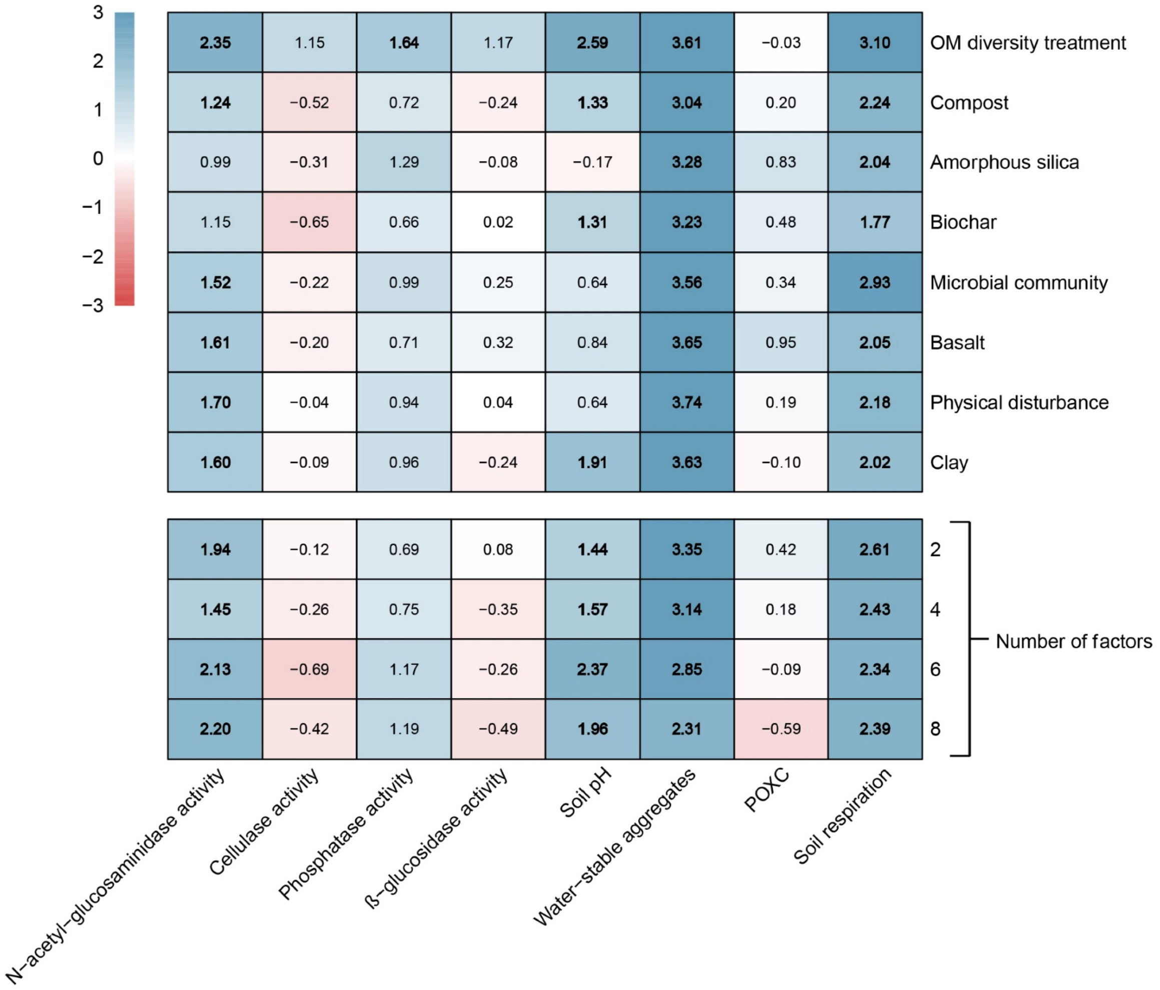
With the exception of silica, all treatments had positive effects on soil pH (Fig. 3m). Both dissimilarity and straw addition showed significant correlation with pH values, the dissimilarity promoted the pH increasing while the straw addition did not lead to pH increase(Fig. 3n and 3o). Among the three random forest models, factor number contributed 17.78% explained variability, with the incorporation of factor dissimilarity and factor composition resulting in increments of the explanatory variability to 30.52% (95%-CI: 14.63% to 52.55%) and 65.57% (95%-CI: 48.17% to 80.68%) respectively (Fig. 3p).

3.6 Effect size for all tested response variables

We calculated the effect size for all tested response variables for both single management practice factors and the 2, 4, 6 and 8 factor combinations. We found significant positive effects for all treatments in water stable aggregates and soil respiration (Fig. 4). From the perspective of soil functions, N-cycling enzyme activity, P-cycling enzyme activity and soil respiration had positive effect sizes across all treatments. The elevated soil pH may have influenced microbial activities.

4 Discussion

Here we tested for an effect of the combination of management practices, reaching up to eight jointly applied practices, thus moving clearly beyond what has previously been considered in experiments of this kind. Our experiment revealed a substantial soil modification effect that was driven by the dissimilarity between management practices. The factor number alone contributed only to a limited extent to explained variance, whereas the addition of factor dissimilarity greatly increased explained variance for all response variables. We could explain greater amounts of variability still with the addition of factor composition, which may indicate contributions from factor identity effects. Our straw addition (as a control for overall amount of carbon added) only influenced soil structure and resulted in only a minor influence on soil functions.



	N−acetyl−glucosaminidase activity	Cellulase activity	Phosphatase activity	ß−glucosidase activity	Soil pH	Water−stable aggregates	POXC	Soil respiration
OM diversity treatment	**2.35**	1.15	**1.64**	1.17	**2.59**	**3.61**	−0.03	**3.10**
Compost	**1.24**	−0.52	0.72	−0.24	**1.33**	**3.04**	0.20	**2.24**
Amorphous silica	0.99	−0.31	1.29	−0.08	−0.17	**3.28**	0.83	**2.04**
Biochar	1.15	−0.65	0.66	0.02	**1.31**	**3.23**	0.48	**1.77**
Microbial community	**1.52**	−0.22	0.99	0.25	0.64	**3.56**	0.34	**2.93**
Basalt	**1.61**	−0.20	0.71	0.32	0.84	**3.65**	0.95	**2.05**
Physical disturbance	**1.70**	−0.04	0.94	0.04	0.64	**3.74**	0.19	**2.18**
Clay	**1.60**	−0.09	0.96	−0.24	**1.91**	**3.63**	−0.10	**2.02**
2	**1.94**	−0.12	0.69	0.08	**1.44**	**3.35**	0.42	**2.61**
4	**1.45**	−0.26	0.75	−0.35	**1.57**	**3.14**	0.18	**2.43**
6	**2.13**	−0.69	1.17	−0.26	**2.37**	**2.85**	−0.09	**2.34**
8	**2.20**	−0.42	1.19	−0.49	**1.96**	**2.31**	−0.59	**2.39**

Fig. 4 Normalized effect size of single practices and combinations of multiple practices for the response variables. Numbers indicate the normalized effect size between single practice and blank control in the corresponding measurement. Significance ($p < 0.05$) is indicated in bold numbers.

4.1 Driving forces for effect size

Here we tested three driving forces–factor dimensionality (factor number), factor dissimilarity and factor identity (factor composition)–in all response variables. We found that, in the context of land management practices, increasing factor number did not bring additional benefit for the soil properties and functions. This may imply that the two factor combinations, which is the most common studied factor number, may be the optimal applied management practice, at least in this soil. Even though this differs from our initial hypothesis, it presents us an opportunity to address multiple management practice combinations.

In our second hypothesis, we proposed that the factor diversity (dissimilarity) can promote soil functions and properties, such as soil water stable aggregates and pH, soil enzymatic activities (Rillig et al., 2024). Our experiment shows that the dissimilarity between individual factors for joint applications greatly increased explained variance for all response variables. We found significant positive correlations between factor dissimilarity and soil respiration, soil enzymatic activities, soil pH, and soil aggregate stability, together with a significant negative correlation between factor dissimilarity and POXC. Greater dissimilarity among factors may have introduced a broad range of substrates that support diverse microbial communities, thereby increasing soil respiration and soil enzymatic activities. This dissimilarity also drives the soil pH towards neutrality by balancing acidic and basic components introduced by diverse factors. On the other hand, the combined microbial activity and diverse organic input can help to stabilize soil aggregates. Finally, the decrease in POXC with the increased factor dissimilarity may indicate that more labile carbon was rapidly utilized by soil microbes due to increased enzymatic activity, which was consistent with the greater soil respiration we observed. Even though multiple management practices did not offer great advantages over any single practice, in consideration of the factor dissimilarity effect, we discuss two main advantages of implementing integration of management practices over single management practices.

First, applying joint management practices at 2-factor level can mitigate the risk of relying on a certain single practice. By applying diverse practices, land managers have a border range of choices. Secondly, the synergistic effect of joint application leads to an overall soil properties and functions improvement. Taking an example of our tested single factor, microbial inoculation can significantly increase soil respiration and enzymatic activities, which can enhance soil properties by accelerating nutrient cycling, promoting organic matter decomposition, and stabilizing soil aggregates, although it had no significant effect on soil pH. However, when combined with other management practices, significant improvements in soil pH at 2, 4, 6 and 8 factor numbers were observed. Therefore, combining management practices facilitates improvements in both soil functions and soil properties.

Last but not least, from an economic perspective, our results offered an alternative to costly single factors: such costly factors may be replaced by applying a broader range of available management practices. However, the implementation cost covers many different aspects, such as labor, energy and product expenses, and this falls beyond our research scope here (Bartkowski et al., 2020).

4.2 Soil structure

Wheat straw amendments lead to more microbial activity, such as filamentous fungal growth supporting the formation and stabilization of soil aggregates (Malhi et al., 2011; Shahbaz et al., 2017; Sun et al., 2017). Our study confirmed that wheat straw significantly contributes to an enhanced aggregate stability. However, because our soil was already quite stable, we did not detect further improvements in aggregate stability.

In the context of explained variability, the factor number alone contributes to 25.97% explained variability. By including factor dissimilarity, the explained variability increased by 14.30%, which is pronounced increment but less in comparison with the factor number contribution. However, the factor number is negatively correlated with aggregate stability while the straw portion and factor dissimilarity are positively correlated. The increase of factor number also means a decrease in straw supplementation, as more carbon amendments may be selected at a high factor number. Therefore, the 25.97% explained variability from factor number may be a consequence of the straw supplementation. Furthermore, the factorial composition contributed to an increase of 17.10% explained variability. This demonstrated that the increase in aggregate stability is driven by all three explanatory variables.

From the context of the pH response, we observed similar results. The straw portion indicated significant correlation with pH response, which might have indicated the factor level contribution to a certain degree. Dissimilarity between factors can increase soil pH ($p<0.05$) and contribute to an explained variability of 12.74%. What differs from aggregate stability is that factorial composition may play a more dominant role in the explanatory variables of pH response as it contributes 35.05%.

In summary, our results indicated that both straw supplementation ($p=0.014$), dissimilarity ($p=0.04$) and factorial composition promote aggregate stability enhancement. The dissimilarity can increase soil pH while straw supplementation can reduce soil pH, whereas the overall pH response might be dominant by the factor composition.

4.3 Soil functions

The N-acetylglucosaminidase enzyme indicates the degradation process of chitin, which demonstrates both carbon and nitrogen utilization (Jackson et al., 2013). Under high soil C content diverse carbon sources may cause N limitation and consequently increase the enzyme activity for nitrogen mineralization (Bowles et al., 2014). This may explain the positive correlation between N-cycling enzyme activity and factor number under the multiple management practices. On the other hand, a negative correlation was noticed between P availability and P related enzyme activity in previous studies (Bowles et al., 2014). Therefore, the positive effect size of N-cycling enzyme activity and P related enzyme activity might be explained with the limitation of N and P under diverse carbon sources and diverse management practices. With the above mentioned assumption of the limitation of N and P, the carbon mineralization process could be inhibited under most treatments. As a consequence, the carbon related enzymes were restrained, which provided solid evidence for the negative effect size of the β-glucosidase and β-D-cellobiosidase enzyme activity.

As we hypothesized, dimensionality plays an important role in soil functional modification. With more management practices involved, keeping the same carbon level, the N- and P-cycling microbes can be activated and, as a consequence, the soil nitrogen and phosphorus mineralization might be improved. The dissimilarity had significantly positive correlation with all enzymatic activity responses and soil respiration, while the straw addition was not correlated to the soil function responses.

Our POXC results demonstrated that both straw addition and factor dissimilarity play an important role in carbon storage under multiple management practices application. POXC has been used as an indicator of the labile carbon and is considered as a sensitive indicator for management responses (Culman et al., 2012; Bongiorno et al., 2019).

5 Conclusion

We conclude that more diverse management practices, in terms of divergence in their individual effects, can elicit beneficial effects on soil properties and functions. The pairwise dissimilarity that is derived from single factor treatments shows significant correlations with all response variables across multiple factor numbers. Additionally, it greatly improves explained variability when included as an added predictor in random forest models. However, treatments with a higher number of combined factors did not yield additional improvements beyond those of single factors. Our findings suggest that land managers and farmers can improve soil health by selecting management practices through diverse functional effects, rather than simply increasing the number of management practices. For instance, combinations of practices with diverse impacts on soil properties–such as pairing microbial inoculation with organic amendments–can achieve more balanced improvements in soil pH, aggregates stability and microbial activities. Our results highlight the value of considering functional dissimilarity between management practices while developing soil management strategies, as the dissimilarity may optimize soil function improvements with fewer inputs. On the other hand, we suggest that more research is needed on such effects that also includes soils that face severe challenges, such as compaction, pollution and erosion. Especially in highly degraded soils, exploring the effects of joint application of several management practices may yet uncover benefits of applying a greater number of factors.

Our study must be seen as a proof-of-concept, and as such we have not considered logistics and economic considerations; nevertheless, given the increasing pressures on soils worldwide, such high-level treatment combinations may represent the most effective strategy to improve soil health, restore soils and maintain ecosystem functionality (Rillig et al., 2023, 2024).

Author contributions

H.L.: design of the study, experiment setup, analysis of data, and writing. B.T., A.L., and R.R.: review and editing. Y.Z.: experiment setup. M.C.R.: conceptualization, review and editing.

Acknowledgements

H.L. and Y.Z. acknowledge the China Scholarship Council for a scholarship (CSC number 202108080156 and 202106320023). Open Access funding enabled and organized by Projekt DEAL.

Data availability statement

Data is available via 10.6084/m9.figshare.26142862

Conflicts of interest

We declare that there is no conflict of interest.

Electronic supplementary material

Supplementary material is available in the online version of this article at https://doi.org/10.1007/s42832-024-0278-7 and is accessible for authorized users.

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