communications
earth & environment

ARTICLE

https://doi.org/10.1038/s43247-023-01047-2 OPEN

Climate change and cropland management compromise soil integrity and multifunctionality

Marie Sünnemann[1,2✉], Remy Beugnon[1,3,4], Claudia Breitkreuz[5,6], François Buscot[5,1], Simone Cesarz[1,2], Arwyn Jones[7], Anika Lehmann[8,9], Alfred Lochner[1,2], Alberto Orgiazzi[7], Thomas Reitz[1,5], Matthias C. Rillig[8,9], Martin Schädler[1,10], Linnea C. Smith[1,11], Anja Zeuner[1,2], Carlos A. Guerra[1,2,11,12] & Nico Eisenhauer[1,2,12]

Soils provide essential ecosystem functions that are threatened by climate change and intensified land use. We explore how climate and land use impact multiple soil function simultaneously, employing two datasets: (1) observational – 456 samples from the European Land Use/Land Cover Area Frame Survey; and (2) experimental – 80 samples from Germany's Global Change Experimental Facility. We aim to investigate whether manipulative field experiment results align with observable climate, land use, and soil multifunctionality trends across Europe, measuring seven ecosystem functions to calculate soil multifunctionality. The observational data showed Europe-wide declines in soil multifunctionality under rising temperatures and dry conditions, worsened by cropland management. Our experimental data confirmed these relationships, suggesting that changes in climate will reduce soil multifunctionality across croplands and grasslands. Land use changes from grasslands to croplands threaten the integrity of soil systems, and enhancing soil multifunctionality in arable systems is key to maintain multifunctionality in a changing climate.

---

[1] German Centre for Integrative Biodiversity Research (iDiv) Halle-Jena-Leipzig, Puschstraße 4, 04103 Leipzig, Germany. [2] Institute of Biology, Leipzig University, Puschstraße 4, 04103 Leipzig, Germany. [3] Leipzig Institute for Meteorology, Leipzig University, Stephanstraße 3, 04103 Leipzig, Germany. [4] Centre d'Ecologie Fonctionnelle et Evolutive (CEFE), UMR 5175, 1919 route de Mende, 34293, Montpellier Cedex 5, France. [5] Department of Soil Ecology, Helmholtz-Centre for Environmental Research – UFZ, Theodor-Lieser-Straße 4, 06120 Halle, Germany. [6] Julius Kühn Institute (JKI) – Federal Research Centre for Cultivated Plants, Institute for Resistance Research and Stress Tolerence, Erwin-Baur-Straße 27, 06484 Quedlinburg, Germany. [7] European Commission, Joint Research Centre, Via Enrico Fermi, 2749 Ispra, Italy. [8] Institute of Biology, Free University of Berlin, Königin-Luise-Straße 1-3, 14195 Berlin, Germany. [9] Berlin- Brandenburg Institute of Advanced Biodiversity Research, Altensteinstraße 34, 14195 Berlin, Germany. [10] Department of Community Ecology, Helmholtz-Centre for Environmental Research – UFZ, Theodor-Lieser-Straße 4, 06120 Halle, Germany. [11] Institute of Biology, Martin Luther University Halle Wittenberg, Weinbergweg 10, 06120 Halle (Saale), Germany. [12] These authors jointly supervised this work: Carlos A. Guerra, Nico Eisenhauer. ✉email: marie.suennemann@idiv.de

Climate change and intensive land use are affecting the functioning of soil ecosystems worldwide[1]. Global temperatures are projected to rise by up to 2 °C by the end of the century, while changes in rainfall patterns will lead to more frequent and severe drought events[2]. Concurrently, the growing demand for raw materials and food is leading to increased intensification of agricultural practices on the finite global land area, which has already drastically altered ecosystems[3]. Such attempts to maximize yields by intensification of land use include monocultures and higher inputs of fertilizers and pesticides[4]. In recent years, knowledge of the substantial effects of climate and land use changes on terrestrial ecosystems has expanded considerably[5]. Yet, information on whether their joint effects will be mitigating, additive, or mutually reinforcing is still lacking[6].

Soils, in particular soil microbes, provide a range of essential ecosystem functions for human well-being that are challenged by climatic and land use changes[7]. Microbes, such as bacteria and fungi, degrade complex organic matter into simpler forms[8]. Enzymes secreted by microorganisms catalyze the breakdown of organic compounds, such as cellulose and lignin, supporting nutrient release and the cycling of elements like carbon, nitrogen, and phosphorus in the ecosystem[9]. Other functions, such as soil stability result from interactions of soil properties and biotic activity; for example, mycorrhizal fungi play an essential part in stabilizing soil aggregates and protecting against erosion[10]. However, soil functioning is also shaped by essential physical features, such as soil structure and water retention capacity[11]. By measuring soil functions, such as microbial respiration, microbial biomass, enzymatic activity, or soil aggregate stability, we can assess the capacity of soils to support these ecosystem processes[12]. The ability of soils to perform multiple functions simultaneously is known as soil multifunctionality[13], but to date there is no agreement on a unified measure for assessing soil multifunctionality[14]. Here, we chose a subset of seven ecosystem functions that are crucial for decomposition and nutrient cycling, and are therefore tightly linked to ecosystem services, such as primary productivity and soil fertility[15]. Ecosystem functions are highly sensitive to the interaction of warming and soil moisture[16], suggesting that climatic changes will be an important factor limiting soil functions under future conditions. Understanding the drivers of soil functions, especially when considered collectively, enables more comprehensive predictions of how soil ecosystems will respond to a rapidly changing world[17].

Today's world is already subject to increased mean temperatures and longer dry periods, which are expected to increase in the future[2]. Drought is expected to reduce microbial abundance and diffusion rate, resulting in a decline in enzyme activity[18]. However, the overall impact of drought can be augmented or mitigated by additional mechanisms, such as enzyme stabilization within the soil matrix, shifts in microbial community composition, and the potential acclimation and adaptation of microbial populations[19, 20]. As a result, the response of enzyme activity to drought exhibits variability across different soil types, levels of drought intensity, and durations[21]. Warming initially increases enzymatic processes, but can also inactivate enzymes and reduce substrate affinity over time and led to an overall decrease of microbial efficiency in decomposing soil organic matter[16,17,22]. In the natural environments, elevated temperatures can give rise to indirect detrimental impacts by amplifying evapotranspiration rates, causing declines in soil moisture and thus microbial functions[23,24].

At the same time, conventional land-use practices are known to reduce soil biodiversity and functions by decreases in soil organic matter, habitat destructing, soil disturbance, and chemical inputs[25,26]. For example, croplands are often dominated by bacteria[27] due to the detrimental effects of field management on soil fungal communities, as frequent tillage activities damage their hyphal networks[27]. At the same time, croplands often experience elevated pesticide use, which harms soil fauna diversity, abundance, and beneficial plant symbionts[26,28], consequently restricting soil ecosystem functioning. This susceptibility could potentially amplify the effects of changing climate conditions, as these systems might be less resilient against climate extremes[29]. This suggests that changes in land use, such as the conversion of grassland to cropland throughout Europe, will alter the provision of key soil functions[30].

Here, we address this gap by examining the relationship between multiple ecosystem functions, climate, and land use. As there have been few attempts to bridge existing gaps between observational and experimental studies, to explore large-scale ecological patterns, and identify causal relationships in targeted experiments[31], we used two complementary approaches (Fig. 1): (1) an observational study of 456 locations across European croplands and grasslands; and (2) a large-scale field experiment in Germany that combines simulated climate change and varying cropland and grassland management intensities. We distinguished between two broad types of cultivation to examine differences in land use: areas where crops are grown and grasslands. Croplands are areas cultivated with crops, such as maize, wheat, olives and fruit trees (please see Supplementary Table 49 for a detailed overview). Grasslands, on the other hand, are managed grasslands with and without shrub cover[32]. Soil samples for the European Land Use/Cover Area frame Survey (LUCAS) were collected in 2018. In 2019, we sampled the Global Change Experimental Facility (GCEF), a large-scale field experiment studying the combined effects of climate change and land use on ecosystem functions[25], to test whether patterns observed in the European survey were supported experimentally. The GCEF includes a future climate scenario (ambient climate vs. +0.6 °C temperature increase; 20% less rainfall in summer, 10% rainfall increase in spring and fall), two cropland treatments and two grassland treatments of different management intensities (conventional and organic croplands; intensive and extensive grasslands). For consistency with the LUCAS data, whose cropland and grassland categories incorporate several management intensities, we also combined these two intensity levels at the GCEF within the broader categorizations of grass- and croplands. We used the soil samples from LUCAS and the GCEF to measure microbial respiration and biomass, the activity of four key soil enzymes involved in decomposition processes (xylosidase, N-acetylglucosaminidase, phosphatase, cellulase), and water-stable aggregates to calculate soil multifunctionality with the averaging approach[26]. We hypothesized that (1) drier conditions would reduce soil multifunctionality and that (2) higher temperature would show a direct positive effect on soil multifunctionality and an indirect negative effect through a decrease of soil moisture. We further expected that (3) cropland management as compared to grassland, would also reduce soil multifunctionality. Moreover, we hypothesized that (4) cropland practices would exacerbate the negative effects of climate change. Previous studies have demonstrated that bacterial communities are more susceptible to drought[33,34] than fungal communities[29].

Results

We calculated soil multifunctionality based on the same seven soil functions we measured in both the observational and the experimental study, using the same analytical methods to ensure standardization and comparability. All soil functions were significantly positively related to each other (Fig. 1a, b), with the exception of water-stable aggregates; this parameter was not significantly correlated with any of the other functions in the

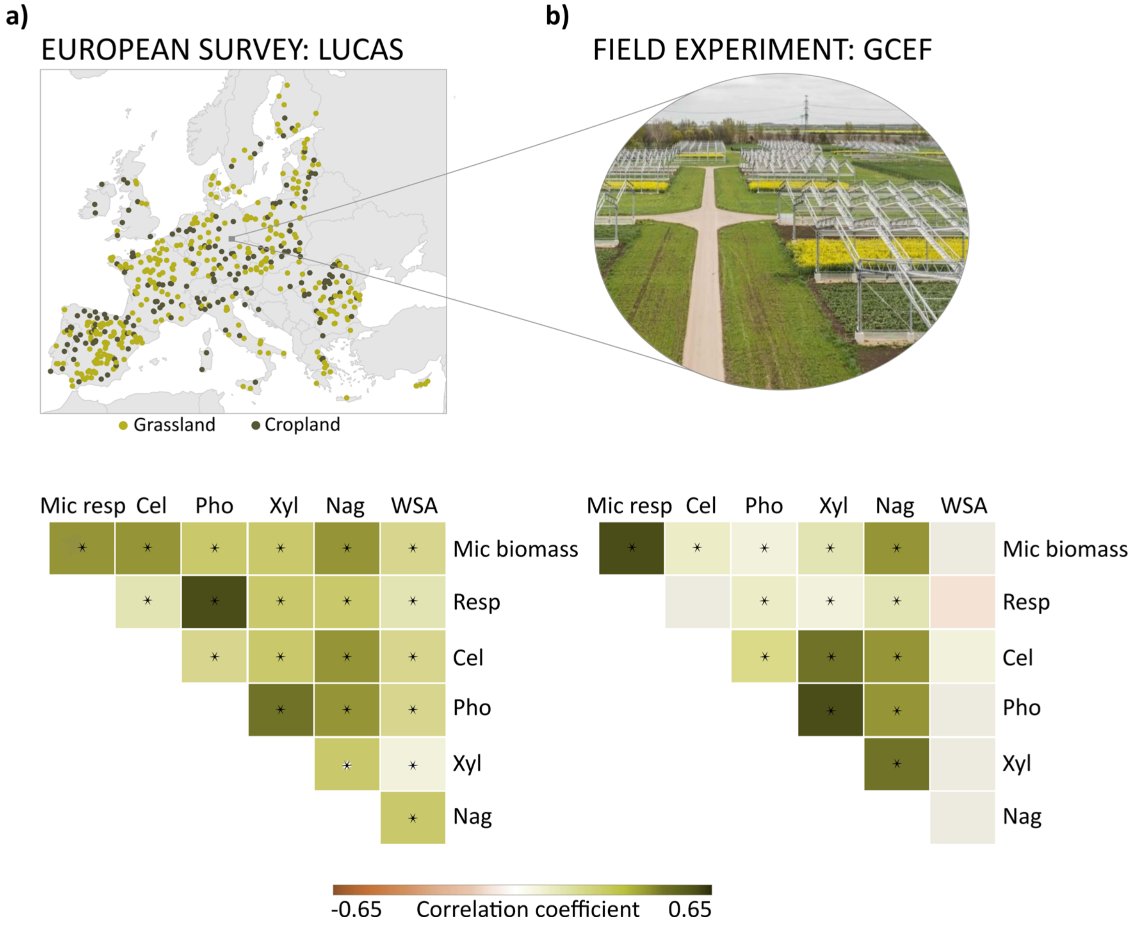

Fig. 1 Location of sites and correlation of soil functions. Pairwise relationships (Pearson correlation coefficients) between soil functions in grasslands and croplands in **a** the European survey (LUCAS) and **b** the field experiment (GCEF). Stars reflect significant relationships. The seven variables are labeled as follows: Mic Resp soil microbial respiration, Cel Cellulase, Pho acid phosphatase, Xyl Xylosidase, Nag N-acetylglucosaminidase, WSA water-stable aggregates, Mic biomass soil microbial biomass. Photo credit for picture of GCEF: Andre Künzelmann/UFZ.

GCEF (Fig. 1b). We then used these seven variables to calculate a multifunctionality index using the averaging approach of Byrnes et al.[35], based on the mean of all standardized functions as a measure of soil multifunctionality. Afterwards, we used structural equation modeling (SEM) to determine the direct effects of precipitation, temperature, and land use, as well as indirect effects via differences in soil water, carbon content, and pH on soil multifunctionality. For the observational dataset, we also included soil texture (composed of silt, sand, and clay content), latitude and elevation as potential drivers.

Our SEMs revealed that soil multifunctionality is driven by climate and land use, in both the observational and the experimental study (Fig. 2). At the European level, we discovered that climate is directly and significantly related to soil multifunctionality (Fig. 2a), with higher mean annual temperature reducing multifunctionality, while higher mean annual precipitation increases it (Figs. 2a, c and 3a). At the same time, we found that climate also influences soil multifunctionality through indirect pathways, for example, by changing soil water and organic carbon content (Fig. 2a). Higher temperatures (both annually and prior to sampling) reduce soil water content, whereas soil water content is positively associated with multifunctionality. A higher mean precipitation (annually) increases soil water content and thereby also soil multifunctionality. Similarly, precipitation and temperature are positively associated with higher amounts of soil organic carbon (Fig. 2a). We also found that land use is a significant driver of soil multifunctionality. Cropland management directly reduces soil multifunctionality and also reduces soil water and organic carbon content, thus also indirectly decreasing multifunctionality. Cropland cover also lowers pH, but pH was not associated with multifunctionality in the observational study. We did not detect any interactive effects of climate and land use. Considering both direct and indirect effects by summing them, we identified land use, precipitation, and temperature as the most relevant factors affecting multifunctionality of European soils.

We also used SEM to explore the causal effects of a future climate treatment and land use on soil multifunctionality in the field experiment. Here, the future climate treatment significantly decreases soil multifunctionality (Figs. 2b and 3b). We also found, however, that the future climate increases soil organic carbon, thereby exerting an indirect positive effect on soil multifunctionality and partly mitigating the negative effect of future climate (Fig. 3b). At the same time, cropland management significantly reduced soil multifunctionality and soil organic carbon (Figs. 2b and 3b). Similar to the observational study, we did not find any interaction effects between the future climate treatment and land use.

Discussion

In this study, we used an unprecedented combination of observational and experimental approaches to investigate how climate and land use affect soil multifunctionality. We found that soil multifunctionality is strongly influenced by climate; higher

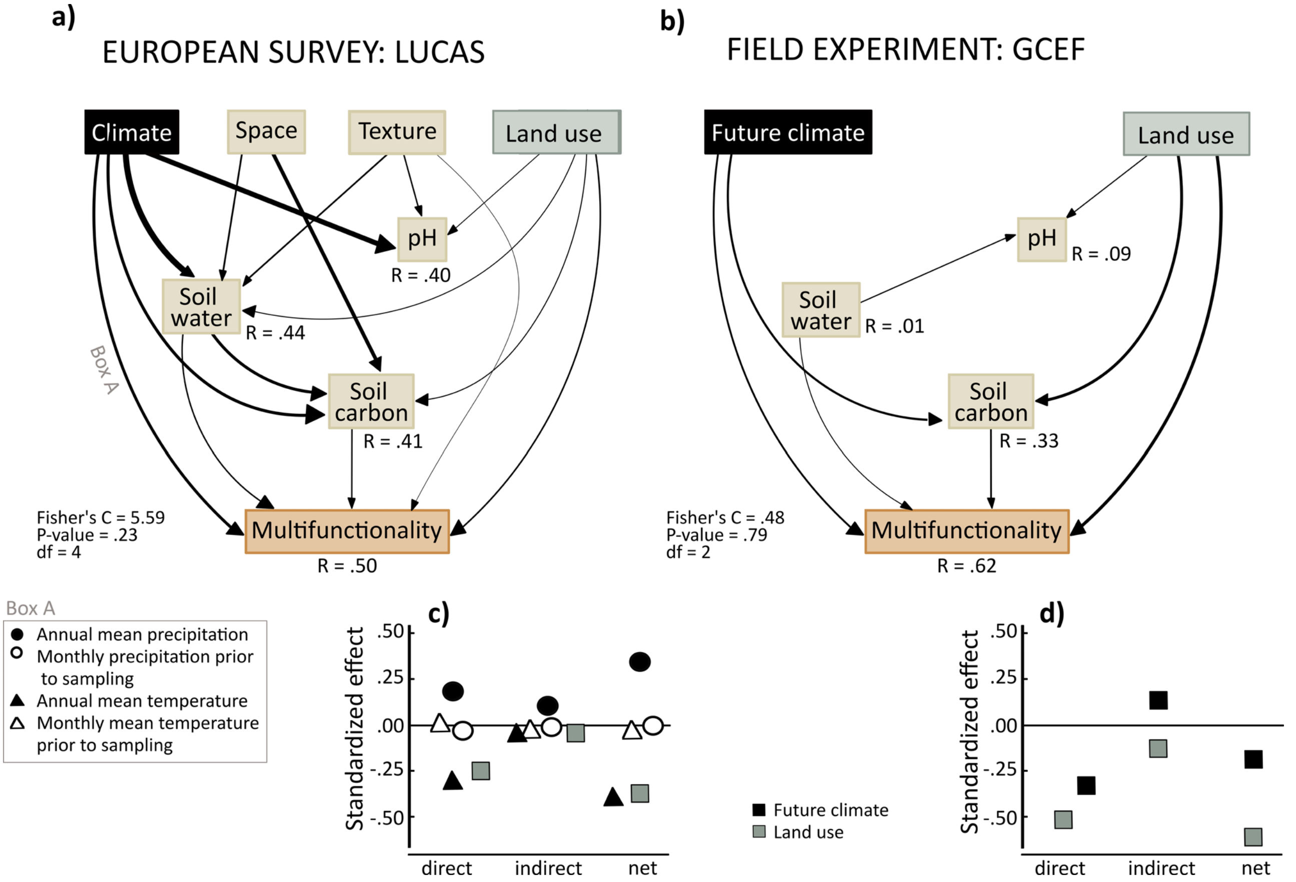

Fig. 2 Structural Equation Models showing the results from two complementary studies on the effects of climate (change) and land use (cropland versus grassland) on soil multifunctionality. **a** SEM using data from 456 sampling sites across Europe and **b** samples collected at the field experiment GCEF ($n = 40$ experimental plots). The thickness of the arrows corresponds to the strength of the association based on standardized path coefficients (sum of the absolute standardized effect sizes); only significant relationships ($P < 0.05$) are shown. The climate variable (**a**) is a composite variable including temperature and precipitation measurements, each with a monthly and annual value, shown in Box A. Space constitutes elevation and latitude, soil texture is composed of clay, sand, and silt. In both the observational and experimental studies, there was no interactive effect of climate and land use. Direct, indirect and net effect from **c** climate variables (Box A) and land use on multifunctionality in LUCAS and **d** standardized direct, indirect and net effect of the future climate treatment and land use on soil multifunctionality in the GCEF. Fishers C is a measure of SEM fit.

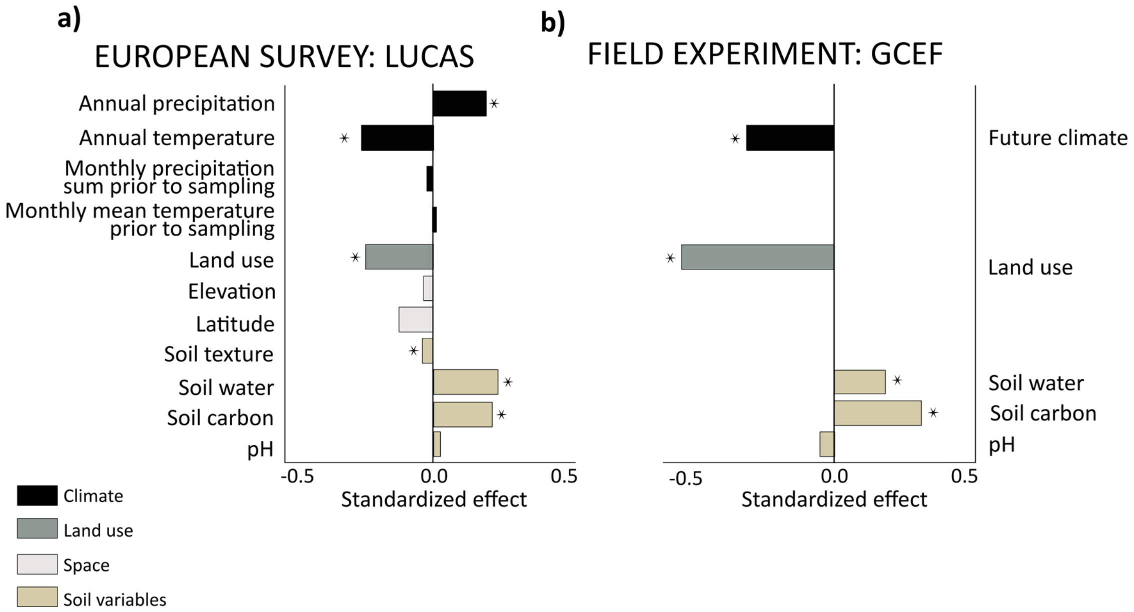

Fig. 3 Direct effect of the climate, land use and explanatory variables on soil multifunctionality. **a** The European survey (LUCAS) and **b** the field experiment (GCEF). The direct standardized effect sizes derived from the structural equation models are shown.

temperatures and drier conditions reduced multifunctionality in a large-scale survey in Europe. In addition, cropland management had a detrimental effect on multifunctionality. We observed a similar pattern in a large-scale field experiment: cropland management and the warmer future climate that also entails drier summers reduced soil multifunctionality. However, future climate conditions also increased soil carbon here, which in turn promoted soil multifunctionality, partly mitigating the strong negative effect of future climate conditions. Taken together, these results provide empirical evidence for the cumulatively detrimental effects of future climate and land use, threatening the integrity of soils.

Although we did not find any significant interactive effects of climate and land use, our results suggest that both climate and land-use change will have major implications for soil functioning. Given the strong link between the microbial community and their associated functions to temperature and soil moisture, shifts in climate patterns may cause significant declines of soil functioning. The anticipated climate changes are expected to result in notable alterations in soil functions. In line with our hypotheses, we found that higher temperatures and lower rainfall amount were related to lower soil multifunctionality. However, warming and drought interact[36], as higher temperatures stimulate evapotranspiration, reinforcing dry conditions[23]. We noted a similar mechanism in the observational study, where warming was linked to reduced soil water content, consequently impacting soil multifunctionality through indirect pathways. As soils get drier, microbial physiology responds to drought stress, while soil enzymes are immobilized, and both substrate and enzyme diffusion rates decrease[37]. This decrease causes microbial and enzyme activities to decline[38]. Similarly, the future climate treatment in our field experiment, involving warming and summer drought, reduced soil multifunctionality. While our study captures warming and changes in precipitation, it does not consider extreme weather events, which will become more frequent with climate change, and also exert substantial impacts on soil functioning[39,40].

At the same time, we observed an additional mechanism in the field experiment. The future climate treatment had a positive effect on soil carbon, partially counteracting the negative impact of future climate conditions on multifunctionality. Carbon accumulation relies on specific factors: high plant biomass production at the beginning of the year, followed by a dry summer and a cold winter that prevent organic matter decomposition. In the future climate treatment of the GCEF, spring conditions become even wetter, favouring plant biomass production. However, the increased summer drought associated with the future climate treatment impairs the decomposition of organic material, leading to an accumulation of carbon in the soil throughout the fall[41]. Nevertheless, climate change can reduce soil organic carbon stocks by increasing carbon release after droughts[42]. Our findings demonstrate a positive effect on soil carbon in the short term; however, this mechanism may be limited to specific climate conditions at the study location and also dependent on season[43]. At the same time, these dynamics might also vary significantly depending on the soil type, such as dry sandy soils or soils with waterlogging conditions. Both specific climate conditions and soil types highlight the importance to consider potential negative long-term climate change impacts on soil carbon stocks[44].

We also observed that cropland management compared to and grassland management—reduced soil multifunctionality across Europe, a pattern which was confirmed by the results of our field experiment. The mechanisms by which cropland management impairs soil functions are manifold[30]. They include regular tillage that adversely affects soil microorganisms by destroying microhabitats and fungal hyphal networks[45]. Tillage also leads to soil oxygenation and reduces soil organic carbon by removing root organic releases and by increasing susceptibility to erosion[46,47]. In addition, considerably more fertilizers are used on arable land with annual crops compared to grasslands[48]. Although direct data on fertilization regimes was not available in the observational dataset, we observed that cropland management practices led to a reduction in pH, likely indicating higher fertilizer inputs[49]. Fertilization may initially have a positive effect on microbial and enzyme activity, for example by increasing rhizodeposition via enhanced plant growth[49] or removing stoichiometric limitations[50], but long-term studies often show inhibiting effects, e.g., caused by excessive nitrogen accumulation[51]. In addition, although pesticides are intended to have a target-specific effect, they are in fact usually harmful to other organisms and can therefore also affect microbial biomass and thus impair soil functions[52]. Finally, croplands are often cultivated as monocultures, which are known to have limited benefits to soil life and functions[53]. In contrast, grasslands usually grow multiple plant species, and this plant diversity is beneficial for microbial and enzymatic activity[54,55] At the same time, the absence of tillage promotes soil physical properties[56] and allows the build-up of plant-beneficial soil microbial communities with multiple ecosystem benefits[57].

However, while there is a strong link between soil functioning and land use, the capacity of soils to provide essential functions also relies on other factors, including soil type, chemical composition, and physical properties[58]. The soil type used in our field experiment, for example, is known for its fertility, which likely provides it with a higher capacity to buffer extreme conditions than many other arable soils. Therefore, soil functioning is highly influenced by its specific context and considering these factors becomes crucial when exploring measures to promote the health of the soil microbial community and enhance soil functions[59]. At the same time, our analysis focussed on seven soil functions at a specific soil depth and did not include production of food, water purification, carbon sequestration or habitats for biodiversity[58]. This highlights the need for future studies to investigate multifunctionality measures encompassing a broader range of functions[60].

Taken together, our results indicate that changes in climate, as predicted for many European regions, could reduce the multifunctionality of soils. We confirm this pattern in a field experiment that simulates future conditions in a controlled setting, where higher temperatures and shifts in precipitation patterns (including summer drought) also reduced soil multifunctionality, independently of land use. Our findings confirm that a shifting climate could potentially limit the effectiveness of soil ecosystem functions in cropland management. Considering the crucial role of these functions, this situation is expected to lead to adverse effects on human well-being in the coming decades. Promoting sustainable land use practices may be a powerful approach to maximize the provisioning of multiple ecosystem benefits[25,61,62] under changing climatic conditions[2,63,64]. As Earth's climate changes, deepening our understanding of the drivers of soil multifunctionality is going to be critical to inform policy decisions that safeguard soils and their functions for current and future generations.

Methods

European survey. To determine the effects of climate and land use on soil multifunctionality across Europe, we used soil samples from the Land Use/Cover Area frame Survey (LUCAS). Briefly, soil samples were collected from 881 unique sites across Europe in 2018, covering a wide range of environmental conditions, taken from April to December with no particular sampling strategy. Detailed sampling time information can be found in Appendix 2 of Smith et al. 2021 (Figs. S2–2)[65]. After collection, samples were stored on ice and transferred to Ispra, Italy, prior to measurements in Leipzig and Halle, Germany, in March 2019. For this study, we selected a subset of the sampling sites. As we were interested in the effects of agricultural land-use intensities, we selected 318 cropland sites and 160 grassland sites, excluding forest sites.

Field experiment. We used the 6-year-old, large-scale field experiment "Global Change Experimental Facility" to test the impacts of climate change and land use in an experimental setup. Located at the field research station of the Helmholtz-Center for Environmental Research UFZ in Bad Lauchstädt, Saxony-Anhalt, Germany (51°22060 N, 11°50060 E, 118 m above sea level), the region is characterized by mean annual rainfall averages of 489 mm and a mean temperature of 8.9 °C. The soil type is a haplic Chernozem, developed under carbonatic loess substrates, which have one of the best capacities for storing soil organic carbon[41]. The experiment is comprised of a split-plot design, with 50 subplots (16 m × 24 m) arranged in 10 main plots. Half of the main plots are subjected to a climate change scenario informed by regional climate projections that include an increase in temperature by 0.6 °C, a 20% reduction of rainfall in summer, and a 10% increase in spring and fall (see Schädler et al.[66] for details). Each main plot is split into five subplots, implementing five different land use treatments: conventional cropland, organic cropland, intensive grassland, extensive grassland, and extensive pasture grazed by sheep instead of being mown (see Supplementary Fig. 1). We sampled four of the five land use types ($n = 40$ subplots; 4 land use types × 2 climate treatments × 5 replicates) and omitted extensive pasture. Land use treatments were divided into two land use types (cropland vs. grassland) to reflect the design of the LUCAS survey. In the croplands, a crop rotation of winter oilseed rape, winter wheat, and winter barley was implemented, with legumes added every third year instead of rapeseed, in the organically managed areas, providing atmospheric N fixation and plant N supply[67]. The plots were fertilized depending on the cultivated crop and in accordance with the respective management method. Pesticides (herbicides, fungicides, and insecticides) were used according to regional recommendations. In organic croplands, pesticide use was completely avoided. Grasslands were represented by an intensively- and extensively-used meadow. The intensive grassland was sown with five grass varieties, fertilized with nitrogen (N), phosphorus (P), and potassium (K), and mown up to four times per year. In contrast, the extensively used meadows contained 56 plant species (grasses, legumes, and herbs), received no fertilization, and were mown twice a year. We collected soil cores in spring (May) and fall (September/October) 2019 using a steel core sampler (1.5 cm diameter; 15 cm deep). Eight fresh subsamples were pooled, sieved to 2 mm, and stored at 4 °C.

Measurement of microbial respiration, biomass and soil water content. For the European survey, 50 g soil samples that had been previously stored frozen at −20 °C were taken, thawed to 4 °C, and then sieved to 2 mm. For logistical reasons, samples were then stored at 4 °C for four weeks. Five days before measurement, the samples were placed in sealed bags and acclimatized to room temperature (20 °C) to maintain constant soil moisture. Thereafter, basal respiration was measured using an O_2-microcompensation system[68]. Depending on soil density, 5–7 g of fresh soil was used to measure basal respiration (µl O_2 h^{-1} g^{-1} soil dry weight) for a 24 h interval. Microbial biomass (µg C_{mic} g^{-1} soil dry weight) was measured using substrate-induced respiration with the same soil samples by adding 4 mg glucose per g soil dry weight, dissolved in 1–1.5 ml distilled water for 12 h[69]. We used 1-1.5 ml of distilled water, adjusting based on soil dry weight, to ensure the samples were uniformly moist without being waterlogged. Afterwards, soil samples were dried at 75 °C for 24 h. By accurately measuring the initial weight of the soil samples before drying, we were able to determine the percentage of soil water content afterwards (for detailed information, please see Smith et al.[65]).

In the field experiment, measuring soil microbial respiration and biomass was done by means of the same O_2-microcompensation system setup, using 6 g of fresh soil[59]. Following the same protocol, soils were acclimated at 20 °C before determining microbial basal respiration (µl O_2 h^{-1} g^{-1} soil dry weight) at a 24 h interval. Subsequently, maximum respiratory activity was measured by adding glucose (4 mg g^{-1} soil dry weight dissolved in 1.5 ml distilled water), which allowed the determination of soil microbial biomass (µg C_{mic} g^{-1} soil dry weight) as done before[27]. Afterwards, soil samples were dried as described above to determine soil water content.

Measurement of water-stable aggregates. To measure water-stable aggregates (WSA), we employed the wet-sieving method, a well-established technique for assessing water-stable aggregates[70,71]. The wet-sieving device used was the Eijkelkamp soil & Water from Giesbeek, the Netherlands. We measured three replicates for each GCEF subplot and one replicate for each LUCAS sample. We placed 4 g of fresh soil (FM) into 0.25-mm sieves and allowed the soil to soak capillarily rewet for 5 min. Samples were then wet-sieved for 3 min and dried overnight at 70 °C, after which dry matter (DM) was measured. Sand, roots, and particles were extracted by crushing the aggregates and rinsing them in sieves until the water was clean. The coarse matter (CM) was weighed after another night in the drying oven at 70 °C. The percentage of water-stable aggregates was calculated as follows:

$$\%\mathrm{WSA} = \left(\frac{\mathrm{WSA} - \mathrm{CM}}{\mathrm{FM} - \mathrm{CM}}\right) \times 100$$

Measurement of soil enzymes and properties. Determination of the activities of four hydrolytic enzymes was based on 4-methylumbelliferone (MUF)-coupled substrates. 4-MUB-b-D-cellobioside, 4-MUB-b-D-xyloside, 4-MUB-N-acetyl-b-D-glucosaminide and 4-MUB-phosphate are used to estimate the activities of enzymes involved in carbon (cellobiohydrolase, xylosidase), nitrogen (N-acetylglucosaminidase), and phosphorus (phosphatase) cycling, respectively. For each soil sample, a separate black 96-well microplate was prepared. The plates contained all substrates, MUF dilutions to calculate quench and extinction coefficients (1.25 and 2.5 µM), as well as substrate and soil suspension controls. Then, approximately 250 mg of fresh soil sample were suspended in 50 ml of 50 µM acetate buffer (pH 5) for analysis. The pH range for soils of the GCEF platform was between 5.5 and 7.5[72]. We chose pH 5 for two reasons. Firstly, it ensured that all enzymes in the soil suspension exhibited sufficient activity and prevented bias from other phosphatases. Secondly, enzyme production is concentrated in soil hotspots around litter and plant roots, which lower the pH due to plant exudation and microbial metabolism[73]. Thus, the working pH of enzymes in soil may differ from the measured pH using standard methods. The method employed standardized conditions, removing temperature and moisture differences, allowing for direct comparison of enzymatic potentials across diverse samples. To break up soil aggregates, the soil suspensions were sonicated for 5 min, then transferred to the prepared microplates and incubated at 25 °C for 60 min. The addition of 30 µl 1 M NaOH solution stopped the enzymatic reactions. Subsequently, fluorescence was measured for eight technical replicates (to account for soil heterogeneity) using an Infinite 200 PRO instrument (Tecan Group, Männedorf, Switzerland) with 360 nm excitation and 465 nm emission filters. Enzyme activities were provided as turnover rate of the substrate in nmol per gram dry soil and hour. Total organic carbon was determined by dry combustion with a Vario EL III C/H/N analyzer (Elementar, Hanau, Germany) and soil pH by using a pH electrode (InLab Expert Pro-ISM, Mettler-Toledo, Giessen, Germany).

Statistical analyses. Data processing and statistical analyses were performed using R version 4.2.1. We used the "corrplot" package to analyze the correlation between the individual functions. Afterwards, we used the same seven functions to calculate soil multifunctionality with the averaging and the threshold approach according to Byrnes and colleagues[35]. In order to avoid any model-fit deviation due to scale differences between variables, all explanatory variables were centered and divided by two standard deviations.

We tested the relationships between climate, land use, soil water content, soil carbon content, and pH as well as their effects on soil multifunctionality using a Structural Equation Modeling (SEM) framework. To account for the split-plot design of the field experiment, we included "mainplot" as random factor. Our SEM was fitted using the R function "psem" from the "piecewise" package[62]. For the LUCAS dataset, we also included latitude, elevation, and soil texture in the model. For soil texture, silt, sand, and clay were combined by a principal component analysis (PCA). To assess the interactive effects of climate change and land use on soil multifunctionality, and to test the interaction effect between the predictors we employed a model that included the interaction. However, since the interaction was not found to be statistically significant, we proceeded with a simpler model (without the interaction term) for the final analysis. We also tested the model for potential non-linear relationship. For model fit and model quality we used Fisher C. To test the robustness of our results, we used two multifunctionality measures in our model: the averaging approach, which provides the average value of the standardized functions that is part of our main results, and the threshold approach. As we sampled the field experiment in spring and fall, we also tested both samplings separately. We also tested covariation between the exogenous variables of the SEMs. In addition, we tested all seven soil functions individually for both LUCAS and GCEF (for additional information on the analyses please see Supplementary Methods; Supplementary Tables 2–48 and Supplementary Figs. 2–24).

Data availability

Datasets used for this study can be accessed here: https://zenodo.org/record/8386710.

Code availability

All R scripts used for this study can be accessed here: https://zenodo.org/record/8386710.

Received: 15 December 2022; Accepted: 9 October 2023;

References

1. FAO. State of knowledge of soil biodiversity - status, challenges and potentialities. https://doi.org/10.4060/cb1928en (2020).
2. Pörtner, H.-O. et al. Scientific outcome of the IPBES-IPCC co-sponsored workshop on biodiversity and climate change. https://doi.org/10.5281/ZENODO.4659158 (2021).
3. Díaz, S. et al. Pervasive human-driven decline of life on Earth points to the need for transformative change. *Science* **366**, eaax3100 (2019).
4. Beckmann, M. et al. Conventional land-use intensification reduces species richness and increases production: a global meta-analysis. *Glob. Change Biol.* **25**, 1941–1956 (2019).
5. Schwarz, B. et al. Warming alters energetic structure and function but not resilience of soil food webs. *Nat. Clim. Change* **7**, 895–900 (2017).
6. Rillig, M. C. et al. The role of multiple global change factors in driving soil functions and microbial biodiversity. *Science* **366**, 886–890 (2019).
7. Wall, D. H. & Six, J. Give soils their due. *Science* **347**, 695–695 (2015).
8. Bardgett, R. D. & van der Putten, W. H. Belowground biodiversity and ecosystem functioning. *Nature* **515**, 505–511 (2014).
9. Burns, R. G. et al. Soil enzymes in a changing environment: current knowledge and future directions. *Soil Biol. Biochem.* **58**, 216–234 (2013).
10. Merino-Martín, L. et al. Interacting effects of land use type, microbes and plant traits on soil aggregate stability. *Soil Biol. Biochem.* **154**, 108072 (2021).
11. Rabot, E., Wiesmeier, M., Schlüter, S. & Vogel, H.-J. Soil structure as an indicator of soil functions: a review. *Geoderma* **314**, 122–137 (2018).
12. Hooper, D. U. et al. Effects of biodiversity on ecosystem functioning: a consensus of current knowledge. *Ecol. Monogr.* **75**, 3–35 (2005).
13. Eisenhauer, N. et al. Plant diversity maintains multiple soil functions in future environments. *eLife* **7**, e41228 (2018).
14. Garland, G. et al. A closer look at the functions behind ecosystem multifunctionality: a review. *J. Ecol.* **109**, 600–613 (2021).
15. Kopittke, P. M., Menzies, N. W., Wang, P., McKenna, B. A. & Lombi, E. Soil and the intensification of agriculture for global food security. *Environ. Int.* **132**, 105078 (2019).
16. Frey, S. D., Lee, J., Melillo, J. M. & Six, J. The temperature response of soil microbial efficiency and its feedback to climate. *Nat. Clim. Change* **3**, 395–398 (2013).
17. Meng, C. et al. Global meta-analysis on the responses of soil extracellular enzyme activities to warming. *Sci. Total Environ.* **705**, 135992 (2020).
18. Alster, C. J., German, D. P., Lu, Y. & Allison, S. D. Microbial enzymatic responses to drought and to nitrogen addition in a southern California grassland. *Soil Biol. Biochem.* **64**, 68–79 (2013).
19. Allison, S. D. & Goulden, M. L. Consequences of drought tolerance traits for microbial decomposition in the DEMENT model. *Soil Biol. Biochem.* **107**, 104–113 (2017).
20. Nannipieri, P., Trasar-Cepeda, C. & Dick, R. P. Soil enzyme activity: a brief history and biochemistry as a basis for appropriate interpretations and meta-analysis. *Biol. Fertil. Soils* **54**, 11–19 (2018).
21. Xiao, W., Chen, X., Jing, X. & Zhu, B. A meta-analysis of soil extracellular enzyme activities in response to global change. *Soil Biol. Biochem.* **123**, 21–32 (2018).
22. Fanin, N. et al. Soil enzymes in response to climate warming: Mechanisms and feedbacks. *Funct. Ecol.* **36**, 1378–1395 (2022).
23. Manning, C. et al. Soil moisture drought in Europe: a compound event of precipitation and potential evapotranspiration on multiple time scales. *J. Hydrometeorol.* **19**, 1255–1271 (2018).
24. Sheik, C. S. et al. Effect of warming and drought on grassland microbial communities. *ISME J.* **5**, 1692–1700 (2011).
25. Soliveres, S. et al. Biodiversity at multiple trophic levels is needed for ecosystem multifunctionality. *Nature* **536**, 456–459 (2016).
26. Beaumelle, L. et al. Pesticide effects on soil fauna communities—a meta-analysis. *J. Appl. Ecol.* 1365–2664.14437 https://doi.org/10.1111/1365-2664.14437 (2023)
27. Sünnemann, M. et al. Low-intensity land-use enhances soil microbial activity, biomass and fungal-to-bacterial ratio in current and future climates. *J. Appl. Ecol.* **58**, 2614–2625 (2021).
28. Edlinger, A. et al. Agricultural management and pesticide use reduce the functioning of beneficial plant symbionts. *Nat. Ecol. Evol.* **6**, 1145–1154 (2022).
29. de Vries, F. T. et al. Land use alters the resistance and resilience of soil food webs to drought. *Nat. Clim. Change* **2**, 276–280 (2012).
30. Tsiafouli, M. A. et al. Intensive agriculture reduces soil biodiversity across Europe. *Glob. Change Biol.* **21**, 973–985 (2015).
31. Delgado-Baquerizo, M. et al. The proportion of soil-borne pathogens increases with warming at the global scale. *Nat. Clim. Change* **10**, 550–554 (2020).
32. Labouyrie, M. et al. Patterns in soil microbial diversity across Europe. *Nat. Commun.* **14**, 3311 (2023).
33. De Vries, F. T. et al. Soil bacterial networks are less stable under drought than fungal networks. *Nat. Commun.* **9**, 3033 (2018).
34. Piton, G. et al. Using proxies of microbial community-weighted means traits to explain the cascading effect of management intensity, soil and plant traits on ecosystem resilience in mountain grasslands. *J. Ecol.* **108**, 876–893 (2020).

35. Byrnes, J. E. K. et al. Investigating the relationship between biodiversity and ecosystem multifunctionality: challenges and solutions. *Methods Ecol. Evol.* **5**, 111–124 (2014).
36. Thakur, M. P. et al. Reduced feeding activity of soil detritivores under warmer and drier conditions. *Nat. Clim. Change* **8**, 75–78 (2018).
37. Wallenstein, M. D., McMahon, S. & Schimel, J. Bacterial and fungal community structure in Arctic tundra tussock and shrub soils: Community structure in Arctic tundra tussock and shrub soils. *FEMS Microbiol. Ecol* **59**, 428–435 (2007).
38. Carbone, M. S. et al. Seasonal and episodic moisture controls on plant and microbial contributions to soil respiration. *Oecologia* **167**, 265–278 (2011).
39. Bardgett, R. D. & Caruso, T. Soil microbial community responses to climate extremes: resistance, resilience and transitions to alternative states. *Philos. Trans. R. Soc. B Biol. Sci.* **375**, 20190112 (2020).
40. Reichstein, M. et al. Climate extremes and the carbon cycle. *Nature* **500**, 287–295 (2013).
41. Altermann, M. et al. Chernozem—Soil of the Year 2005. *J. Plant Nutr. Soil Sci.* **168**, 725–740 (2005).
42. Canarini, A., Kiær, L. P. & Dijkstra, F. A. Soil carbon loss regulated by drought intensity and available substrate: A meta-analysis. *Soil Biol. Biochem.* **112**, 90–99 (2017).
43. Simon, E. et al. Microbial growth and carbon use efficiency show seasonal responses in a multifactorial climate change experiment. *Commun. Biol.* **3**, 584 (2020).
44. García-Palacios, P. et al. Evidence for large microbial-mediated losses of soil carbon under anthropogenic warming. *Nat. Rev. Earth Environ.* **2**, 507–517 (2021).
45. Wilkes, T. I., Warner, D. J., Edmonds-Brown, V., Davies, K. G. & Denholm, I. Zero tillage systems conserve arbuscular mycorrhizal fungi, enhancing soil glomalin and water stable aggregates with implications for soil stability. *Soil Syst.* **5**, 4 (2021).
46. Doetterl, S. et al. Erosion, deposition and soil carbon: a review of process-level controls, experimental tools and models to address C cycling in dynamic landscapes. *Earth Sci. Rev.* **154**, 102–122 (2016).
47. Wright, A. L. & Hons, F. M. Soil carbon and nitrogen storage in aggregates from different tillage and crop regimes. *Soil Sci. Soc. Am. J.* **69**, 141–147 (2005).
48. Einarsson, R. et al. Crop production and nitrogen use in European cropland and grassland 1961–2019. *Sci. Data* **8**, 288 (2021).
49. Geisseler, D. & Scow, K. M. Long-term effects of mineral fertilizers on soil microorganisms – a review. *Soil Biol. Biochem.* **75**, 54–63 (2014).
50. Taylor, P. G. & Townsend, A. R. Stoichiometric control of organic carbon–nitrate relationships from soils to the sea. *Nature* **464**, 1178–1181 (2010).
51. Treseder, K. K. Nitrogen additions and microbial biomass: a meta-analysis of ecosystem studies. *Ecol. Lett.* **11**, 1111–1120 (2008).
52. Beaumelle, L. et al. Soil fauna diversity and chemical stressors: a review of knowledge gaps and roadmap for future research. *Ecography* **44**, 845–859 (2021).
53. Culman, S. W. et al. Long-term impacts of high-input annual cropping and unfertilized perennial grass production on soil properties and belowground food webs in Kansas, USA. *Agric. Ecosyst. Environ.* **137**, 13–24 (2010).
54. Curtright, A. J. & Tiemann, L. K. Intercropping increases soil extracellular enzyme activity: A meta-analysis. *Agric. Ecosyst. Environ.* **319**, 107489 (2021).
55. Lange, M. et al. Plant diversity increases soil microbial activity and soil carbon storage. *Nat. Commun.* **6**, 6707 (2015).
56. Blanco-Canqui, H. & Ruis, S. J. No-tillage and soil physical environment. *Geoderma* **326**, 164–200 (2018).
57. Eisenhauer, N., Cesarz, S., Koller, R., Worm, K. & Reich, P. B. Global change belowground: impacts of elevated CO2, nitrogen, and summer drought on soil food webs and biodiversity. *Glob. Change Biol.* **18**, 435–447 (2012).
58. Schulte, R. P. O. et al. Functional land management: a framework for managing soil-based ecosystem services for the sustainable intensification of agriculture. *Environ. Sci. Policy* **38**, 45–58 (2014).
59. Guerra, C. A. et al. Global hotspots for soil nature conservation. *Nature* **610**, 693–698 (2022).
60. Schwilch, G. et al. Operationalizing ecosystem services for the mitigation of soil threats: a proposed framework. *Ecol. Indic.* **67**, 586–597 (2016).
61. Wittwer, R. A. et al. Organic and conservation agriculture promote ecosystem multifunctionality. *Sci. Adv.* **7**, eabg6995 (2021).
62. Lefcheck, J. S. et al. Biodiversity enhances ecosystem multifunctionality across trophic levels and habitats. *Nat. Commun.* **6**, 6936 (2015).
63. Loreau, M. et al. Biodiversity as insurance: from concept to measurement and application. *Biol. Rev.* **96**, 2333–2354 (2021).
64. Isbell, F. et al. Benefits of increasing plant diversity in sustainable agroecosystems. *J. Ecol.* **105**, 871–879 (2017).
65. Smith, L. C. et al. Large-scale drivers of relationships between soil microbial properties and organic carbon across Europe. *Glob. Ecol. Biogeogr.* **30**, 2070–2083 (2021).
66. Schädler, M. et al. Investigating the consequences of climate change under different land-use regimes: a novel experimental infrastructure. *Ecosphere* **10**, e02635 (2019).
67. Castellano, M. J., Mueller, K. E., Olk, D. C., Sawyer, J. E. & Six, J. Integrating plant litter quality, soil organic matter stabilization, and the carbon saturation concept. *Glob. Change Biol.* **21**, 3200–3209 (2015).
68. Scheu, S. Automated measurement of the respiratory response of soil microcompartments: Active microbial biomass in earthworm faeces. *Soil Biol. Biochem.* **24**, 1113–1118 (1992).
69. Anderson, J. P. E. & Domsch, K. H. A physiological method for the quantitative measurement of microbial biomass in soils. *Soil Biol. Biochem.* **10**, 215–221 (1978).
70. Kroetsch, D., & Wang, C. *Soil Sampling and Methods of Analysis* (Canadian Society of Soil Science; CRC Press, 2008).
71. Seybold, C. A. & Herrick, J. E. Aggregate stability kit for soil quality assessments. *CATENA* **44**, 37–45 (2001).
72. Sinsabaugh, R. L. et al. Stoichiometry of soil enzyme activity at global scale: Stoichiometry of soil enzyme activity. *Ecol. Lett.* **11**, 1252–1264 (2008).
73. Hinsinger, P., Bengough, A. G., Vetterlein, D. & Young, I. M. Rhizosphere: biophysics, biogeochemistry and ecological relevance. *Plant Soil* **321**, 117–152 (2009).

Acknowledgements

We thank the staff of the Bad Lauchstädt Experimental Research Station (especially Ines Merbach and Konrad Kirsch) for their work in maintaining the plots and infrastructures of the Global Change Experimental Facility (GCEF), and Harald Auge and Stefan Klotz for their role in setting up the GCEF. We also thank Tom Künne and Ulrich Pruschitzki, for their support with field work. MSü and NE acknowledge support of iDiv funded by the German Research Foundation (DFG– FZT 118, 202548816). The LUCAS Survey is coordinated by Unit E4 of the Statistical Office of the European Union (EUROSTAT). The LUCAS Soil sample collection is supported by the Directorate-General Environment (DG-ENV), Directorate-General Agriculture and Rural Development (DG-AGRI), Directorate-General Climate Action (DG-CLIMA) and Directorate-General Eurostat (DG-ESTAT) of the European Commission. We also express our gratitude to the three reviewers who contributed to the improvement of our manuscript.

Author contributions

A.O. and A.J. coordinated the LUCAS Soil survey and associated measurements. M.Sch. and F.B. are part of the GCEF steering committee that developed the experimental platform. N.E. and C.A.G. conceived the study. M.Sü., C.B., S.C., A.Le, A.Lo., T.R., M.C.R., L.C.S. and A.Z. collected the data. M.Sü. and R.B. analyzed the data. M.Sü., C.A.G., and N.E. wrote the manuscript with contributions from all authors.

Funding

Open Access funding enabled and organized by Projekt DEAL.

Competing interests

The authors declare no competing interests.

Inclusion and ethics statement

We support inclusive, diverse, and equitable conduct of research

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s43247-023-01047-2.

Correspondence and requests for materials should be addressed to Marie Sünnemann.

Peer review information *Communications Earth & Environment* thanks Gabin Piton and the other, anonymous, reviewer(s) for their contribution to the peer review of this work. Primary handling editors: Erika Buscardo and Aliénor Lavergne. A peer review file is available.