



No detectable elevated soil carbon under organic farming in German croplands – results from two soil surveys

Axel Don ^{*}, Kimberley Brügge, David Emde, Konstantin Aiteew, Christopher Poeplau

Thünen Institute of Climate-Smart Agriculture, Bundesallee 65, 38116 Braunschweig, Germany

ARTICLE INFO

Handling Editor: Dr Daniel Said-Pullicino

Keywords:

Soil management
Soil organic matter
Low-input agriculture
Farming practice
Soil carbon
Machine learning

ABSTRACT

Organic farming contributes to multiple environmental targets in agriculture. Long-term field experiments found that organic farming cropland not only emit lower greenhouse gas emissions but can also increase soil organic carbon (SOC) stocks relative to conventionally farmed plots. It is yet unknown whether the same SOC effect can be found in agricultural reality. In this study, two independent large scale soil inventory datasets (2159 and 811 sites) including both organic and conventional farming sites in Germany were analysed. Differences in SOC due to pedo-climatic conditions between sites were corrected using a *random forest* model. Croplands under organic farming showed neither higher SOC content nor higher SOC stocks compared to those under conventional farming in both data sets. The amount of organic fertilisers applied was comparable between organic farming (0.47 Mg C ha⁻¹ a⁻¹) and conventional farming (0.45 Mg C ha⁻¹ a⁻¹). The crop rotations under organic farming contained more crops that are known to enhance SOC (e.g. grass-clover mixtures, 39 %) than in conventional farms (11 %). However, yields in organic farming were on average 31 % lower than in conventional farming, which most likely led to less crop residue returned to soil to build up SOC. Our results challenge the previous perception that organic farming builds up SOC. Agricultural practice reality may not be representatively captured in existing organic farming long-term field trials. Microbial N mining and lower yield resulting from lower N availability in organic farming may hamper the build-up of SOC in organic farming systems. Thus, the extension of organic farming in Central Europe will likely not contribute to additional SOC accrual. However, SOC in organic farms is built up with less environmental costs, e.g. via nitrogen losses, and can thus be considered as more sustainable than SOC in conventional systems.

1. Introduction

Organic farming is an alternative to conventional farming that focuses on reducing the environmental impact of crop production by limiting the use of synthetic pesticides, enlarging the crop diversity in crop rotations and by prohibiting the application of mineral synthetic fertilisers (Sanders et al., 2025). By following such practices, biodiversity is enhanced, nutrient losses are limited, and greenhouse gas emissions per area are lower compared to conventional management practices (Skinner et al., 2019; Smith et al., 2019; Wittwer et al., 2021). All these aspects suggest a positive environmental and climate impact of expanding organic farming (Muller et al., 2017). Due to these multiple positive effects and the growing market for organic food, this agricultural system is increasingly being promoted. At the European level, the fraction of organically farmed agricultural land was 10 % in 2021 (Eurostat, 2025). The European Union has set itself the target of

increasing this proportion to 25 % by 2030 (European Commission, 2020). In Germany, an even higher target of 30 % has been set, which corresponds to a tripling of area for the period from 2022 to 2030 (German Federal Ministry of Agriculture, 2024).

Soils are the largest terrestrial carbon reservoir actively involved in the global carbon cycle and thus influencing climate change (Janzen, 2004). A decrease in soil organic carbon (SOC) stocks leads to a release of carbon, mainly as CO₂, into the atmosphere; an increase in SOC stocks, meanwhile, can lead to C sequestration (Don et al., 2024). The potential climate mitigation effect of C storage in soils is becoming increasingly important as a measure to reach the goal of greenhouse gas neutrality (Lal, 2004). In addition, SOC in the form of organic matter improves essential soil properties such as aggregate stability, water storage capacity and nutrient availability (Chaney & Swift, 1984; Gerke, 2022; Hudson, 1994). Thus both, soil fertility and yield, is known to be linked to the SOC content (Kätterer & Bolinder, 2024) even though the

^{*} Corresponding author.

E-mail address: axel.don@thuenen.de (A. Don).

<https://doi.org/10.1016/j.geoderma.2025.117634>

Received 28 July 2025; Received in revised form 12 November 2025; Accepted 24 November 2025

Available online 29 November 2025

0016-7061/© 2025 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

relations are complex and partly lost in intensively management agricultural systems. Therefore, the amount of SOC in the soil is an important property of agricultural soils that needs to be maintained and, where possible, enhanced as part of a sustainable agriculture.

Soil organic carbon stocks are the result of a long-term balance between carbon inputs to the soil (C inputs) and C losses mainly via respiration (e.g. Luo et al., 2017). In agricultural soils this balance is strongly influenced by management practices, which control both the quantity and quality of the C input as well as its microbial transformation (e.g. McLauchlan, 2006; Poeplau et al., 2021). Organic farming differs from conventional farming in key farming practices. A central feature is the prohibition of synthetic pesticides and mineral fertilisers. Instead, fertilisation is based on organic fertilisers (e.g. farmyard manure or compost) and the use of crop rotations with a higher proportion of legumes. Organic fertilisers are known to directly increase SOC by approximately 0.1 Mg C per Mg C of added farmyard manure (Maillard & Angers, 2014). Among legumes, perennial fodder legumes in long-term field experiments significantly increased SOC compared to annual crops due to their high C input to soils (Bolinder et al., 2012; Panagea et al., 2025). On the other hand, yields in organic farming are generally lower than in conventional farming, thus requesting more agricultural land to achieve the same production with possible impact natural vegetation areas (Kirchmann, 2019). Lower yield may also reduce the amount of crop residues as the most important C input, including roots, stubble and straw (e.g. de Ponti et al., 2012; Seufert et al., 2012). The impact of an expansion of organic farming on SOC is therefore the net result of a combination of different effects.

Numerous field experiments have been conducted to compare the net effect of organic farming on SOC compared to conventional farming (e.g. Marinari et al., 2010; Murata & Goh, 1997). In a global meta-analysis of 74 field experiments, Gattinger et al. (2012) showed significantly increased SOC stocks in organic farming systems compared to conventional farming. Further meta-analyses support these results (Aguilera et al., 2013; García-Palacios et al., 2018). However, there is remaining uncertainty about the effect of organic farming in agricultural practice outside of field experiments (Leifeld et al., 2013). The dependence of organic farming systems on external C inputs in the form of organic fertilisers (from grasslands or from outside farm boundaries), raises the question of whether organic farming is viable at a large scale and how much of such increased SOC stocks can be considered climate mitigation if C is important from other systems. Alvarez (2022a) was unable to detect any significant difference between organic farming and conventional farming without such external C inputs. Gaudaré et al. (2023) even modelled a decrease in SOC stocks for a scenario with expansion of organic farming to the entire global agricultural area. Thus, the actual potential of increasing SOC with the expansion of organic farming remains unclear under practical farming conditions. Studies based on data from agricultural practice are therefore needed to clarify the influence of organic farming on SOC.

One approach to closing this gap is to analyse soil inventory data. Soil inventories are able to provide a representative picture of SOC stocks, other soil properties, as well as management practices at a national scale. Two unique soil inventory datasets are available for this approach, the German Agricultural Soil Inventory (BZE-LW) and the soil dataset collected from more than 800 field sites as part of the HumusKlimaNetz project. With the BZE-LW, a standardised soil inventory was carried out throughout Germany, in which the SOC content and SOC stocks of agricultural soils as well as site characteristics and management factors were recorded on a representative basis (Poeplau et al., 2020). As part of the HumusKlimaNetz demonstration project, a soil survey was carried out also across Germany at 150 farms, 75 of which were organic farms. Soil organic carbon is strongly dependent on pedo-climatic site characteristics (Vos et al., 2019). Since the site characteristics of organic and conventional farming are different across Germany, it is necessary to account for site-specific influences on SOC. We addressed this using tailored machine learning algorithms as proposed

by Schneider et al. (2021). These models, trained with pedo-climatic factors, can account for the differences in site conditions and help to quantify the SOC effect of organic farming across diverse site conditions.

Based on these data and methods, the following questions are to be answered:

1. Does organic farming lead to an increase in SOC content and SOC stocks compared to conventional farming on German croplands, and if so, to what extent?
2. What management, site and soil factors influence the differences in SOC content and SOC stocks between organic and conventional farming?

2. Material and methods

2.1. The two data sets

2.1.1. Data from the German agricultural soil inventory

The BZE-LW comprises data from agricultural soils sampled in a systematic, 8×8 km, grid between 2011 and 2017 (Poeplau et al., 2020). A total of 3104 soils were analysed, of which 2159 croplands were used for this study, excluding sites with permanent crops such as vineyards and grasslands. Sampling for chemical analysis was performed at multiple depth increments from a soil pit, of which the depth increments in 0–30 cm were used for this study. Soil rings with undisturbed samples were collected to derive the bulk density. The SOC content was analysed using dry combustion (LECO Trumac and RC612, St. Joseph, MI, USA). In the presence of carbonates, organic carbon (combustion at 550 °C) and inorganic carbon (subsequent combustion at 1000 °C) were determined by ramped heating (LECO RC612). For more details see Poeplau et al. (2021). Farmer's management data was recorded via a questionnaire. The questionnaire contained information on the management of the site over the last ten years prior to sampling. The information on the starting year of organic farming was not part of the questionnaire and had to be collected separately for this study. These dates were collected for 65 out of 99 organically managed sites. The parameters recorded in the BZE-LW and used in this study are listed in the Supplement in Table S1.

The SOC content for the topsoil (0–30 cm) was calculated as the fine soil mass-weighted average of the 0–10 and 10–30 cm depth increments. The SOC stock in the topsoil was then determined by multiplying the averaged SOC content by the fine soil stock – derived from the bulk density measurements and accounting for the coarse fraction (Poeplau et al., 2017). This study was restricted to mineral soils with SOC < 87 g kg⁻¹ in the upper 0–30 cm and excluded organic soils (Jacobs et al., 2018). This selection resulted in 2159 mineral soil cropland sites of which 2060 were farmed conventionally and 99 organically (4.6 % of croplands in Germany). With the exception of the Alpine region in southern Bavaria, all of Germany was evenly covered by the sampling points both under conventional and under organic farming (Fig. 1). The longest-running organic farm started in 1954, the latest 2015. The duration of organic farming before sampling was between 1 and 62 years (Suppl. Fig. S1). 14 % of the farms started organic farming less than 5 years before the time of sampling.

The organically farmed croplands differed in pedo-climatic conditions from those under conventionally farmed croplands (Fig. 2). The proportion of sandy soils was 54 % under organic farming and 46 % under conventional farming. Conversely, there was a slightly higher proportion of clayey soils (14 %) under organic farming than under conventional farming (11 %).

2.1.2. Data from the HumusKlimaNetz project

The second soil survey dataset, which this study is based on, is the first soil sampling campaign of the HumusKlimaNetz model and demonstration project (<https://www.humus-klima-netz.de>). For this dataset, a total of 814 croplands from 148 farms were sampled in 2023

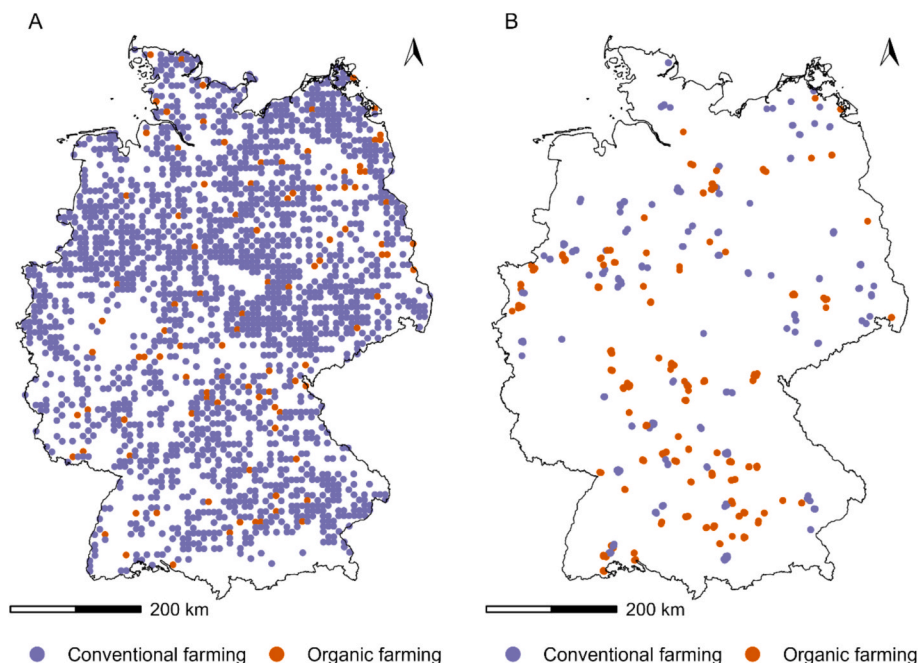


Fig. 1. Location of the sampled croplands under organic (N = 99) and conventional farming (N = 2060) in the BZE-LW dataset (A) and croplands under organic (N = 464) and conventional farming (N = 350) from the HumusKlimaNetz dataset (B).

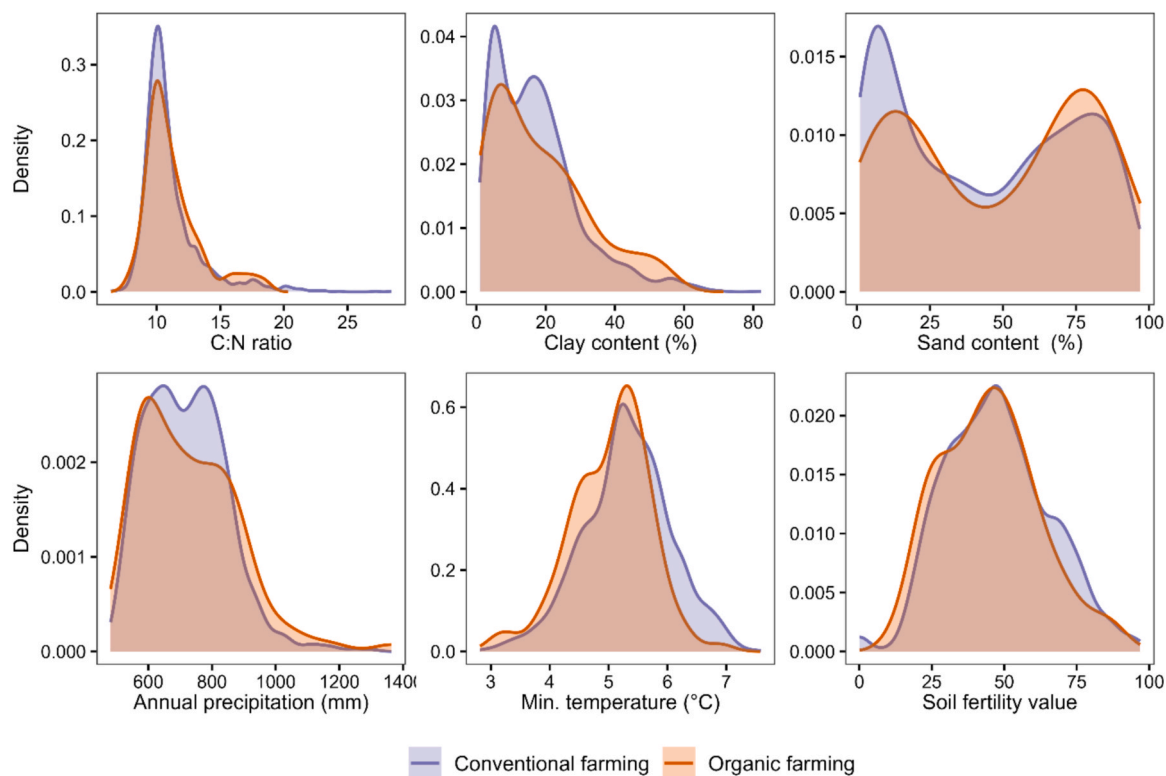


Fig. 2. Site characteristics of the croplands sampled in the BZE-LW under organic and conventional farming.

and 2024, of which 464 croplands were farmed organically and 350 conventionally. Therefore, the field sites may not be completely independent since some of the sites belong to the same farm. Sampling was undertaken across total fields with 15 topsoil samples per hectare and then combined to form a single composite sample. Analysis was performed at commercial labs using dry combustion. The bulk density was determined with one sampling point per hectare using three 200 cm³

cylinders across the total soil depth increment. The soil texture was determined with texture by feel (Vos et al., 2016) and categorised into eight soil texture classes. To estimate the clay and sand contents of the sampled soils, the median of the soil texture range in each class was used.

The data from the HumusKlimaNetz project were used in two ways: firstly, as independent validation for the model trained on the

conventionally farmed cropland from the BZE-LW. Secondly, this validated model was applied to the organically farmed croplands of this dataset as an independent quantification of the organic farming effects on SOC. To do this, the site characteristics of the HumusKlimaNetz data had to lie within the scope of the model, i.e. within the range of values covered by the conventionally farmed arable land of the BZE-LW. This was ensured by removing all points, which were outside the value range of the conventionally farmed arable land of the BZE-LW for at least one of the predictors. After this selection, the data set was reduced to 803 arable plots, of which 458 were organically and 345 conventionally farmed (Fig. 1B). Missing bulk density measurements from some sites prevented the calculation of SOC stocks and, therefore, further reduced the data to 783 sites: 441 organically and 342 conventionally farmed. Within the HumusKlimaNetz soil inventory, the distribution of soil texture for conventionally and organically farmed arable land differed slightly (Fig. 3).

In the HumusKlimaNetz dataset the distributions between organic farming and conventional farming differed slightly in some site properties (e.g., elevation) but generally had similar data distributions (Fig. 3). The measured distribution of SOC content, SOC stocks and bulk density of both data sets can be found in the Supplement (Figs. S2 and S3).

2.2. Modelling approach

Soil organic carbon at large scale is primarily dependent on the site characteristics such as soil texture, pH value and climate factors (e.g. Poeplau et al., 2020; Cora Vos et al., 2019). The reciprocal modelling approach was used to account for the effect of differences in such site characteristics on cropland SOC (Schneider et al., 2021). A site characteristics model was created with the SOC content or SOC stock as the target variable (Fig. 4).

The algorithm was trained on sites under conventional agriculture so that it learns to predict the SOC contents or SOC stocks for soils under conventional agriculture under the diverse site conditions. The

validation and verification of the applicability of this model to new sites was carried out in two steps: (1) a cross-validation (five folds with random sample selection) within the BZE-LW data set and (2) the application of the model to the independent data set from the HumusKlimaNetz. The model was an ensemble using the individual model runs of the cross-validation. Further analysis was carried out with a model in which all conventionally farmed croplands were included as training data. We did not train any such model on the organic sites, due to much smaller data set covering sites that are farmed organically resulting in larger model uncertainties. As fewer site properties were recorded in the HumusKlimaNetz, these were supplemented with geodata for the modelling (see below). In the next step, the model that was trained to predict SOC for conventional farmland was applied to the organic farmlands in order to predict the potential SOC content and SOC stock under conventional farming conditions. The differences between the actual measured value under organic farming and the predicted value shows the per-site effect of organic farming on SOC (Fig. 4) to which we refer as “treatment effects” below. In causal inference this is called the average treatment effect on the treated.

In the last step, a second, “explanatory” model was trained to predict these treatment effects based on management factors that are likely to affect SOC and are common to both conventional and organic farming but differ somehow between the two (e.g., organic fertilisation). This explanatory model allowed us to investigate the relative importance of each included variable and analyse partial dependencies. R software (version 4.2.2) was used for all analyses and presentations.

We used the Random Forest algorithm implemented in R in the *ranger* package (Wright & Ziegler, 2017). The number of possible predictors per decision point, m_{try} , was set to the commonly used value of

$$m_{try} = \sqrt{n} \quad (1)$$

where n is the total number of predictors in the model. 1000 trees were set up per model run. As error measures we used the mean squared error (MSE), the coefficient of determination (R^2), the root mean squared

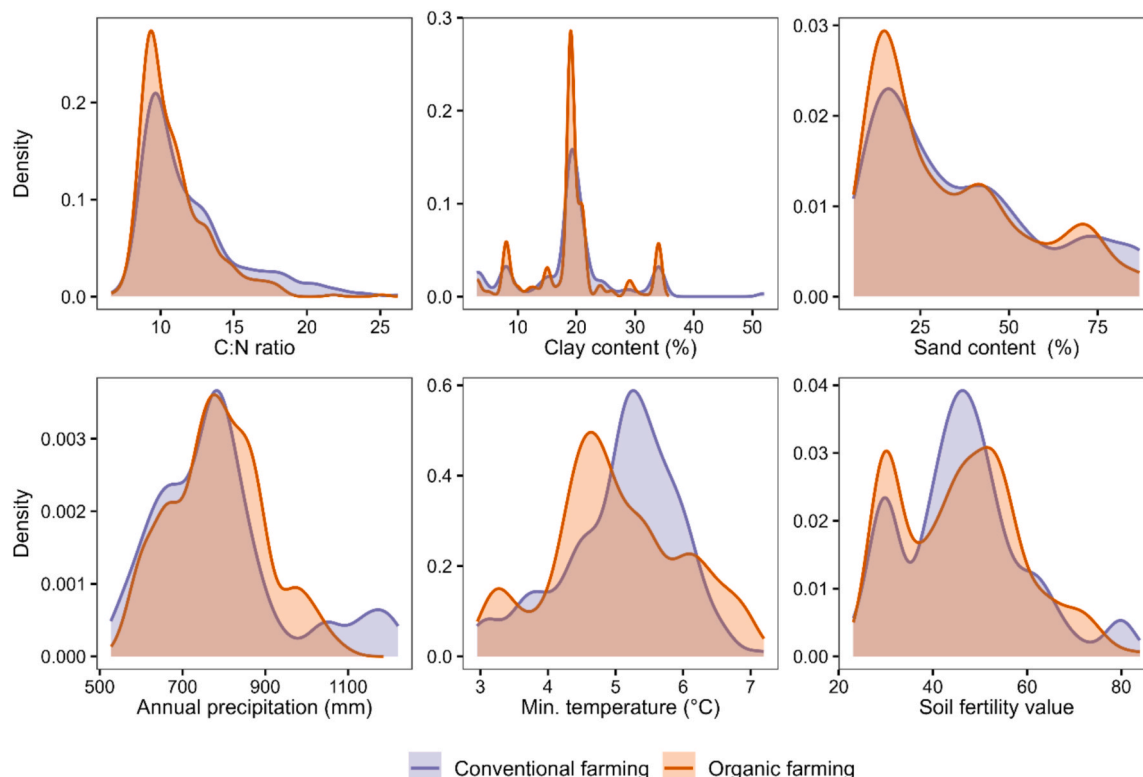


Fig. 3. Site characteristics of the croplands sampled in the HumusKlimaNetz under organic and conventional farming.

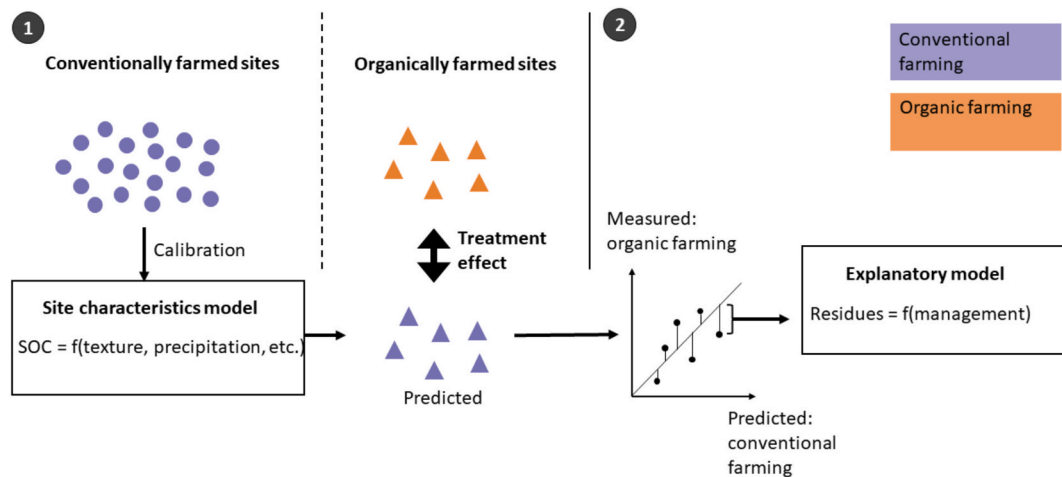


Fig. 4. Schematic of the modelling approach. The first step was to calibrate a model to predict SOC based on the site characteristics under conventional farming. This model was then used to predict the SOC content and stocks for site that are organically farmed. The comparison between measured SOC (organic) and predicted SOC (conventional) serves as an indicator of the effect of organic farming on SOC. In the second step, a second model was created to explain the SOC differences (residuals) by management factors such as organic fertilisation.

error (RMSE), the mean absolute error (MAE), the mean absolute percentage error (MAPE), as well as the ratio of performance to deviation (RPD), the ratio of performance to interquartile range (RPIQ) and the bias (for calculations see [Supplement](#)). The model quality and error measures were determined in two ways: cross validation of the training data and independent validation using the HumusKlimaNetz dataset. Cross-validation was performed for the model applied to the BZE-LW data. For this purpose, the data set was divided into five subsets based on spatial stratification (50 strata in a 100×100 km grid). Individual data points from each stratum were then randomly divided into the five subsets. The model was trained on four of these subsets (leave one out) and repeated five times for each subset. An average of the five predictions was calculated for each data point. Independent validation was carried out for the model based on the BZE-LW dataset using the conventionally farmed croplands of the independent HumusKlimaNetz dataset.

Various modelling tests were carried out with different site properties used as predictors. The predictors that were included in the final model are shown in [Table 1](#). These geodata were adopted from raster maps from independent sources as in [Sakhaee et al. \(2021\) \(Suppl. Tab. S2\)](#). The soil fertility index, which describes the fertility and productivity of German soils with values between 1 and 100, was adapted from data supplied by the German federal states ([Altermann, Friedrich, Gehrt, & Nestroy, 2023](#)). In the model that was used for the HumusKlimaNetz

data, the soil texture data were excluded due to the approximate nature of determining soil texture by hand.

In order to identify the quality and possible bias of the modelling, the distributions of the measured and predicted SOC contents and SOC stocks were visualised using a density function with the *density* function in R ([R Development Core Team, 2022](#)). The importance of the variables in the model was determined via permutation using the *ranger* function that specifies the change in the MSE resulting from the permutation of the influencing variable. The relationship between the predictors and the target variable (SOC content or SOC stock) was visualised using partial dependence plots, generated with the *partial* function from the R package *pdp*. However, it should be noted that no causal relationships are shown there.

2.2.1. Effect size of organic farming

In order to analyse the effect of organic farming on SOC, the model trained on conventional croplands was applied to the organically farmed croplands of the BZE-LW dataset and as validation also to the croplands of the HumusKlimaNetz dataset. The effect of organic farming was calculated as the following difference:

$$\text{Effect of organic farming} = (V - \text{bias}) - M \quad (2)$$

where V is the mean value of the predicted SOC (conventionally farmed) and M is the mean value of the measured SOC (organically farmed). The *bias* refers to the systematic deviation of the mean value determined in the model validation. The *bias* can be only approximated assuming that a similar data structure of drivers and SOC in the predicted data set result in a similar *bias* as in the calibration. The *mean_diff* function from the R package *dabestr* was used to calculate the 95 % confidence interval of the effect with 5000 bootstraps resamples with bias-corrected and accelerated (BCa) adjustment. Differences were considered as significant if 95 % confidence intervals did not overlap.

2.2.2. Explanatory model

An additional random forest model was trained to predict the estimated treatment effects of the first model for the individual sites. The predictors included in the model were the measured SOC content, the duration of organic farming, the C input from organic fertilisers and the proportion of SOC enhancing crops in the crop rotation. Only sites from the BZE-LW where management-related variables were available for at least five years prior to sampling were included. This reduced the number of organically farmed croplands to 69. For the crop rotation, the

Table 1

Predictors used in the model for predicting SOC content and stock under conventional croplands.

Predictor	Unit/expression
Geological bedrock	16 classes
Large-scale soil landscapes	35 classes
Soil climate regions	49 classes
Soil fertility value ("Bodenzahl")	—
C:N ratio	—
Geomorphographic units	21 classes
Slope	°
Elevation	m
Total annual precipitation	mm
Annual number of summer days	—
Annual sunshine duration	h
Minimum air temperature	°C
Sand content	Mass %
Clay content	Mass %
Topographic wetness index	—

main crops were categorised as “SOC enhancing”, “SOC depleting” and “neutral” (see Tab. S3 in the Supplement) (Körschens et al., 2004; Panagea et al., 2025). The classification is based on the amounts of crop residues from above ground biomass and roots. Mostly perennial crops such as fodder legumes produce large amounts of crop residues and are thus classified as SOC enhancing. The importance of the predictors and the partial dependence plots were created for the resulting model as described above.

Beside the explanatory model, drivers for differences between organic and conventional croplands were assessed including the so-called yield gap. The yield gap between conventional and organic farming was calculated across all sites i for each crop type j as

$$\text{yield gap}_j(\%) = \sum_{i=0}^n \frac{1}{n} \left(1 - \frac{\text{Yield organic } i}{\text{Yield conventional } i} \right) 100\% \quad (3)$$

Since we did not use reciprocal modelling here, site variability between the two farming systems remains unaccounted for.

3. Results

3.1. Modelling of pedo-climatic effects on soil carbon

The models for the SOC content and SOC stock were trained to account for pedo-climatic influences between sites in order to be able to quantify organic farming effects (subsection 3.2). The models reached an R^2 of 0.50 and 0.55, respectively (Table 3). The model performance indicators were always slightly better for the SOC stock model compared to the SOC content model. The bias was low for both models.

The range of the SOC contents and SOC stocks was lower in the model predictions than in the measurements. The predicted SOC content ranged from 7.9 to 40.5 g kg^{-1} and from 2.7 to 78.5 g kg^{-1} in the measurements (Fig. 5). The predicted SOC stocks ranged from 36.0 to 144.4 Mg ha^{-1} , while the measured SOC stocks were between 15.1 and 226.1 Mg ha^{-1} . There are two potential reasons for the smaller range of prediction values: first, by trimming the sites of the organic farming sites to match the range of predictors in the conventional farming site, we may be inadvertently removing the most extreme values. Second, many statistical models tend to regress towards the mean (i.e., croplands with low SOC content and SOC stocks were overestimated by the model, while croplands with high SOC content and SOC stocks were underestimated); ensemble algorithms like random forest reduce this regression, but it is still present (Fig. 5). However, the average predicted SOC content and SOC stock were similar to the measured average values: The

measured SOC content averaged 16.2 g kg^{-1} , while the model predicted 16.3 g kg^{-1} . For the SOC stocks, the mean values were 64.0 Mg ha^{-1} in the measurements and 64.3 Mg ha^{-1} in the predictions. Moreover, there was no regional specific bias (Supplement Fig. S2). This indicates that while individual data points may carry a range of uncertainties depending on where in the predictor range the site falls, average values for the group were predicted with high accuracy.

The C:N ratio was the predictor with the largest influence on the predictions in the model, followed by the clay and sand content (Fig. 6). The SOC contents and the SOC stocks increased with increasing clay contents and C:N ratios and decreased with increasing sand contents (Fig. 7). Since the SOC curve is rather flat but sand is important to the model performance, sand is likely interacting with some other important variable such as the clay content. The elevation range between 50 and 350 m.a.s.l. showed decreased SOC as compared to lower and higher elevations. The comparison between the models for SOC content and SOC stock also shows that the six most important predictors were identical in both models.

3.1.1. Independent validation (HumusKlimaNetz dataset)

For validation the model was applied to the independent dataset from the HumusKlimaNetz project. Results showed a similar model quality as in the cross-validation of the BZE-LW dataset (Table 3). The bias also remained low. Overall, it was shown that the model maintained a similar model performance when applied to the independent validation data.

The variability of the predicted SOC contents was lower (9.3 to 36.3 g kg^{-1}), than that of the measured values (7.9 to 67.4 g kg^{-1}). Nevertheless, the mean SOC content could be modelled with high accuracy (predicted: 18.2 g kg^{-1} , measured: 18.8 g kg^{-1}). There were no regional patterns of underestimation or overestimation (Suppl. Fig. S5).

3.2. Soil carbon differences between organic and conventional farming

In order to quantify the influence of organic farming on SOC, the model trained on all conventionally farmed croplands of the BZE-LW was applied to the organically farmed croplands. Using this approach, the SOC content and SOC stock under conventional farming were predicted for these organically farmed sites and compared with the measured values. We found no significant differences for SOC contents or for SOC stocks between conventional farming and organic farming (Fig. 8A). The average SOC content estimated for conventional farming was 16.7 g kg^{-1} , compared to a measured 16.0 g kg^{-1} in organic

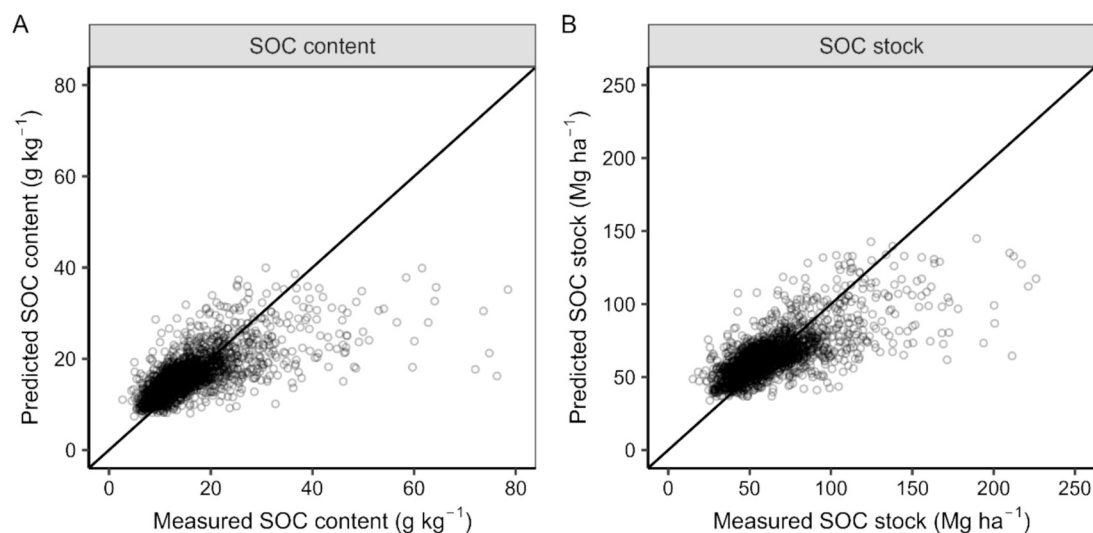


Fig. 5. Scatter plot of the measured and predicted values of the SOC content (A) and the SOC stock (B) of the conventionally farmed arable land of the BZE-LW. The diagonal line shows an exact match between measured and predicted values.

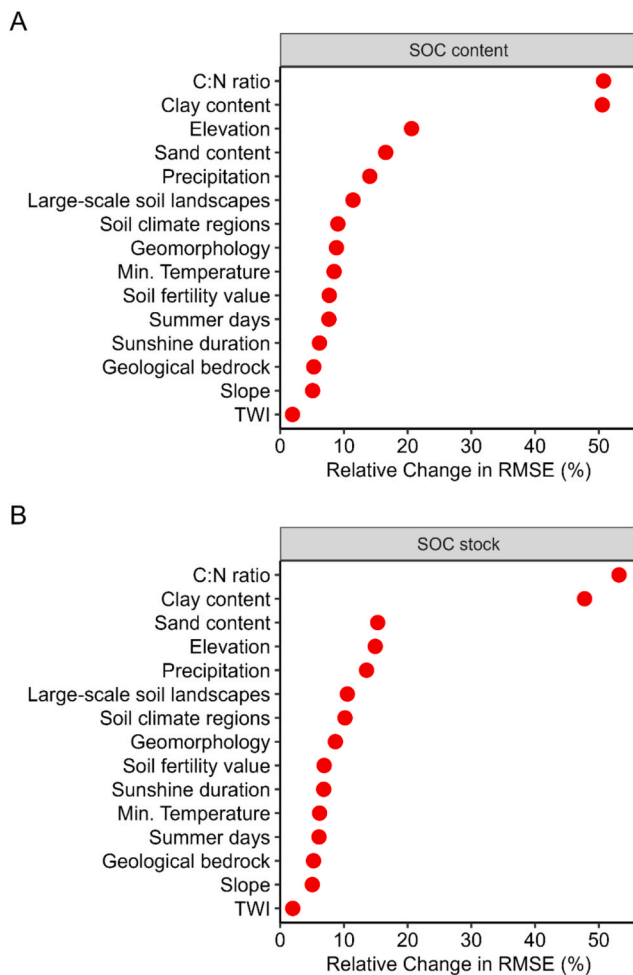


Fig. 6. Importance of the predictors of the models for SOC content (A) and SOC stock (B) expressed as the relative change in RMSE (%) due to the permutation of the predictor. TWI: Topographic wetness index.

farming. Thus, the bias corrected average difference was 0.85 g kg^{-1} with a 95 % CI ranging from -1.17 to 2.51 . Similarly, measured SOC stocks of organic croplands were on average 64.5 Mg ha^{-1} and predicted SOC stocks 65.2 Mg ha^{-1} for conventional croplands with a bias corrected difference of 1.11 (95 %CI $-5.71, 6.93$), indicating no significant difference between the two farming systems (Fig. 8B).

To validate these findings, the independent dataset from the HumusKlimaNetz project was used with more than three times as many organically farmed croplands. Similar to the BZE-LW dataset, we found no increase in SOC contents and SOC stocks under organic farming compared to the predicted conventional reference (Fig. 9).

3.3. Underlying drivers for soil carbon differences

The estimated treatment effects, i.e. the difference between the measured organic farming minus predicted conventional farming values, represent the effect of organic farming management on SOC. An explanatory model was created to explain this effect using management factors such as crop rotation or duration of organic farming. There was a high variability in the treatment effects for the SOC content, which were both positive and negative, ranging from -19.1 g kg^{-1} to 17.5 g kg^{-1} . The models were able to explain around half of the variability (R^2 of 0.48). The measured SOC content was by far the most important predictor compared to the management factors (Suppl. Fig. S7).

As mentioned before, sites with high SOC content were underestimated by the model (positive treatment effect) and sites with low

SOC were overestimated (Fig. 10A). The measured SOC content had by far the strongest effect on the treatment effects (Suppl. Fig. S7). That is why other drivers should be interpreted carefully, taking into account their lower contributions to the explained variance of the model. The treatment effect increased with increasing duration of organic farming, indicating that SOC decreases the longer a site is managed organically. No clear consistent effect of organic amendments was found in the model to explain the differences between measured and predicted SOC (Fig. 10). The average C input from organic fertilisation differed only slightly between organic and conventional farming in the BZE-LW dataset with $0.47 \text{ Mg C ha}^{-1} \text{ a}^{-1}$ for organically farmed croplands and $0.45 \text{ Mg C ha}^{-1} \text{ a}^{-1}$ for conventional (Fig. 11). A comparable fraction of sites in both farming systems received no organic fertiliser at all: 33 % of organic and 28 % of conventional croplands. The proportion of farms without livestock was also comparable with 29 % in organic farming and 32 % in conventional farming.

Another key management factor is the crop rotation with the proportion of SOC depleting (e.g. potatoes and sugar beet) and SOC enhancing crops (e.g. clover grass and forage legumes). In organic farming, the proportion of SOC enhancing crops was significantly higher in the crop rotations than in conventional farming (Fig. 12). In organic farming 39 % of the crops were SOC enhancing but only 11 % in conventional farming. The proportion of SOC depleting crops was 7 % in conventional farming and 4 % in organic farming. On 60 % of the conventionally farmed croplands no SOC enhancing crops were cultivated at all in the last five to ten years prior to sampling. In organic farming, cover crops were cultivated in 14 % of the crop-years and in conventional farming in 11 % of the crop-years.

The yield of the crops is an important indicator of the C input to the soil through the harvest residues (Jacobs et al., 2020). For all crop types, organic farming achieved lower yields compared to conventional farming with an average decrease of -31 % across all crop types weighted according to their abundance in German croplands (Fig. 13). This so-called yield gap varied depending on the crop type in the range of -14 to -46 %: The largest differences were found in potatoes (-46 %) and winter wheat (-40 %), the smallest in winter oilseed rape (-14 %) and fodder legumes (-19 %).

4. Discussion

4.1. How well can site-specific differences in soil carbon be modelled?

The models were able to explain around 50 % of the variance in the SOC content and SOC stocks of the Germany-wide soil inventories using pedo-climatic drivers (Tables 2 and 3). Such model performance is comparable to other studies at similar scale that also used statistical approaches such as machine learning algorithms to predict SOC (Emadi et al., 2020; Sakhaee et al., 2021; Vos et al., 2019; Wiesmeier et al., 2013). The prediction errors did not show any regional patterns (Suppl. Fig. S4 and S5), which indicates site-specific and not regional-specific uncertainties in the predictions. The large uncertainty in large scale SOC modelling may be due to long-term impacts on SOC that are not captured by static predictors: land-use change has been shown to influence SOC stocks for more than one century (Emde et al., 2024) and erosion can also change small-scale conditions of topography that is relevant for SOC (Lin et al., 2022). There may be also other factors at play that we have not captured in our dataset and thus not in our models. Our models included site specific soil data as predictors such as the clay content and the C:N ratio (Fig. 6). The C:N ratio serves as indicator for formal land use as heathland or peatland that left large amount of rather recalcitrant SOC and thus increase SOC (Springob and Kirchmann, 2003). It is rather unusual to use a predictor that could potentially be influenced by the treatment. However, the impact of the land use history is by far more important for the C:N ratio than any possible effects of current management. This can be also seen by the missing correlation between C:N ratio and SOC content (Fig. S8). Modelling based solely on

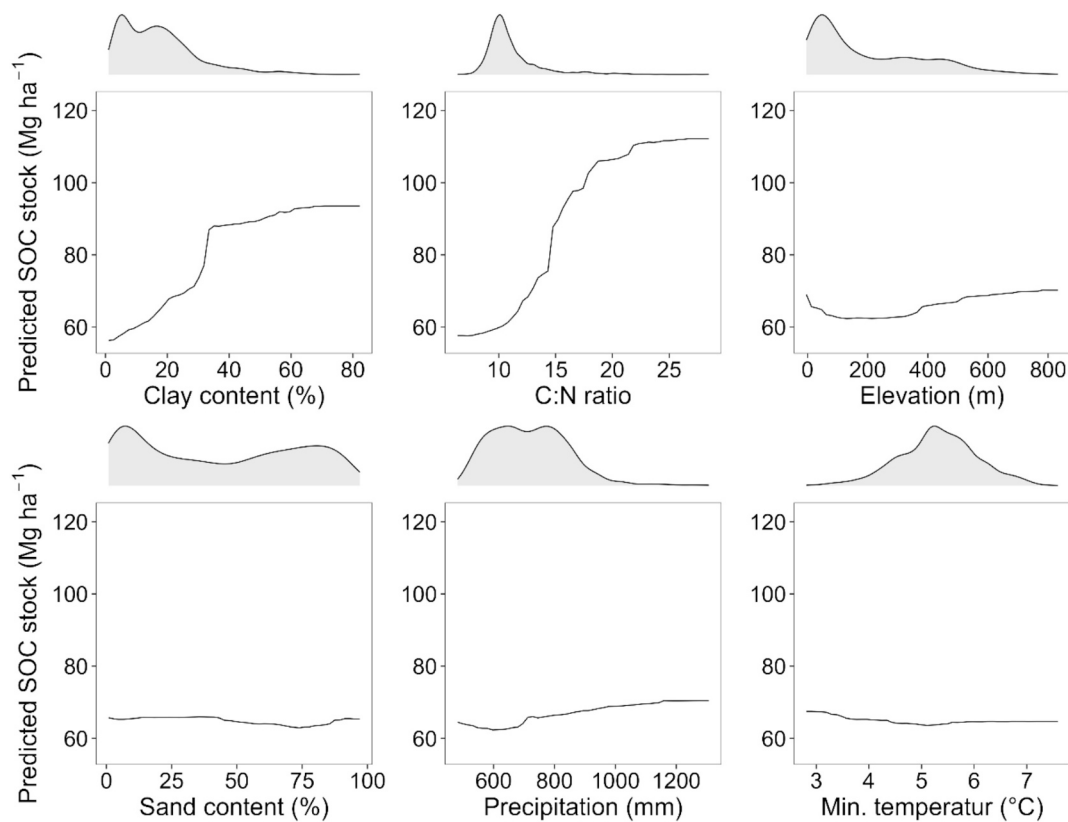


Fig. 7. Partial dependence plots showing the modelled response of the SOC stock on the individual predictors. The density distributions above show the distribution of the predictors in the training data (cropland in conventional farming of the BZE-LW, $n = 2060$). The same figure for SOC content can be found in the supplement (S6).

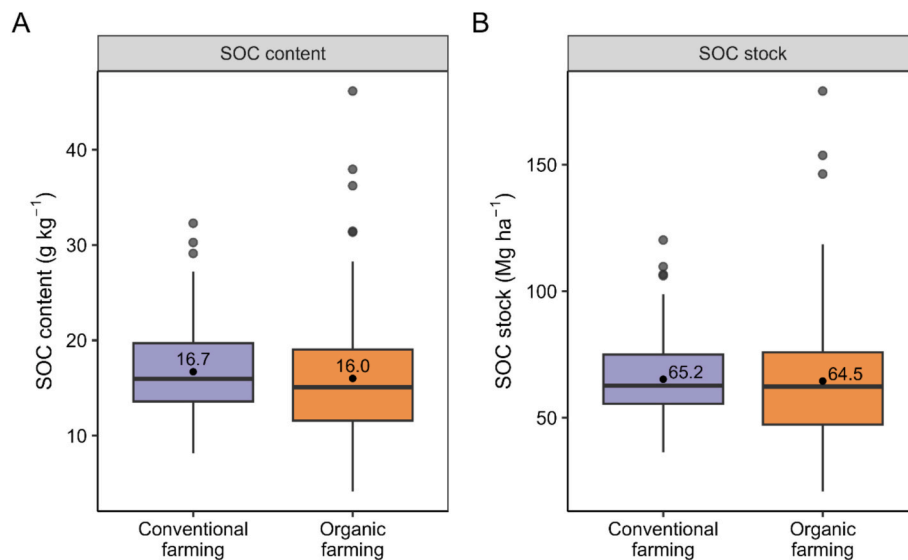


Fig. 8. Comparison of the SOC content (A) and SOC stock (B) of the prediction for conventional farming and the measurement in organic farming at 99 sites in the BZE-LW dataset. The model bias was subtracted from the mean values of the predictions.

geodata and without these measured soil properties led to lower model performance (SOC content: $R^2 = 0.30$; SOC stock: $R^2 = 0.33$, [Suppl. Tab. S5](#)). This illustrates the uncertainty in geodata insufficiently capturing site specific soil conditions. In the independent validation with the data from the HumusKlimaNetz, a similar model performance was achieved as in the cross-validation within the BZE-LW data ([Table 3](#)). This indicates that the model is not overfitted and captures the most important

site-specific variables influencing SOC. Moreover, the site conditions between organic and conventional sites were rather similar ([Figs. 3 and 4](#)) and thus only minor site-adjustments are required with our model approach.

A typical feature of modelling with the *RandomForest* algorithm is the regression to the mean ([Zhang & Lu, 2012](#)). With this model, it is therefore not intended to predict SOC at the individual sites due to their

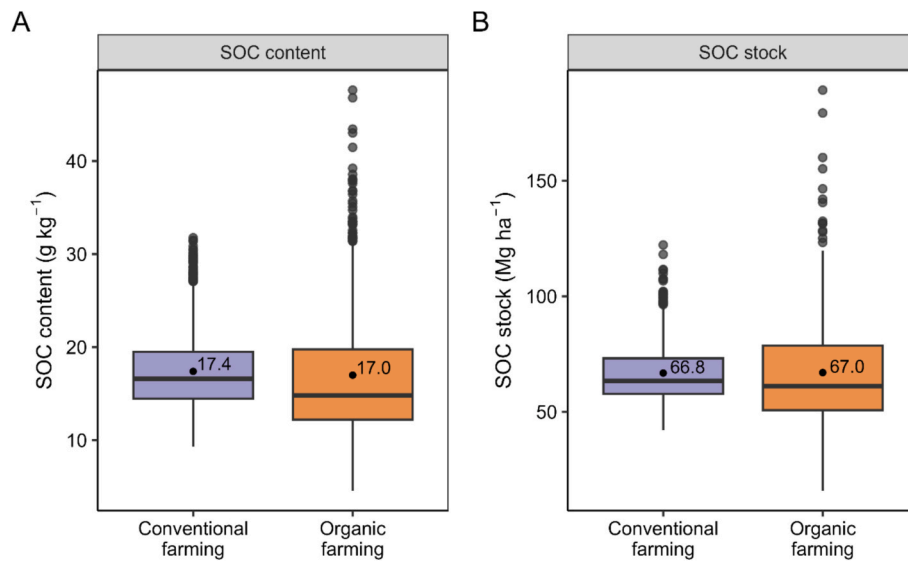


Fig. 9. Comparison of the SOC content of the prediction for conventional farming and the measurement in organic farming for 464 sites of the HumusKlimaNetz dataset. The model bias was subtracted from the mean values of the predictions.

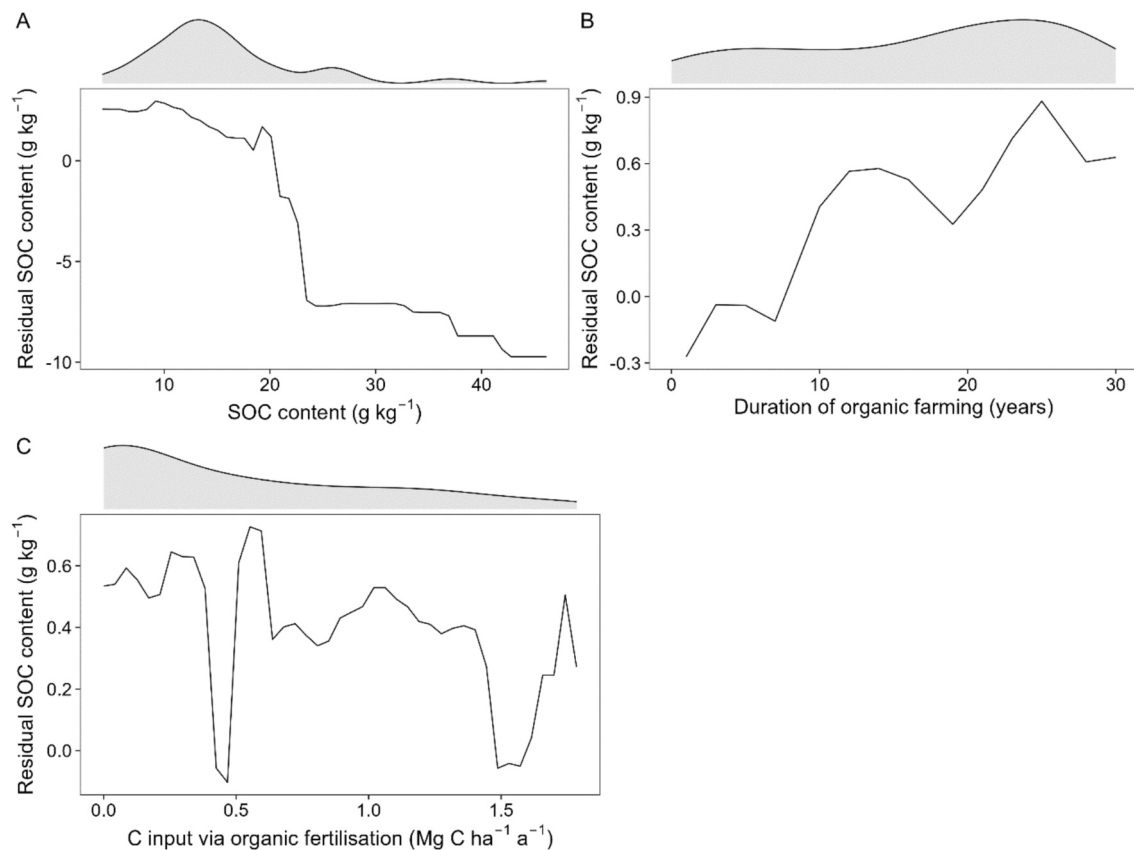


Fig. 10. Partial dependence of the estimated treatment effects of the model in g kg^{-1} on the individual predictors in the explanatory model. The density distributions above show the distribution of the predictors in the training data (cropland in organic farming of the BZE-LW, $n = 65$). Residuals were calculated organic farming (measured) – conventional farming (predicted).

high uncertainty at site scale. In contrast, the effect of organic farming was assessed across all sites, where the impact of over- and underestimation at the extremes is likely to compensate for each other. It is therefore only possible to conclude on the average practice of organic farming in Germany and leaves open the questions of why individual organically farmed croplands behave differently from the average.

Individual organic farms were indeed able to build-up SOC in comparison to conventional farms as shown by the distribution of the SOC data. Some indications are derived from the explanatory model (Fig. 10) but variability due to the interplay between pedoclimatic variables and decadal soil management remains large. Despite some large differences between measured and predicted values on individual cropland sites,

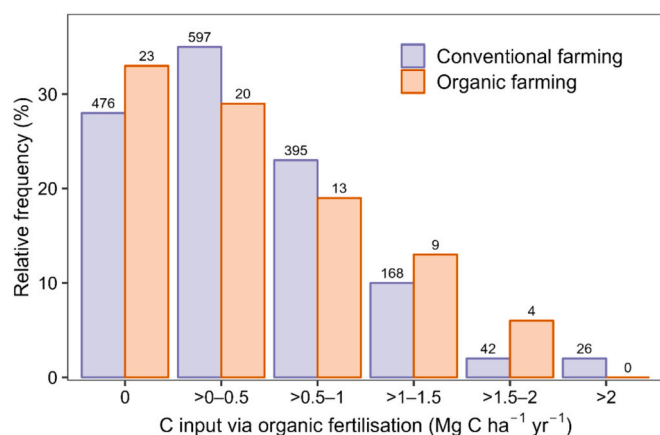


Fig. 11. C input to the soil via organic fertilisation at organically and conventionally farmed cropland in classes. The numbers above the bars indicate the number of croplands per class.

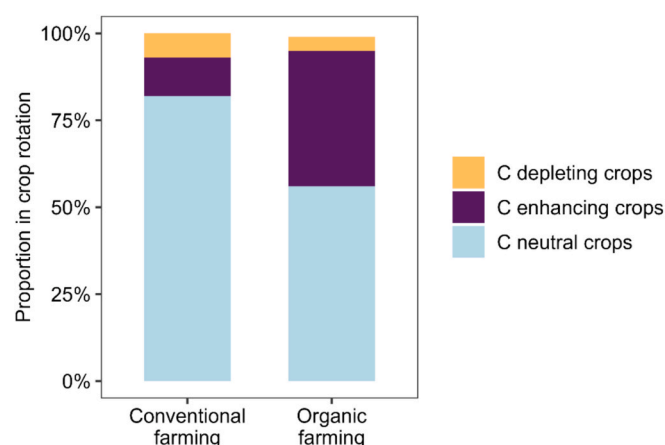


Fig. 12. Proportions of SOC depleting, SOC enhancing and neutral crops in the crop rotations in organic farming ($n = 69$) and conventional farming ($n = 1702$). For the definition of the classes see Table S3 in the supplement.

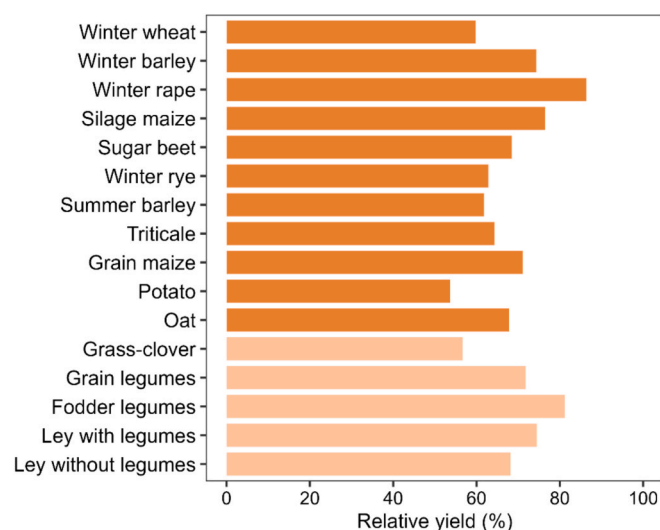


Fig. 13. Relative yields of different crops in organic farming compared to yields in conventional farming (100 %). Results for forage crops (light bars) have high uncertainties due to a small sample size with less than 50 sampling-years.

the model bias was low (Tables 2 and 3) indicating that differences in SOC due to pedo-climatic drivers could be well predicted on average despite the skewed distribution of the data. There are methodological and data-related limitations that we were not able to overcome and include possible unobserved confounding variables. However, the results were tested in various different model versions and resulted in all these versions in similar results, which could be thus considered as robust (see Suppl. Tab. S5).

The simple bootstrap approach generated large 95 % confidence intervals of the treatment effects that ranged across zero. Thus, indicating no statistical differences between the two farming systems. However, the large confidence intervals also show the limitations of this approach to detect statistically significant treatment effects. The large spatial variability of SOC as compared to small expected treatment effects limits approaches based on soil inventory data to determine supposing small treatment effects on SOC. Expected SOC increases of 2 to 4 Mg SOC ha⁻¹ (Gattinger et al. 2012) may not be detectable with significance with our approach. However, robustness of results can also be increased by using multiple methodological approaches (see Supplement Tab. 5) and multiple independent data sets, as it was done in our study.

4.2. Why does organic farming not increase soil carbon?

Our study showed no significant increase in the SOC content and SOC stocks of cropland as a result of organic farming (Figs. 8 and 9). Additionally, our data suggest that a potential SOC build-up under organic farming is not a question of the duration of organic farming or that the duration may have been insufficient in our data sets. On the contrary, SOC appeared to decline the longer the soil was farmed organically (Fig. 10).

These findings contradict the results of other studies that found an increase in SOC due to organic farming. For example, in a meta-analysis, Gattinger et al. (2012) showed an average 1.8 g kg⁻¹ higher SOC content and 3.5 Mg ha⁻¹ higher SOC stock in organic farming compared to conventional farming. Overall, previous meta-analyses showed an increasing effect of organic farming on SOC compared to conventional farming (Aguilera et al., 2013; Alvarez, 2022a; Bai et al., 2018; García-Palacios et al., 2018; Gattinger et al., 2012; Leifeld & Fuhrer, 2010; Smith et al., 2019; Tuomisto, Hodge, Riordan, & Macdonald, 2012), although the difference was not significant in one of the studies (Leifeld & Fuhrer, 2010). A key difference between our study and the previous studies is that our study analysed data from the agricultural practice of a country. In the meta-analyses, mainly field experiments were analysed that may not necessarily be representative of organic farming at large. For example, yields in field experiments are often higher than on farms (Kravchenko et al., 2017). There is ongoing discussion about how to compare the results of field trials with active farm systems; moreover, which management factors are representative of organic and conventional farming (Kirchmann et al., 2016; Leifeld et al., 2013). A recent study on 53 cropland sites managed according to regional, agricultural practice in the Netherlands covering both organic and conventional farms, did not find differences in soil functionality and SOC between the two farming types (van Rijssel et al., 2025). Instead, they found large variability in soils functions among the sites of both systems and thus potential for improvements. In the following, several differences between organic and conventional farming measures are discussed, that are of relevance for SOC storage and might explain differences in SOC between the two farming systems.

4.2.1. Organic fertilisation in organic and conventional farming

Organic fertilisation, mostly in the form of farmyard manure and slurry, results in an increase in SOC stocks (Maillard & Angers, 2014). We showed that, on average, organic farming in Germany does not receive higher amounts of organic fertilisers compared to conventional farming. In contrast, in most field experiments comparing the two

Table 2

Model quality and error measures of the models with cross-validation of the conventionally farmed arable land of the BZE-LW.

	R ²	MSE	RMSE	MAE	MAPE	RPD	RPIQ	Bias
SOC content	0.50	34.4 (g kg ⁻¹) ²	5.8 g kg ⁻¹	3.6 g kg ⁻¹	23.3 %	1.43	1.32	0.1 g kg ⁻¹
SOC stock	0.55	309.2 (Mg ha ⁻¹) ²	17.6 Mg ha ⁻¹	12.0 Mg ha ⁻¹	19.6 %	1.49	1.55	0.3 Mg ha ⁻¹

Table 3

Model quality and error measures of the geodata-based model with application to the conventionally farmed arable land of the HumusKlimaNetz soil inventory.

	R ²	MSE	RMSE	MAE	MAPE	RPD	RPIQ	Bias
SOC content	0.47	42.8 (g kg ⁻¹) ²	6.5 g kg ⁻¹	4.6 g kg ⁻¹	26.0 %	1.37	1.51	0.4 g kg ⁻¹
SOC stock	0.40	454.7 (Mg ha ⁻¹) ²	21.3 Mg ha ⁻¹	15.4 Mg ha ⁻¹	22.7 %	1.29	1.60	0.7 Mg ha ⁻¹

systems, much more organic fertiliser is applied to the organic farming treatment than to conventionally farmed plots (Aguilera et al., 2013; Gattinger et al., 2012; Leifeld & Fuhrer, 2010). Conventional agriculture in these experiments is also often depicted without any organic fertilisation (e.g. Aguilera et al., 2013). This illustrates that experiments do not necessarily correspond to real-world agricultural practices as recorded in the BZE-LW data used in our study. Experiments in which the same amount of organic fertiliser were applied to organic and conventional cropland showed no significant differences in the SOC content or SOC stocks and thus support the results of our study (Aguilera et al., 2013; Alvarez, 2022a; Leifeld & Fuhrer, 2010).

Organic fertilisation has both a direct effect on SOC through the carbon it contains and an indirect effect through the stimulation of plant growth (Cai et al., 2018; Kätterer et al., 2012; Obour et al., 2017). Provided no mineral fertilisation was applied, Kätterer et al. (2012) estimated this indirect effect of stimulating plant growth and thus increasing C inputs via crop residues to be at least as important as the direct effect of C inputs with organic fertilisers. With increasing mineral fertilisation in addition to organic fertilisation, this indirect effect decreases as plant growth is less nutrient-limited (Kätterer et al., 2012). Since mineral fertilisation is not used in organic farming, organic fertilisation has generally stronger effects on SOC in organic farming than in conventional farming. Higher organic fertilisation in organic farming in the field experiments therefore distorts the comparison to the real-world agricultural practice. In any case, the organic fertilisation effect is or can be an import of carbon from external sources and thus require careful treatment in carbon balances (Don et al., 2024).

Surprisingly, the proportion of organic farms with animal husbandry was quite low (29 %); similar, in fact, to that in conventional farming (32 %), although organic farming is relying on organic fertilisers as a main source of nutrients. However, the BZE-LW data agreed with the data from the German agricultural structure survey in farming systems and animal husbandry (Federal Office for Agriculture and Food, 2024). The original idea of organic farming envisaged animal husbandry connected to arable farming according to the principles of the circular economy. The high proportion of livestock-free farms shows that organic farming is no longer fully implemented in line with its traditional roots. Higher organic fertilisation in organic farming than in conventional farming would, therefore, only be possible with a transfer of high quantities from external sources (Don et al., 2024).

4.2.2. Yield gap in organic farming reduces C inputs

The annual C inputs to the soil from organic fertilisation in Germany is only 12 % of the total C input (Jacobs et al., 2020). The crop residues are much more decisive for the C input into the soil, which primarily depend on plant growth and productivity (Bolinder et al., 2012). In practice, the quantity and type of crop residues are therefore key factors for SOC and differences between the systems.

The yield gap in organic farming compared to conventional farming was 31 % in our study across all crop types (Fig. 13). This indicates a relevant reduction in net primary production leading to correspondingly

reduced C inputs into the soil. The limited availability of nutrients in organically managed soils is a major factor limiting primary production, especially due to the insufficient supply of mineral nitrogen (N) during periods of strong plant growth (Berry et al., 2002). Kätterer et al. (2012) showed that SOC stocks can be significantly increased by N fertilisation. For every kilogram of N applied in the form of mineral fertiliser, the SOC stocks in Swedish long-term experiments increased by 1 to 2 kg C. In a multi-year field trial in Southern Germany, it was shown that the yield gap in organic farming can be significantly reduced by applying mineral fertilisers while continuing “organic” farming with no chemical pesticides (Claß-Mahler et al., 2023). On average over three trial years, the yield gap for winter wheat in organic farming was 62 %, while only 14 % in the treatment with mineral fertilisation and without pesticides compared to the conventional control.

The yield gap in organic farming in our study is in line with the results of global meta-analyses, which found an average yield gap of 18 % to 25 % in organic farming (Alvarez, 2022b; de la Cruz et al., 2023; de Ponti et al., 2012; Ponisio et al., 2015; Seufert et al., 2012). It depends on the growing region: In North-West Europe the yield gap was larger (27 %) than in other regions (e.g. Asia 11 %; De Ponti et al., 2012). There may also be a difference in the yield gap between field experiments and agricultural practice (Kravchenko et al., 2017). Most meta-analyses on yields contained results from field experiments and not from practice (Alvarez, 2022b; de Ponti et al., 2012; Ponisio et al., 2015; Seufert et al., 2012). Organic farming in particular relies heavily on the effectiveness of mechanical and biological measures, the success of which often depends on optimal timing. While optimal timing is usually achieved in field experiments, farms are often constrained by limited resources and a trade-off in the use of inputs (Kravchenko et al., 2017). These findings indicate that results from plot-level experiments should be interpreted with caution when extrapolating to agricultural reality, especially in organic farming.

The reduction in C input in organic farming may be lower than the reduction in yield as compared to conventional croplands as net primary production on the croplands differs less between the two farming systems than yield. This is because weed biomass can sometimes reach 1.85 Mg C ha⁻¹ in organic farming, while it is significantly lower in conventional farming (0–0.05 Mg C ha⁻¹) (Wortman et al., 2010). Weed biomass is a largely unaccounted C input to the soil. A yield reduction due to heavy weed pressure is therefore not always necessarily a disadvantage from a SOC perspective. Additionally, the harvest index (ratio of harvestable crop to plant biomass) can be lower for the cultivars in organic systems (Hirte et al., 2021), thus the crop residue fraction is not linearly and directly linked to yield.

In order to assess the extent to which the yield differences between organic and conventional farming are system-related, it is important to consider pedo-climatic site differences (Kirchmann et al., 2016). A comparison of the pedo-climatic characteristics showed minor differences between organically farmed croplands and conventional croplands and average conditions were similar (Figs. 3 and 4). In German agriculture, the soil fertility and productivity are measured using a soil

fertility index (Altermann et al., 2023). On average, there were almost no differences in these soil fertility values between the two farming systems (BZE-LW: 45 for organically and 48 for conventionally farmed croplands, HumusKlimaNetz: 45 for organically and 46 for conventionally farmed croplands). It can therefore be concluded that organic farming is not at a systematic disadvantage due to poorer soils or less favorable site conditions. The yield differences observed in this study are therefore primarily due to management.

There are considerable trade-offs between yield and soil functioning including SOC storage. Productive deintensification has been proposed as the way forward in conventional high-input farming such as in Central Europe (van Rijssel et al., 2025). For organic farming it is crucial to reduce the yield gap to conventional farms e.g. by the promotion of innovation and close-to-farm research. Possible approaches include more efficient fertilisation, the breeding of varieties that are adapted to organic farming, improved methods of biological plant protection and new active substances to regulate plant diseases (Andersen et al., 2015; van Bruggen et al., 2016). This is important, since yield gaps increase the demand for agricultural land and thus increase the pressure on natural ecosystems to be converted into agriculture (Kirchmann, 2019). On the other hand, only 28 % of cropland is used for food production in Germany, but 48 % is used for fodder production, 21 % for renewable biomass (mainly bioenergy) and 3 % is set aside (Osterburg et al. 2023). Thus, reduced yield with organic farming could be compensated by reducing the demand for non-food purposes or animal-based products.

4.2.3. Crop rotation in organic farming promotes soil carbon

Crop rotations in organic farming should promote SOC accrual more strongly than conventional crop rotations, as more SOC-enhancing crops are grown such as grass-clover and perennial forage legumes (Fig. 12). Higher proportions of these crops are commonplace for organic farming, as these crops fulfil several crucial functions on which organic farming depends: supply of N with leguminous crops and the prevention of plant diseases and weed control (Hoeffner et al., 2021; Kayser et al., 2010; Zani et al., 2021). The reason for the positive effect of grass-clover and other perennial forage legumes on SOC lies primarily in the high root biomass and the overall high C input to the soil (Bolinder et al., 2012; Johnston et al., 2017). This results in a higher proportion of the C input as below ground C input which particularly supports the build-up of SOC (Rasse et al., 2005). Perennial crops in rotation also ensure that the period without vegetation is reduced which enhances the net primary production (Kätterer et al., 2012). In addition, the yield gap in organic farming tends to be smaller for legumes and perennial crops as N-fixing plants are less dependent on external N-sources and therefore have an advantage in organic farming compared to other crops (Seufert et al., 2012). This lower yield gap could not be found in our data (Fig. 13), since these fodder crops are often used for the farmers' own animal feed and rarely sold; yield data are often not determined accurately by the farmers in such circumstances. This makes the data in the BZE-LW particularly imprecise. Other studies show a lower yield gap for grass-clover (de Ponti et al., 2012) than our data showed. Also, the small sample size (51 years of cultivation at 21 croplands) suggests that the BZE-LW data are not representative (Fig. 13).

The cultivation of cover crops can increase primary production on cropland, leading to an increase in SOC (Poeplau & Don, 2015). The BZE-LW data shows that cover crops are cultivated on organically farmed croplands with a similar frequency as in conventional systems (14 % and 11 % of cultivation years respectively). In Germany, cover crops are therefore neither system-specific for organic farming nor for conventional farming.

No analysis of root biomass was carried out in our study, and published studies report ambiguous results on the influence of organic farming on root formation. Some studies found that organic farming fosters the investment of plants into roots despite reduced above-ground biomass and yields (Chirinda et al., 2012; Głąb et al., 2016; Pallant et al., 1997). To our knowledge, only one study has examined root biomass

differences between the two systems on farms, rather than solely in field experiments (Hirte et al., 2021). In this study from Switzerland, a 40 % increase in root biomass under organic farming was found compared to conventional farms. Other studies found no difference in root biomass between the two systems (Hirte et al., 2018; Steingrobe et al., 2001).

4.2.4. N mining and soil microbial response

Nitrogen-poor systems can trigger soil microbial communities to decompose stabilized soil organic matter in order to gain additional N – so called N-mining (Craine et al., 2007; Finn et al., 2018). In two long-term field experiments with different historic N-fertilisation trials, Mahal et al. (2019) showed that differences in net primary productivity between fertilised and unfertilised treatments did not explain the reducing effect of N fertiliser on SOC mineralisation. In contrast, microbial activity was directly affected by N fertilisation. Nitrogen-limiting soil conditions were shown to result in increased transcription of genes involved in SOC mineralisation such as cellulase (Finn et al., 2018). Nitrogen availability also affects the microbial carbon use efficiency (CUE), which is the ratio between microbial growth (biosynthesis) and respiration and represents the buildup of C in microbial biomass (Manzoni et al., 2012). Higher nutrient availability increased CUE can therefore ensure that a larger proportion of the C input to the soil is stabilised. Poeplau et al. (2019) showed increases in SOC stocks of fertilised grassland compared to unfertilised grassland along with higher CUE. Fertilisation therefore shows advantages for the build-up of SOC in two respects at microbial scale. However, the total greenhouse gas balance of the soil that includes N₂O emissions that are strongly related to N fertilisation and thus are lower under organic farming as compared to conventional farming (Skinner et al. 2019). The greenhouse gas emissions per product are less or not at all different between the two farming systems (Tuomisto et al. 2012).

5. Conclusions

The results of this study suggest that organic farming in the actual applied form is no strategy for promoting SOC in comparison to intensive conventional farming systems of Central Europe. Comparable SOC stocks are achieved in both, organic and conventional farming systems but most likely through distinct pathways: In organic farming, crop rotations are used that contain on average significantly more SOC promoting crops than in conventional farming. These crops are notable for their high C input to the soil through roots, root exudates and above-ground biomass, although the latter is typically removed and used as fodder in livestock farming. In conventional agriculture, the build-up of SOC is achieved through the intensive use of mineral fertilisers. Compared to the 1950 s, N-fertilisation almost tripled in Germany (Rahlf, 2022). This was accompanied by a doubling of average crop yields, flanked by innovations in technologies. However, the massive use of N fertilisers results in considerable environmental damage due to the loss of N compounds to other ecosystems, e.g. as nitrate leaching into groundwater and other water bodies, ammonia emissions or emissions of the greenhouse gas nitrous oxide (de Vries et al., 2024). These N losses are threatening adjacent ecosystems and biodiversity and are thus not sustainable. Conventional high input agriculture, on the other hand, achieves high yields that lead to lower area footprint and thus reduce the pressure on natural ecosystems (Kirchmann et al., 2016). Both, organic and conventional agriculture have advantages and disadvantages in addressing the three major challenges in agriculture: food security, climate crisis and biodiversity crisis. The aim of sustainable agriculture must be to develop and implement systems that support the key environmental, biodiversity and climate goals as well as yield. Changing climate conditions impose additional challenges for agriculture. Maintaining soil functions is becoming increasingly important for a sustainable and resilient agriculture. Many soil functions are closely linked to SOC (Kopittke et al., 2022). A loss of SOC is therefore always accompanied by reduced soil functions, resulting in possible negative feedback

on crop production and soil protection. A sustainable farming strategy must therefore address SOC as an important indicator for soil health.

CRedit authorship contribution statement

Axel Don: Writing – review & editing, Writing – original draft, Methodology, Data curation, Conceptualization. **Kimberley Brügge:** Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **David Emde:** Writing – review & editing, Methodology. **Konstantin Aiteew:** Writing – review & editing, Data curation. **Christopher Poeplau:** Writing – review & editing, Data curation.

Funding

This study has been co-funded by the European Union's Horizon 2020 research and innovation programme under grant agreement No 862695 EJP SOIL and by the German Federal Ministry of Food and Agriculture via the Federal Office for Food and Agriculture in the model and demonstration project HumusKlimaNetz.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We thank Florian Schneider for his support with the modelling and Jenny Feilke, Gunda Schrader and Johanna Ohlms for their support in working with the BZE-LW data and the farmers.

We would like to thank the BZE-LW team for providing the data basis for this study and the German Federal Ministry of Agriculture, Food and Regional Identity BMLEH for funding. For the data from the HumusKlimaNetz project, we would like to thank our colleagues from the German Farmers' Association (DBV), the German Federation of Organic Food Producers (BÖLW) and the Thünen Institute.

We would also like to thank all participating farmers from the HumusKlimaNetz and the BZE-LW, who have made this study possible through their cooperation, provision of data and sampling authorisations.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.geoderma.2025.117634>.

Data availability

The soil data from the BZE-LW are open-access available at <https://doi.org/10.3220/DATA20200203151139>. The data from the HumusKlimaNetz are available on request. Farm-specific management data cannot be shared due to data protection laws.

References

- Aguilera, E., Lassaletta, L., Gattinger, A., Gimeno, B.S., 2013. Managing soil carbon for climate change mitigation and adaptation in Mediterranean cropping systems: a meta-analysis. *Agric. Ecosyst. Environ.* 168, 25–36. <https://doi.org/10.1016/j.agee.2013.02.003>.
- Altermann, M., Friedrich, K., Gehrt, E., Nestroy, O., 2023. Bodenschätzung in Deutschland und Österreich. In: Joisten, B., Giani, L., Kochan, N., Kühn, D., Sauer, D., Schad, P., Sponagel, H. (Eds.), *Böden Deutschlands, Österreichs Und Der Schweiz: Ein Bildatlas*. Springer, Berlin Heidelberg, Berlin, Heidelberg, pp. 55–60.
- Alvarez, R., 2022a. Comparing productivity of organic and conventional farming systems: a quantitative review. *Arch. Agron. Soil Sci.* 68 (14), 1947–1958. <https://doi.org/10.1080/03650340.2021.1946040>.
- Alvarez, R., 2022b. Organic farming does not increase soil organic carbon compared to conventional farming if there is no carbon transfer from other agroecosystems. A meta-analysis. *Soil Res.* 60 (3), 211–223. <https://doi.org/10.1071/sr21098>.
- Andersen, M.M., Landes, X., Xiang, W., Anyshchenko, A., Falhof, J., Osterberg, J.T., Palmgren, M.G., 2015. Feasibility of new breeding techniques for organic farming. *Trends Plant Sci.* 20 (7), 426–434. <https://doi.org/10.1016/j.tplants.2015.04.011>.
- Bai, Z., Caspari, T., Gonzalez, M.R., Batjes, N.H., Mäder, P., Bünemann, E.K., Tóth, Z., 2018. Effects of agricultural management practices on soil quality: a review of long-term experiments for Europe and China. *Agric. Ecosyst. Environ.* 265, 1–7. <https://doi.org/10.1016/j.agee.2018.05.028>.
- Berry, P.M., Sylvester-Bradley, R., Philipps, L., Hatch, D.J., Cuttle, S.P., Rayns, F.W., Gosling, P., 2002. Is the productivity of organic farms restricted by the supply of available nitrogen? *Soil Use Manag.* 18 (s1), 248–255. <https://doi.org/10.1111/j.1475-2743.2002.tb00266.x>.
- Bolinder, M.A., Katterer, T., Andren, O., Parent, L.E., 2012. Estimating carbon inputs to soil in forage-based crop rotations and modeling the effects on soil carbon dynamics in a Swedish long-term field experiment. *Can. J. Soil Sci.* 92 (6), 821–833. <https://doi.org/10.4141/cjss2012-036>.
- Cai, A., Zhang, W., Xu, M., Wang, B., Wen, S., Shah, S.A.A., 2018. Soil fertility and crop yield after manure addition to acidic soils in South China. *Nutr. Cycl. Agroecosyst.* 111 (1), 61–72. <https://doi.org/10.1007/s10705-018-9918-6>.
- Chaney, K., Swift, R.S., 1984. The influence of organic-matter on aggregate stability in some British soils. *J. Soil Sci.* 35 (2), 223–230. <https://doi.org/10.1111/j.1365-2389.1984.tb00278.x>.
- Chirinda, N., Olesen, J.E., Porter, J.R., 2012. Root carbon input in organic and inorganic fertilizer-based systems. *Plant Soil* 359 (1), 321–333. <https://doi.org/10.1007/s11104-012-1208-5>.
- Claß-Mahler, I., Zimmermann, B., Hermann, W., Schwarz, J., Piepho, H.-P., Lewandowski, I., Bahrs, E., 2023. Yield potential of cropping systems without chemical synthetic plant protection products in NOcsPS field trials in Germany. *Landbauforschung* 72 (1).
- Craine, J.M., Morrow, C., Fierer, N., 2007. Microbial nitrogen limitation increases decomposition. *Ecology* 88 (8), 2105–2113. <https://doi.org/10.1890/06-1847.1>.
- de la Cruz, V.Y.V., Tantriani, Cheng, W., Tawaray, K., 2023. Yield gap between organic and conventional farming systems across climate types and sub-types: a meta-analysis. *Agric. Syst.* 211, 103732. <https://doi.org/10.1016/j.agry.2023.103732>.
- de Ponti, T., Rijk, B., van Ittersum, M.K., 2012. The crop yield gap between organic and conventional agriculture. *Agric. Syst.* 108, 1–9. <https://doi.org/10.1016/j.agry.2011.12.004>.
- de Vries, W., Posch, M., Simpson, D., de Leeuw, F., van Grinsven, H.J.M., Schulte-Uebbing, L.F., Ros, G.H., 2024. Trends and geographic variation in adverse impacts of nitrogen use in Europe on human health, climate, and ecosystems: a review. *Earth Sci. Rev.* 253. <https://doi.org/10.1016/j.earscirev.2024.104789>.
- Don, A., Seidel, F., Leifeld, J., Kätterer, T., Martin, M., Pellerin, S., Chenu, C., 2024. Carbon sequestration in soils and climate change mitigation—definitions and pitfalls. *Glob. Chang. Biol.* 30 (1), e16983. <https://doi.org/10.1111/gcb.16983>.
- Emadi, M., Taghizadeh-Mehrjardi, R., Cherati, A., Danesh, M., Mosavi, A., Scholten, T., 2020. Predicting and mapping of soil organic carbon using machine learning algorithms in northern Iran. *Remote Sens. (Basel)* 12 (14). <https://doi.org/10.3390/rs12142234>.
- Emde, D., Poeplau, C., Don, A., Heilek, S., Schneider, F., 2024. The centennial legacy of land-use change on organic carbon stocks of German agricultural soils. *Glob. Chang. Biol.* 30 (8). <https://doi.org/10.1111/gcb.17444>.
- European Commission. (2020). *A Farm to Fork Strategy for a fair, healthy and environmentally-friendly food system*. Retrieved from Brussels.
- Eurostat. (2025). *Organic crop area by agricultural production methods and crops*. Federal Office for Agriculture and Food. (2024). *Strukturdaten zum Ökologischen Landbau in Deutschland*. Retrieved from: https://www.ble.de/DE/Themen/Landwirtschaft/Oekologischer-Landbau/functions/StrukturdatenOekolandbau_table.html.
- Finn, D., Catton, K., Heenan, M., Kopittke, P.M., Ouwkerk, D., Klieve, A.V., Dalal, R.C., 2018. Differential Gene Expression in the Model Actinomycete *Streptomyces coelicolor* A3(2) Supports Nitrogen Mining Dependent on the Plant Carbon to Nitrogen Ratio. *Agriculture* 8 (12). Retrieved from doi:10.3390/agriculture8120192.
- García-Palacios, P., Gattinger, A., Bracht-Jorgensen, H., Brussaard, L., Carvalho, F., Castro, H., Milla, R., 2018. Crop traits drive soil carbon sequestration under organic farming. *J. Appl. Ecol.* 55 (5), 2496–2505. <https://doi.org/10.1111/1365-2664.13113>.
- Gattinger, A., Muller, A., Haeni, M., Skinner, C., Fliessbach, A., Buchmann, N., Niggli, U., 2012. Enhanced top soil carbon stocks under organic farming. *Proc. Natl. Acad. Sci. USA* 109 (44), 18226–18231. <https://doi.org/10.1073/pnas.1209429109>.
- Gaudaré, U., Kuhnert, M., Smith, P., Martin, M., Barbieri, P., Pellerin, S., Nesme, T., 2023. Soil organic carbon stocks potentially at risk of decline with organic farming expansion. *Nat. Clim. Change*. <https://doi.org/10.1038/s41558-023-01721-5>.
- Gerke, J., 2022. The central role of soil organic matter in soil fertility and carbon storage. *Soil Syst.* 6 (2), 33.
- German Federal Ministry of Agriculture. (2024). *Bio-Strategie 2030*. Retrieved from Berlin.
- Głab, T., Puzyńska, K., Puzyński, S., Palmowska, J., Kowalik, K., 2016. Effect of organic farming on a Stagnic Luvisol soil physical quality. *Geoderma* 282, 16–25. <https://doi.org/10.1016/j.geoderma.2016.07.008>.
- Hirte, J., Leifeld, J., Abiven, S., Oberholzer, H.-R., Mayer, J., 2018. Below ground carbon inputs to soil via root biomass and rhizodeposition of field-grown maize and wheat at harvest are independent of net primary productivity. *Agric. Ecosyst. Environ.* 265, 556–566.
- Hirte, J., Walder, F., Hess, J., Büchi, L., Colombi, T., van der Heijden, M.G., Mayer, J., 2021. Enhanced root carbon allocation through organic farming is restricted to

- topsoils. *Sci. Total Environ.* 755, 143551. <https://doi.org/10.1016/j.scitotenv.2020.143551>.
- Hoefner, K., Beylich, A., Chabbi, A., Cluzeau, D., Dascalu, D., Graefe, U., Pérès, G., 2021. Legacy effects of temporary grassland in annual crop rotation on peat ecosystem services. *Sci. Total Environ.* 780, 146140. <https://doi.org/10.1016/j.scitotenv.2021.146140>.
- Hudson, B.D., 1994. Soil organic-matter and available water capacity. *J. Soil Water Conserv.* 49 (2), 189–194.
- Jacobs, A., Flessa, H., Don, A., Heidkamp, A., Prietz, R., Dechow, R., . . . Freibauer, F. (2018). *Landwirtschaftlich genutzte Böden in Deutschland – Ergebnisse der Bodenzustandserhebung*. Retrieved from Braunschweig.
- Jacobs, A., Poeplau, C., Weiser, C., Fahrion-Nitschke, A., Don, A., 2020. Exports and inputs of organic carbon on agricultural soils in Germany. *Nutr. Cycl. Agroecosyst.* 118 (3), 249–271. <https://doi.org/10.1007/s10705-020-10087-5>.
- Janzen, H.H., 2004. Carbon cycling in earth systems—a soil science perspective. *Agric. Ecosyst. Environ.* 104 (3), 399–417. <https://doi.org/10.1016/j.agee.2004.01.040>.
- Johnston, A.E., Poulton, P.R., Coleman, K., Macdonald, A.J., White, R.P., 2017. Changes in soil organic matter over 70 years in continuous arable and ley–arable rotations on a sandy loam soil in England. *Eur. J. Soil Sci.* 68 (3), 305–316. <https://doi.org/10.1111/ejss.12415>.
- Kätterer, T., Bolinder, M.A., 2024. Response of maize yield to changes in soil organic matter in a Swedish long-term experiment. *Eur. J. Soil Sci.* 75 (2). <https://doi.org/10.1111/ejss.13482>.
- Kätterer, T., Bolinder, M.A., Berglund, K., Kirchmann, H., 2012. Strategies for carbon sequestration in agricultural soils in northern Europe. *Acta Agric. Scand. Sect. A-Anim. Sci.* 62 (4), 181–198. <https://doi.org/10.1080/09064702.2013.779316>.
- Kayser, M., Müller, J., Isselstein, J., 2010. Nitrogen management in organic farming: comparison of crop rotation residual effects on yields, N leaching and soil conditions. *Nutr. Cycl. Agroecosyst.* 87 (1), 21–31. <https://doi.org/10.1007/s10705-009-9309-0>.
- Kirchmann, H., 2019. Why organic farming is not the way forward. *Outlook Agric.* 48 (1), 22–27. <https://doi.org/10.1177/0030727019831702>.
- Kirchmann, H., Kätterer, T., Bergström, L., Börjesson, G., Bolinder, M.A., 2016. Flaws and criteria for design and evaluation of comparative organic and conventional cropping systems. *Field Crop Res.* 186, 99–106. <https://doi.org/10.1016/j.fcr.2015.11.006>.
- Kopittke, P.M., Berhe, A.A., Carrillo, Y., Cavignaro, T.R., Chen, D.L., Chen, Q.L., Minasyan, B., 2022. Ensuring planetary survival: the centrality of organic carbon in balancing the multifunctional nature of soils. *Crit. Rev. Environ. Sci. Technol.* 52 (23), 4308–4324. <https://doi.org/10.1080/10643389.2021.2024484>.
- Körschens, M., Rogasik, J., Schulz, E., Böning, H., Eich, D., Ellerbrock, R., . . . Zimmer, J. (2004). *Humusbilanzierung - Methode zur Beurteilung und Bemessung der Humusversorgung von Ackerland*. Retrieved from Bonn.
- Kravchenko, A.N., Snapp, S.S., Robertson, G.P., 2017. Field-scale experiments reveal persistent yield gaps in low-input and organic cropping systems. *Proc. Natl. Acad. Sci.* 114 (5), 926–931. <https://doi.org/10.1073/pnas.1612311114>.
- Leifeld, J., Angers, D.A., Chenu, C., Fuhrer, J., Kätterer, T., Powlson, D.S., 2013. Organic farming gives no climate change benefit through soil carbon sequestration. *PNAS* 110 (11), E984. <https://doi.org/10.1073/pnas.1220724110>.
- Leifeld, J., Fuhrer, J., 2010. Organic farming and soil carbon sequestration: what do we really know about the benefits? *Ambio* 39 (8), 585–599. <https://doi.org/10.1007/s13280-010-0082-8>.
- Lin, H.H., Duan, X.W., Li, Y.W., Zhang, L.L., Rong, L., Li, R.M., 2022. Simulating the effects of erosion on organic carbon dynamics in agricultural soils. *Catena* 208. <https://doi.org/10.1016/j.catena.2021.105753>.
- Luo, Z.K., Feng, W.T., Luo, Y.Q., Baldock, J., Wang, E.L., 2017. Soil organic carbon dynamics jointly controlled by climate, carbon inputs, soil properties and soil carbon fractions. *Glob. Chang. Biol.* 23 (10), 4430–4439. <https://doi.org/10.1111/gcb.13767>.
- Mahal, N.K., Osterholz, W.R., Miguez, F.E., Poffenbarger, H.J., Sawyer, J.E., Olk, D.C., Castellano, M.J., 2019. Nitrogen fertilizer suppresses mineralization of soil organic matter in maize agroecosystems. *Front. Ecol. Evol.* 7–2019.
- Maillard, É., Angers, D.A., 2014. Animal manure application and soil organic carbon stocks: a meta-analysis. *Glob. Chang. Biol.* 20 (2), 666–679. <https://doi.org/10.1111/gcb.12438>.
- Manzoni, S., Taylor, P., Richter, A., Porporato, A., Agren, G.I., 2012. Environmental and stoichiometric controls on microbial carbon-use efficiency in soils. *New Phytol.* 196 (1), 79–81. <https://doi.org/10.1111/j.1469-8137.2012.04225.x>.
- Marinari, S., Lagomarsino, A., Moscatelli, M.C., Di Tizio, A., Campiglia, E., 2010. Soil carbon and nitrogen mineralization kinetics in organic and conventional three-year cropping systems. *Soil Tillage Res.* 109 (2), 161–168. <https://doi.org/10.1016/j.still.2010.06.002>.
- McLauchlan, K., 2006. The nature and longevity of agricultural impacts on soil carbon and nutrients: a review. *Ecosystems* 9 (8), 1364–1382. <https://doi.org/10.1007/s10021-005-0135-1>.
- Muller, A., Schader, C., Scialabba, N.E.H., Brüggemann, J., Isensee, A., Erb, K.H., Niggli, U., 2017. Strategies for feeding the world more sustainably with organic agriculture. *Nat. Commun.* 8. <https://doi.org/10.1038/s41467-017-01410-w>.
- Murata, T., Goh, K.M., 1997. Effects of cropping systems on soil organic matter in a pair of conventional and biodynamic mixed cropping farms in Canterbury, New Zealand. *Biol. Fertil. Soils* 25 (4), 372–381. <https://doi.org/10.1007/s003740050328>.
- Obour, A., Stahlman, P., Thompson, C., 2017. Long-term residual effects of feedlot manure application on crop yield and soil surface chemistry. *J. Plant Nutr.* 40 (3), 427–438. <https://doi.org/10.1080/01904167.2016.1245323>.
- Osterburg, B., Ackermann, A., Böhm, J., Bösch, M., Dauber, J., de Witte, T., Elsasser, P., Erasmí, S., Gocht, A., Hansen, H., Heidecke, C., Klimek, S., Krämer, C., Kuhnert, H., Moldovan, A., Nieberg, H., Pahmeyer, C., Plaas, E., Rock, J., Röder, N., Söder, M., Tetteh, G., Tiemeyer, B., Tietz, A., Wegmann, J., Zinnbauer, M., 2023. Flächennutzung und Flächennutzungsansprüche in Deutschland. Thünen Working Paper 224. <https://doi.org/10.3220/WP1697436258000>.
- Pallant, E., Lanksy, D.M., Rio, J.E., Jacobs, L.D., Schuler, G.E., Whimpenny, W.G., 1997. Growth of corn roots under low-input and conventional farming systems. *Am. J. Altern. Agric.* 12 (4), 173–177. <https://doi.org/10.1017/S0889189300007517>.
- Panagea, I.S., Quataert, P., Alonso-Ayuso, M., Barcena, T.G., De Boever, M., Diacono, M., Ruyschaert, G., 2025. Forage vs. grain legumes: contrasting effects on soil organic carbon stocks-evidence from 30 European field experiments. *Eur. J. Soil Sci.* 76 (2). <https://doi.org/10.1111/ejss.70086>.
- Poeplau, C., Don, A., 2015. Carbon sequestration in agricultural soils via cultivation of cover crops - a meta-analysis. *Agric. Ecosyst. Environ.* 200, 33–41. <https://doi.org/10.1016/j.agee.2014.10.024>.
- Poeplau, C., Don, A., Schneider, F., 2021. Roots are key to increasing the mean residence time of organic carbon entering temperate agricultural soils. *Glob. Chang. Biol.* 27 (19), 4921–4934.
- Poeplau, C., Helfrich, M., Dechow, R., Szoboszlai, M., Tebbe, C.C., Don, A., Geerts, R., 2019. Increased microbial anabolism contributes to soil carbon sequestration by mineral fertilization in temperate grasslands. *Soil Biol. Biochem.* 130, 167–176. <https://doi.org/10.1016/j.soilbio.2018.12.019>.
- Poeplau, C., Jacobs, A., Don, A., Vos, C., Schneider, F., Wittnebel, M., Flessa, H., 2020. Stocks of organic carbon in German agricultural soils—key results of the first comprehensive inventory. *J. Plant Nutr. Soil Sci.* 183 (6), 665–681. <https://doi.org/10.1002/jpln.202000113>.
- Poeplau, C., Vos, C., Don, A., 2017. Soil organic carbon stocks are systematically overestimated by misuse of the parameters bulk density and rock fragment content. *Soil* 3 (1), 61–66. <https://doi.org/10.5194/soil-3-61-2017>.
- Ponisio, L.C., M'Gonigle, L.K., Mace, K.C., Palomino, J., de Valpine, P., Kremen, C., 2015. Diversification practices reduce organic to conventional yield gap. *Proc. R. Soc. B Biol. Sci.* 282 (1799), 20141396. <https://doi.org/10.1098/rspb.2014.1396>.
- R Development Core Team. (2022). *R: A language and environment for statistical computing. R Foundation for Statistical Computing*. Vienna: <http://www.R-project.org>.
- Rahlf, T., 2022. *Deutschland in Daten. Zeitreihen zur Historischen Statistik*. Bundeszentrale für politische Bildung, Bonn.
- Rasse, D.P., Rumpel, C., Dignac, M.F., 2005. Is soil carbon mostly root carbon? Mechanisms for a specific stabilisation. *Plant Soil* 269 (1–2), 341–356.
- Sakhaee, A., Gebauer, A., Ließ, M., Don, A., 2021. Performance of three machine learning algorithms for predicting soil organic carbon in German agricultural soil. *Soil Discuss.* 2021, 1–24. <https://doi.org/10.5194/soil-2021-107>.
- Sanders, J., Brinkmann, J., Chmelikova, L., Ebertseder, F., Freibauer, A., Gottwald, F., Heß, J., 2025. Benefits of organic agriculture for environment and animal welfare in temperate climates. *Org. Agric.* <https://doi.org/10.1007/s13165-025-00493-w>.
- Schneider, F., Poeplau, C., Don, A., 2021. Predicting ecosystem responses by data-driven reciprocal modelling. *Glob. Chang. Biol.* 27 (21), 5670–5679. <https://doi.org/10.1111/gcb.15817>.
- Seufert, V., Ramankutty, N., Foley, J.A., 2012. Comparing the yields of organic and conventional agriculture. *Nature* 485 (7397), 229–U113. <https://doi.org/10.1038/nature11069>.
- Skinner, C., Gattinger, A., Krauss, M., Krause, H.M., Mayer, J., van der Heijden, M.G.A., Mäder, P., 2019. The impact of long-term organic farming on soil-derived greenhouse gas emissions. *Sci. Rep.* 9. <https://doi.org/10.1038/s41598-018-38207-w>.
- Smith, L.G., Kirk, G.J.D., Jones, P.J., Williams, A.G., 2019. The greenhouse gas impacts of converting food production in England and Wales to organic methods. *Nat. Commun.* 10. <https://doi.org/10.1038/s41467-019-12622-7>.
- Springob, G., Kirchmann, H., 2003. Bulk soil C to N ratio as a simple measure of net N mineralization from stabilized soil organic matter in sandy arable soils. *Soil Biol. Biochem.* 35 (4), 629–632. [https://doi.org/10.1016/S0038-0717\(03\)00052-X](https://doi.org/10.1016/S0038-0717(03)00052-X).
- Steingrobe, B., Schmid, H., Claassen, N., 2001. The use of the ingrowth core method for measuring root production of arable crops - influence of soil and root disturbance during installation of the bags on root ingrowth into the cores. *Eur. J. Agron.* 15 (2), 143–151.
- Tuomisto, H.L., Hodge, I.D., Riordan, P., Macdonald, D.W., 2012. Does organic farming reduce environmental impacts? – a meta-analysis of European research. *J. Environ. Manage.* 112, 309–320. <https://doi.org/10.1016/j.jenvman.2012.08.018>.
- van Bruggen, A.H.C., Gamliel, A., Finckh, M.R., 2016. Plant disease management in organic farming systems. *Pest Manage. Sci.* 72 (1), 30–44. <https://doi.org/10.1002/ps.4145>.
- van Rijssel, S.Q., Koormeef, G.J., Veen, G.F., Pulleman, M.M., de Goede, R.G.M., Comans, R.N.J., Mason-Jones, K., 2025. Conventional and organic farms with more intensive management have lower soil functionality. *Science* 388 (6745), 410–415. <https://doi.org/10.1126/science.adr0211>.
- Vos, C., Don, A., Hobley, E.U., Prietz, R., Heidkamp, A., Freibauer, A., 2019. Factors controlling the variation in organic carbon stocks in agricultural soils of Germany. *Eur. J. Soil Sci.* 70 (3), 550–564. <https://doi.org/10.1111/ejss.12787>.
- Vos, C., Don, A., Prietz, R., Heidkamp, A., Freibauer, A., 2016. Field-based soil-texture estimates could replace laboratory analysis. *Geoderma* 267, 215–219. <https://doi.org/10.1016/j.geoderma.2015.12.022>.
- Wiesmeier, M., Hübner, R., Barthold, F., Spörlein, P., Geuss, U., Hangen, E., Kögel-Knabner, I., 2013. Amount, distribution and driving factors of soil organic carbon and nitrogen in cropland and grassland soils of southeast Germany (Bavaria). *Agric. Ecosyst. Environ.* 176, 39–52. <https://doi.org/10.1016/j.agee.2013.05.012>.
- Wittwer, R.A., Bender, S.F., Hartman, K., Hydbom, S., Lima, R.A.A., Loaiza, V., van der Heijden, M.G.A., 2021. Organic and conservation agriculture promote ecosystem multifunctionality. *Sci. Adv.* 7 (34). <https://doi.org/10.1126/sciadv.abg6995>.

- Wortman, S.E., Lindquist, J.L., Haar, M.J., Francis, C.A., 2010. Increased weed diversity, density and above-ground biomass in long-term organic crop rotations. *Renew. Agric. Food Syst.* 25 (4), 281–295. <https://doi.org/10.1017/S174217051000030X>.
- Zani, C.F., Gowing, J., Abbott, G.D., Taylor, J.A., Lopez-Capel, E., Cooper, J., 2021. Grazed temporary grass-clover leys in crop rotations can have a positive impact on soil quality under both conventional and organic agricultural systems. *Eur. J. Soil Sci.* 72 (4), 1513–1529. <https://doi.org/10.1111/ejss.13002>.
- Zhang, G.Y., Lu, Y., 2012. Bias-corrected random forests in regression. *J. Appl. Stat.* 39 (1), 151–160. <https://doi.org/10.1080/02664763.2011.578621>.