Interim report of the repeated German Agricultural Soil Inventory

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Summary

The dynamics of organic soil carbon (SOC) play an important role in atmospheric CO_2 concentrations and are therefore included in national greenhouse gas inventories. SOC is also essential for soil fertility. On behalf of the Federal Ministry of Food and Agriculture, the Thünen Institute of Climate-Smart Agriculture therefore conducted the first nationwide representative inventory of agricultural soils (BZE-LW) between 2010 and 2018. A total of 3,104 arable, grassland and permanent crop sites were sampled in an 8x8 km grid and analysed for SOC contents and stocks, as well as other parameters, down to a depth of 1 m. The BZE-LW repeat inventory project began in 2022, and since the beginning of 2023, resampling of the sites identified at that time has been in full swing. In addition to soil sampling, annual management data is also being collected. The main objective of this project is to quantify and explain potential changes in SOC contents and stocks over the past decade. This interim report presents the initial results of the ongoing repeat inventory.

Compared to the initial BZE-LW, there were some deviations in the implementation of the repeat inventory. Only the top 50 cm are sampled and organic soils are not resampled. Instead of a central profile pit and eight additional core drillings, four small pits are now excavated for sampling. Some parameters are not recorded again (e.g. soil type, grain size distribution, stone content), while others have been added (e.g. aggregate stability, air capacity, cation exchange capacity). By October 2025, approximately 1,350 sites in eight federal states had been resampled and almost 1,000 had been analysed for bulk density and SOC content in order to calculate mass-corrected SOC stock changes. During the initial evaluation, it was noticed that the initial SOC content of the topsoil from the profile pit was systematically slightly too high, leading to an overestimation of SOC losses. For this reason, the SOC contents from additional core samples of the initial BZE-LW were used instead. However, analysis of those has not been completed yet, which is why only 587 sites have been included in the evaluation at this stage.

Slight changes in SOC content have been observed in arable soils over the past decade. While a slightly positive trend in SOC content was observed on average in 0-10 and 10-30 cm, the change in SOC stocks in 0-30 cm (-1.6%) and 0-50 cm (-2.7%) was significantly negative due to a slight decrease in bulk density despite mass correction. At a depth of 0-10 cm, however, the change in SOC stocks was also slightly positive (0.9%), which can possibly be explained by a nationwide decline in tillage intensity and the resulting redistribution of SOC in the soil profile. However, the evaluation of the management data from the questionnaire was so far focused on one parameter: the frequency of cover cropping. In this respect, the BZE-LW data correspond well with national data, which show approximately a doubling of the annual cover crop area in the period under review. However, this gradual increase in SOC input into German arable soils was apparently not sufficient to compensate for potential negative influences on SOC. For grassland, there was a more pronounced decrease in SOC stocks, which was most pronounced at a depth of 0-10 cm (-8.1%). At depths of 0-30 cm and 0-50 cm, the significant relative decreases were -5.9% and -5.1%. Negative trends were also observed on average at all depth levels for the 14 permanent crop sites to date. The investigation of the causes of these SOC losses is still ongoing.

According to the hypotheses developed here, it is land use history and soil genesis, rapidly advancing climate change, and recent changes in cultivation practices that are affecting the SOC dynamics currently being observed: The historically wet and often SOC-rich sandy soils of north-western Germany tend to suffer particularly severe SOC losses under current land use, which is consistent with the results of long-term soil observations in Lower Saxony and the neighboring Netherlands. Over the last 50 years, there has been an average air temperature increase of 2.1°C at the BZE-LW sites, about half of which has occurred in the last 1-2 decades. According to modelling and experimental work, warming alone is sufficient to explain the magnitude of average SOC losses. Finally, national statistics clearly indicate a reduction in livestock farming and nitrogen fertilisation, which is also likely to have a negative impact on SOC stocks.

Separating the various factors influencing SOC stocks requires complex methodology and will be a central part of the next project phase, alongside the completion of resampling and the remeasurement of the initial core samples. Another challenge will be the preparation and implementation of new reporting requirements, in particular the EU Soil Monitoring Law. The trends observed to date only apply to part of the Federal Republic of Germany. The average rates of change presented here should therefore not be extrapolated.

Keywords: Agricultural soils, soil monitoring, soil organic matter, soil carbon, greenhouse gas reporting

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1 Introduction

National soil inventories generate key information on the condition of soils (Froger et al., 2024). The German Agricultural Soil Inventory (BZE-LW) is therefore of great importance for the protection of soil as a vital resource. However, the primary motivation for conducting a representative inventory of agricultural soils in Germany is and has always been to improve national greenhouse gas reporting for the *Land Use, Land Use Change and Forestry* (LULUCF) sector, in which changes in organic soil carbon stocks (amount per hectare and depth) SOC stocks (quantity per hectare and depth) must be reported as accurately as possible at the national level. Declining SOC stocks are associated with CO_2 emissions, while increasing stocks are a carbon sink through which atmospheric CO_2 can be bound and rendered harmless to the climate (Don et al., 2024b; Paustian et al., 2016). Almost half of the land area in Germany is used for agriculture, which means that even small changes in SOC stocks per hectare can lead to large emissions or removals of CO_2 on a national scale. In this way, agriculture can contribute to climate protection. Generating negative emissions by building up soil carbon is also the goal of the 4per1000 initiative, which Germany has also joined (Minasny et al., 2017). In addition, almost all physical, chemical, and biological processes in the soil are related to organic soil matter (Don et al., 2024a). For example, all soil life depends on SOC as an energy source. The infiltration of rainwater into soils, known as rain digestibility, is directly and positively linked to SOC and thus to flood protection issues, to name just two examples. Monitoring SOC is therefore a key component in assessing the condition of agricultural soils in general.

Between 2010 and 2018, the initial BZE-LW quantified for the first time, on a representative basis for Germany, how much SOC is bound in cropland and grassland soils and how this stock is spatially distributed (Jacobs et al., 2018; Poeplau et al., 2020). In total, around 2.5 billion tons of SOC are stored in the top meter of German agricultural soils, which is roughly the same amount as in forest biomass and forest soils combined (Jacobs et al., 2018). The distribution of SOC stocks on a national scale was primarily determined by site factors such as soil texture and groundwater influence (Drexler et al., 2022; Vos et al., 2019), as well as by land use (Poeplau et al., 2021) and is the result of thousands of years of soil development and use. Recent management influences (10 years prior to initial sampling) did not play a decisive role in explaining the nationwide variability of SOC (Jacobs et al., 2018) . Temporal changes in SOC, on the other hand, are much more strongly influenced by current soil management and climate change (Heikkinen et al., 2013).

The repeat inventory, which has been ongoing since 2022, aims to quantify and explain changes in soil properties over the past decade. This can provide insight into how social, funding policy, legal, market economy, or technical developments, as well as climate change, affect the condition of used soils. Examples of significant drivers of changes in land use include changing dietary habits among the population, the amendment of the Fertilizer Ordinance, and the EU's Common Agricultural Policy. A concrete example suggests how certain lifestyle developments in societies can also influence the SOC content in soils: In Swedish cropland soils, an increase in private horse ownership has led to a significant increase in SOC because it has greatly increased the demand for forage grass from cropland (Poeplau et al., 2015). Climate change can affect soil condition in several ways. On the one hand, global warming increases microbial activity and thus the turnover of organic matter in the soil (Walker et al., 2018), while on the other hand, drier conditions can inhibit decomposition. However, warmer temperatures and increased CO_2 concentrations in the atmosphere can also promote plant growth, while drought has the opposite effect. On the agricultural side, however, climate change also necessitates certain adjustments, such as the cultivation of new crop varieties or increased irrigation, which can affect soil properties. Finally, the enrichment of SOC is currently being promoted as a climate protection measure (carbon farming) – another consequence of climate change that should become noticeable in agricultural soils at a given scale. Obtaining as accurate a picture as possible of these changes and gaining a comprehensive understanding of the drivers is not only of great importance for the greenhouse gas inventory of the Federal Republic of Germany, but can also influence important political decisions on sustainable land use. In most cases, the loss of SOC in the soil is associated with losses in soil functions and is therefore a warning sign.

The changes in SOC expected as a result of management measures are relatively small and therefore difficult to detect (Freibauer et al., 2004; Schrumpf et al., 2011). Even on a scale of a few decimeters, there is great variability in SOC in soils (Poeplau et al., 2022). This poses particular challenges for sampling in the field, but also for sample preparation and analysis. A significant part of the first phase of the repeat inventory was therefore the development of a suitable methodology for resampling, as well as careful quality control of the initial data. The resulting methodological changes are described in detail here. The repeat inventory will not be completed until 2030 and can therefore only provide a limited overview of changes in soil condition at this point in time. Sampling was carried out in accordance with the first BZE-LW per federal state, meaning that the available results so far only cover parts of Germany. Nevertheless, the results presented here are an important milestone, providing initial conclusions on the development and change in SOC contents and stocks in agricultural soils in Germany. Overall, the aim of this report is to document the status of the evaluations of the repeat inventory, to present the methodological approach in a transparent manner, and to venture initial, preliminary attempts at interpretation.

2 Materials and methods

2.1 Sampling and field data collection

2.1.1 General characteristics of the BZE-LW sampling design

In the initial BZE-LW, which took place between 2010 and 2018 (Jacobs et al., 2018), the sampling locations were determined on an 8x8 km grid. This grid was adapted to the BZE forest and can be regarded as a systematic random sample of agricultural land in Germany (Brus and Saby, 2016). A total of 3104 sites were identified that are used as cropland, grassland or permanent crops such as orchards, vineyards or hop plantations. In cases where the randomly selected grid location could not be sampled because the farmers did not give their consent or the soil scientists on site decided to relocate the point for other significant reasons, an alternative sampling point was determined as close as possible to the theoretical sampling point. If sampling of the respective parcel of land was approved, preliminary investigations were carried out to check for possible explosive ordnance, power lines, drainage systems, and similar features. During sampling, a central profile pit (approx. 1x1x1 m) was excavated, in which a complete profile description was carried out in accordance with the German soil mapping guideline KA5 (Ad-Hoc-Ag Boden, 2005). Sampling (using a soil corer for dry bulk density and a thin soil section across the entire width of the pit for chemical properties) was carried out at specified depth levels (0-10, 10-30, 30-50, 50-70, and 70-100 cm) to the maximum possible depth.

In order to be able to carry out analyses based on pedogenic horizons instead (on top) of fixed depth levels, an additional sample was taken. This was done when the distance between the horizon and depth level boundary was greater than four cm. The proportion of skeleton (gravel and rocks larger than 2 mm) was visually estimated for each depth level (vol. %) and also sampled using cutting cylinders or, depending on the frequency and shape of the rocks, various other methods (Jacobs et al., 2018). In addition to the profile pit sampling, eight soil cores were taken using a ram core probe within a radius of 10 m around the initial pit in order to record the spatial variability at each location. The analysis of these additional samples was not completed in full due to a lack of time and financial resources within the scope of the initial BZE-LW. A total of 1236 sites were analyzed, and a systematic deviation in SOC content, dry bulk density, and SOC stock was found between the central profile pit and the ram core probes (Jacobs et al., 2018). The differences in SOC content were particularly pronounced in cropland soils at a depth of 10-30 cm and in grassland at a depth of 0-10 cm, which could not be explained at that time. The values from the central profile pit were therefore used as a reference in evaluations of the initial BZE-LW.

After sampling, the exact coordinates of the central profile were recorded using differential GPS and an underground marker was buried at a depth of approx. 80 cm to enable the exact location of the sampling point to be determined. The 3104 sites were sampled by federal state over a period of more than seven years (starting in 2011, last sampling in 2017). A total of 257 representative focus sites (so-called *core sites)* were selected, at which additional soil properties were determined.

2.1.2 General characteristics of the first repeat inventory

For an initial repeat sampling, a minimum interval of 10 years was chosen for each site in order to detect changes in SOC stocks and other dynamic soil properties (Schrumpf et al., 2011). The first question was how the sites of the initial BZE-LW should be resampled in order to detect even the smallest changes. Due to the methodological bias observed between soil profile pits and cores, it was decided that the first pit sampling must be followed by further pit sampling. However, it was unclear whether resampling a pit with another pit in the immediate vicinity (basically a reopening with n=1) would be precise enough to determine the expected minor changes in soil properties after ten years.

A comprehensive preliminary test at eight cropland and eight grassland sites in northeastern Germany showed that resampling a pit with a pit 40 cm away on the same day would result in a mean absolute error of 5.1 and 7.6 Mg SOC ha^{-1} at a depth of 0-30 cm for cropland and grassland areas, respectively (Poeplau et al. 2022). This corresponded to a relative deviation of 7.5 and 8.5%, respectively, which is more than the expected average changes in SOC stocks over 10 years, e.g., due to changes in management or climate change (Freibauer et al., 2004; Poeplau and Dechow, 2023). The observed high spatial variability of SOC even at the smallest spatial scale (within 1 m^2) suggested that a higher number of profile pits would be needed to reduce the noise caused by random sampling errors and increase the chance of detecting actual changes. Indeed, increasing the number of profiles to three in the immediate vicinity of the initial pit reduced sampling error by about 50% (Poeplau et al., 2022).

After further preliminary tests and an international evaluation workshop on the concept of repeat inventory, it was decided to resample the soil around the initial profile pit in a checkerboard pattern with four small profiles (Fig. 1). The checkerboard pattern allows for systematic random sampling of the 12x12 m plot through pits arranged in four 2x2 m microplots. For each of the nine potential future samplings, the four pits can be arranged around the initial pit according to the cardinal directions, so that none of the pits would cause soil disturbance for future campaigns. A buffer zone of 4x4 m around the initial pit is maintained to avoid the influence of soil disturbance from the first sampling.

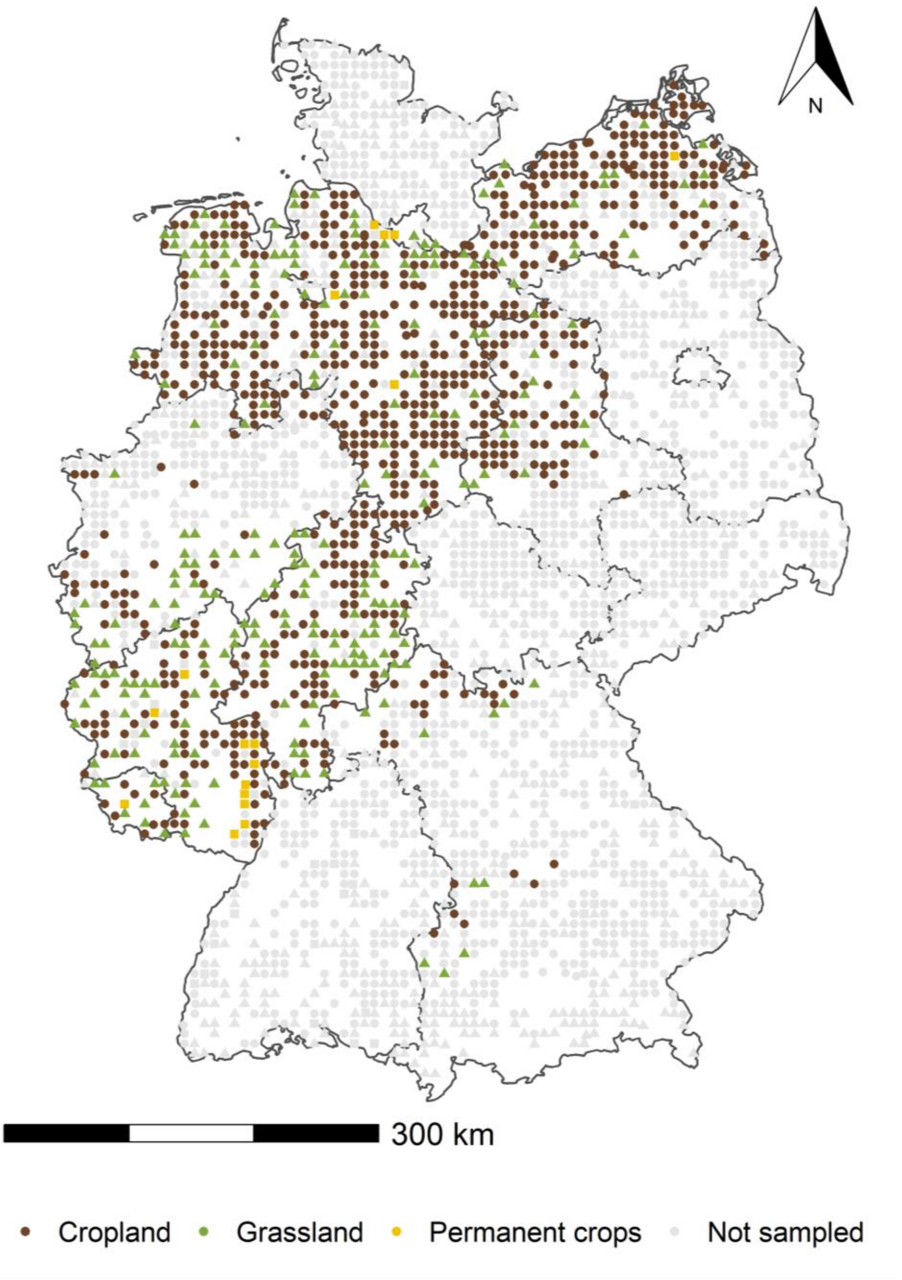
Figure 1 Sampling scheme for up to eight repeat inventories (marked by numbers 2-9) and drone image of a joint sampling of a site with four simultaneously opened profile pits. No. 1 marks the location of the central soil profile of the initial BZE-LW.

Source: Thünen Institute, ©Foto: Stefan Heilek

It was decided that all soils classified as organic (Jacobs et al., 2018) should not be resampled (n=147). This can be explained by the fact that different methods are required to determine changes in SOC stocks in organic soils than in mineral soils. Instead, the Thünen Institute was commissioned to set up a monitoring network specifically for organic soils (Moorbodenmonitoring für den Klimaschutz, MoMoK). This decision reduced the number of BZE-LW sites from 3104 to 2957. In addition, several sites have already been classified as sealed (n=23), reforested (n=7), or inaccessible due to refusal by farmers (n=11). The reforested areas will be resampled and can be examined with particular attention in future inventories as sites with changed land use.

In line with the initial inventory, and in order to maintain the approximate 10-year cycle, samples are taken per federal state. The first federal state was Lower Saxony, followed by Mecklenburg-Western Pomerania, Hesse, Rhineland-Palatinate, Saarland, Saxony-Anhalt, and Bavaria. By the end of October 2025, a total of 1,356 sites had been sampled again (Fig. 2).

Figure 2 Location of sites sampled in the repeat inventory by October 31, 2025, by land use, as well as sites still to be sampled.



Source: Thünen Institute

2.1.3 Sampling and field data collection for the repeat inventory

In the first repeat inventory, the microplots numbered 2 (Fig. 1) are measured and a pit is dug in a central position at each site. The four pits (area approx. 60x40 cm) are dug to a depth of 50 cm. The excavated soil is placed in two larger boxes per pit (one for the topsoil, one for the subsoil) to facilitate refilling the pit after sampling and to minimize the impact on the soil surface. On level ground, the profile wall to be sampled is oriented to the north; on slopes with a gradient of more than 5%, the profile wall is oriented towards the slope in order to minimize gradients within the profile wall and associated sampling errors. If sampling of a microplot is not possible (e.g., due to a wheel track or similar), the pit is relocated to an adjacent grid square within the 12x12 m plot. Once the profile walls have been prepared, a photo is taken of each one. Before taking soil samples, a brief profile description is made for each of the four profiles and compared with the initial profile description, recording the following parameters for each horizon: type and depth, soil type, carbonate content (using the hydrochloric acid fizz test), volumetric skeleton content, root penetration intensity, and special features. After the profile description, each profile is photographed. The subsequent soil sampling is carried out in fixed depth increments of 0-10, 10-30, and 30-50 cm.

For chemical soil properties (disturbed sampling), the soil is sampled in a thin strip across the entire width and depth of each depth level along each profile wall. To determine the physical properties (dry bulk density), the soils are sampled with 250 cm³ volume grab cylinders wherever possible. For very skeletal, stony soils, smaller rings (100 cm³ or, in extreme cases, 5 cm³) are used. Two punch cylinders per depth level are taken vertically from each pit (10 pieces for the 5 cm³ cylinders) and mixed per pit and depth level. In addition to the sample for determining the dry bulk density, the depth of 30-50 cm is also sampled for air capacity measurements, if possible. The two 100 cm³ volume auger cores are taken from the vertical center of 30-40 and 40-50 cm. Since these rings are not combined after sampling, information is available for 30-40 cm (typical plow depth) and 40-50 cm. Finally, two mixed samples are taken at a depth of 0-10 cm in all four pits: one for aggregate stability analysis and one for potential soil biology measurements. After sampling, all samples are stored in the car until they are returned to the central laboratory at the end of the same week (Thursday or Friday). The samples for chemical and physical analysis and for aggregate stability are stored at 7°C until further processing, while the samples for microbiological testing are stored at -20°C.

Due to the high small-scale variability of many soil properties, the exact relocation of the initial sampling point plays a central role in the quality of the monitoring time series (Heikkinen et al., 2020). For this purpose, an underground marker was buried at a depth of approximately 80 cm in a central position on the profile wall during the initial sampling. With the aid of differential GPS and an underground marker detector, the exact location can usually be found without any problems. In some cases, e.g., with tall crops, it is not possible to use the detector. However, the use of differential GPS with correction frequency always ensures a high degree of accuracy (deviation of a few decimeters). To ensure the comparability of soil assessment and sampling among soil mappers, joint sampling is carried out regularly (about three times a year) (Fig. 1).

2.2 Sample preparation, laboratory analyses, and calculations of relevant parameters

2.2.1 Bulk density of fine soil and gravimetric content of coarse soil and water

The samples taken for analysis of the physical properties are weighed and then dried in an oven at 105°C to determine the dry weight of the sample per volume and the water content (weight- %). After drying, the soils are sieved to 2 mm to determine the fine fraction. The coarse material on the sieve (>2 mm) is sorted into skeleton (stones), anthropogenic material (e.g., shards, clinker), agricultural organic material (such as straw), and roots. All four components are weighed individually. Anthropogenic material is given special consideration, as it could provide clues about the history of the site and the general degree of material admixtures in agriculturally used soils. The roots are not washed, but weighed directly after sieving and sorting. Furthermore, no distinction is made between dead and living roots. It is therefore a very rough indicator of the actual root biomass. The bulk density of the entire soil BD_{total} (g cm^{-3}) and the bulk density of the fine soil BD_{fine} (g cm^{-3}) are calculated as follows:

$$BD_{total}=\frac{M_{total}}{Vol_{total}}$$

$$BD_{fine}=\frac{M_{total}-M_{rocks}}{Vol_{total}-\frac{M_{rocks}}{\rho_{rocks}}}$$

Here, M_{total} denotes the total mass of the sample (g), Vol_{total} the total volume of the sample (cm^3), while M_{fine} denotes the mass of the fine soil <2 mm (g), M_{rocks} denotes the mass of the rock fragment fraction >2 mm (g), and ρ_{rocks} denotes the bulk density of the rock fragment fraction (g cm^{-3}) in the sample. The latter was set to 2.65 g cm^{-3} (bulk density of quartz) as standard if there were no indications of significant deviations from this value. For certain sediments or volcanic rocks, the bulk density of the skeleton may deviate significantly from this value. In such cases, that bulk density was analyzed in the initial BZE-LW in order to adjust the calculation of the $BD_{(fine)}$ accordingly (Jacobs et al., 2018) . These specific bulk densities were also used in the repeat inventory.

2.2.2 Organic and inorganic carbon content and total nitrogen content

The samples for chemical analysis are dried at 40°C until their weight remains constant and sieved to 2 mm. For organic and inorganic carbon (SOC, SIC) and total nitrogen (N_{tot}), the samples from each individual pit and depth level are measured separately. This serves to identify small-scale fluctuations and possible outliers. It also provides a measure of uncertainty, which helps in the classification and statistical analysis of observed changes. In addition, it opens up the possibility of calculating the SOC reserve for each individual pit and thus more accurately on average, as the bulk density per pit and depth level is also determined. Prior to elemental analysis, aliquots of approximately 20 g are ground to <63 µm to homogenize the sample. Of these homogenized samples, 300-800 mg are used for elemental analysis. Carbonate-free soils are analyzed for carbon and nitrogen using a CN analyzer (vario MAX cube, Elementar, Langenselbold), while carbonate soils (as identified in the field or via pH measurement) are analyzed using a TOC analyzer (soli TOC cube, Elementar, Langenselbold) with differentiated temperature increase. The threshold between SOC and SIC is set at 550°C according to VD-LUFA. The N_{tot} content in carbonate soils is subsequently measured using a nitrogen analyzer (rapid N exceed, Elementar, Langenselbold).

Since there was a change in the elemental analyzers between the initial inventory of the BZE-LW and the repeat inventory (from LECO to Elementar), a comparison between the different instruments was carried out on a systematically selected sample set by measuring archived samples from the initial BZE-LW again with the new elemental analyzers. A total of 50 carbonate-free and 50 carbonate-containing samples between 0 and 100 g kg^{-1} SOC were selected and measured again. No systematic deviations for SOC and N_{tot} could be detected.

During the initial evaluation of the results, several sites stood out where mean SOC contents varied greatly between the two inventories. Very high spatial variability was identified as a major reason for the significant changes after a decade. Within the four profiles of the repeat inventory, ranges in SOC content of up to 100 g kg^{-1} or 10 percentage points were observed. These were often sites with organic horizons or burials in deeper soil areas. It can be assumed that the sampling design of the BZE-LW, especially with the peculiarity of the non-replicated initial profile pit, reaches its limits at such and other sites with extreme, small-scale variability, or does not allow for a meaningful evaluation of SOC content changes. Based on the distribution of these ranges, threshold values were defined for each land use and depth level, above which a site was excluded from the evaluation in this interim report. In cropland and permanent crop soils, these ranges were 20 g kg^{-1} in 0-10 cm and 10-30 cm, and 40 g kg^{-1} in 30-50 cm, and 40 g kg^{-1} in all depth levels in grassland soils. The variation patterns in N_{tot} content were very similar to those in SOC content, which is why the reduction of sites was limited to filtering based on SOC content. Any site where an exceedance was found at any depth level was excluded from further evaluation. A total of 21 of the resampled sites were excluded from this interim report.

2.2.3 Soil organic carbon stock

The key parameter of the BZE-LW is the SOC stock (Mg C ha^{-1} and given depth). This is determined for each individual profile pit and depth level using the following formulas and then cumulated for the depth levels 0-30 and 0-50 cm:

$$FSS = BD_{fine} \times thickness \times \left(1\text{-}\frac{rocks}{100}\right) \times 100$$

$$\text{SOC stock} = \frac{FSS \ \times SOC\ content}{1000}$$

FSS is the fine soil stock (Mg ha^{-1}), which can be calculated from the BD_{fine}, the thickness of the respective depth level (cm), the volumetric rock fragment fraction (rocks, vol. %) and a conversion factor of 100 (Poeplau et al., 2017). The volumetric rock fragment fraction of the soil was taken from the initial BZE-LW, as this can be considered approximately constant over a 10-year interval and would otherwise cause excessive noise with regard to SOC stock changes (Munera-Echeverri et al., 2025). The SOC stock (Mg ha^{-1}) at any depth level can be obtained by multiplying the FBV by the SOC content (g kg^{-1}) and a conversion factor of 1000.

Changes in the bulk density of the fine soil lead to a change in the soil mass or the fine soil stock at the respective depth level. However, a comparison of SOC stocks between two points in time should be based on identical fine soil stocks in order to track actual changes in the SOC stock in a defined amount of soil (Ellert and Bettany, 1995; von Haden et al., 2020). Since sampling identical fine soil stocks in the field is practically impossible, a mathematical correction must be made. In this case, the fine soil stock in a given soil package (0-10, 0-30, and 0-50 cm) was specified by the initial inventory. For this purpose, first determined the cumulative fine soil stock for the soil package to be corrected for each of the four soil profiles in the repeat inventory.

The procedure for mass correction is that soil packages with an excessively high fine soil stock (compared to the reference) are reduced mathematically at the lower end to simulate a correspondingly shallower sampling, while soil packages with an excessively low mass are extrapolated to reach the reference mass. This is done separately for all three soil packages (0-10, 0-30, and 0-50 cm) and each individual profile, always using the respective fine soil stock of the initial inventory as a reference. The reduction of a soil package and the subsequent correction of the corresponding SOC stock of a profile in the repeat inventory is carried out as follows:

$$\Delta FSS = FSS_{repeat}\text{-}FSS_{initial}$$

$$SOC\ stock_{shortened} = \text{SOC stock} - \frac{\Delta FSS \times SOC\ content_{lowest\ increment}}{1000}$$

Here, FSS_{repeat} denotes the fine soil stock of a profile pit in the repeat inventory down to the depth of the respective soil package (Mg ha^{-1}), while $FSS_{initial}$ denotes the fine soil stock of the respective soil package of the initial profile (Mg ha^{-1}). The difference between these two fine soil stocks is then used to determine a SOC stock, which is subtracted from the previously determined SOC stock of the soil package. To do this, ΔFSS is multiplied by the SOC content (g kg^{-1}) of the lowest depth level of the soil package to be corrected. The extrapolating correction of a soil package is carried out accordingly for each individual soil profile of the repeat inventory as follows:

$$SOC\ stock_{shortened} = \text{SOC stock} - \frac{\Delta FSS \times SOC\ content_{underlying\ increment}}{1000}$$

In comparison to the preceding formula, the SOC content of the underlying increment is now used. For the soil package 0-10 cm, this is the SOC content from 10-30 cm, and for the soil package 0-30 cm, it is the SOC content from 30-50 cm. For the soil package 0-50 cm, extrapolation with SOC content from the repeat inventory is not possible, as no underlying increment is sampled below 50 cm. If extrapolation is nevertheless necessary, the SOC content of the underlying increment (50-70 cm) from the initial inventory is used. However, in order to perform the extrapolation with as little "foreign" data as possible that was not measured in the respective profile, a two-step approach is used for extrapolation below 50 cm: First, the SOC stock of each profile is adjusted to the heaviest mass of the four profiles in the repeat inventory. For this purpose, the SOC content of the 30-50 cm depth level from the respective profile is used. Only the difference between the fine soil stock of the heaviest profile of the repeat inventory and the profile of the initial inventory is extrapolated using the SOC content below 50 cm from the initial inventory.

2.2.4 pH value and electrical conductivity

The pH value is determined both in distilled water (pH_{H2O}) and in calcium chloride (pH_{CaCl2}). For the analysis of pH and electrical conductivity, pool samples are first created for each depth increment of a site. To do so, approximately equal proportions of the individual samples from the four profile pits are mixed into one sample after sieving in order to reduce the analytical effort and the number of archive samples. Only for the selected focus sites (*core sites)* are all individual samples analyzed in order to obtain a measure of the small-scale variability of the respective parameters. For the analysis, five ml of dried fine soil is shaken upside down for 20 minutes with 25 ml of distilled water or a 0.01 molar $CaCl_2$ solution. After subsequent 10-minute centrifugation, the measurement is carried out using a pH-meter (ProLab 4000, SI-Analytics, Mainz) in a measuring robot (SP2000, Skalar, Breda).

2.2.5 Additional parameters

Spectra were also recorded in the laboratory in the mid-infrared range (2500-25000 nm; 4000-400 cm^{-1}) using diffuse reflection infrared Fourier transform spectroscopy (DRIFT-MIR, Nicolet iS50 with Collector II, Thermo Fisher, Waltham). A total of 7000 spectra have been collected out of a planned 28000 spectra. Together with the spectra in the near-infrared range (900-3400 nm; 11000-3000 cm^{-1} (FT-NIRS MPA, Bruker, Billerica) with around 14000 spectra (Jaconi et al., 2017; Vos et al., 2018), this will result in the "German Agricultural Soil Spectral Library" (GASSL).

Infrared spectroscopy enables the estimation of various soil parameters, such as organic carbon, its distribution in fractions of varying stability, but also texture and pH, as well as other parameters (Sanderman et al., 2020). The DRIFT-MIR spectra in particular contain direct information about the chemical and functional composition of the organic soil substance as well as about the properties of the mineral phase (Margenot et al., 2023; Schiedung et al., 2025). The advantage here is that spectroscopy is far less complex than conventional methods and can therefore be used to perform qualitative and quantitative assessments for all samples, not just a selection, using the GASSL in the future. At the same time, several parameters can be estimated from a single spectrum. Thus, in the further course of the BZE-LW, models for the quantitative estimation of various soil parameters and also qualitative parameters will be integrated into the evaluation. However, GASSL will not be discussed further in this report.

In addition, the samples from the repeat inventory are analyzed for cation exchange capacity and base saturation (all depth levels) as indicators of nutrient supply, as well as aggregate stability (topsoil, 0-10 cm) and air capacity (subsoil, 30-40 cm and 40-50 cm) as indicators of structural stability and subsoil compaction. In addition, topsoil samples (0-10 cm) were selected from 300 cropland sites to characterize the microbial community and investigate various functional microbial properties. An analysis of the proportion of pyrogenic carbon in the soils of the core sites is also planned. Previous results of these additional parameters are not covered in this report.

2.2.6 Archiving of soil samples

The finely ground aliquot of each sample (approx. 20 g of dry soil), which was also used for elemental analysis, is archived. In addition, 2 kg of each mixed sample from the individual depth levels of the four profiles is set aside for future analysis, if available. No mixed samples are kept from the core sites; instead, all individual samples are retained. The archive is dark (UV-protected), cool, and dry to ensure minimal change and maximum shelf life of the soil samples and containers.

2.3 Collection of management data

In order to interpret changes in soil properties, field- and farm-specific management information since the initial inventory is of great importance. This information is collected using a questionnaire, which is available in both digital and analog formats. The following data is requested, which is limited to the central question of the BZE-LW: Type of farm, farming method (conventional/organic, since when), land area of the farm, average purchase and sale quantities of organic fertilizers or substrates, cropland and grassland area of the sampled parcel, size of the sampled field, and distance of the sampling point from the central farm location. Annual data is collected on the type and yield of the main crop, removal of straw and by-products, type, sowing date, incorporation date and use of any catch crops, type of permanent grassland use, number of cuts in grassland, date of 1st and 2nd cut, type and depth of grassland renewal, type, number and duration of livestock farming on the sampled plot, type and amount of fertilization, type and amount of liming, type and depth of grassland renewal, type, number and duration of livestock farming on the sampled plot. cut, type and depth of grassland renewal, type, number and duration of livestock farming on the sampled plot, type and amount of fertilization, type and amount of liming, type and depth of tillage, additional measures such as drainage, irrigation, deep loosening, soil or plant additives, or alternative land use. The questionnaires received are quality assured and, if information is missing or too inaccurate, the farmers are contacted by telephone. This is also the case if questionnaires are not received even after multiple reminders. Since participation in the BZE-LW is voluntary and completing the questionnaire requires a considerable amount of effort, some farmers are unwilling to participate. As a result, the response rate for the questionnaires is not optimal, but this can only be influenced to a limited extent. To date, 1,756 questionnaires have been sent out and 889 have been completed and returned (51%).

Quality assurance and processing of the management information are ongoing. Harmonizing the data from both questionnaires into a consistent time series is a particularly challenging task. For this reason, the focus at this stage has been on a single parameter that is central to SOC dynamics in cropland soils: the proportion of catch crops in crop rotation. In order to calculate this trend for all questionnaires received to date and to create a general time series, 1) only those sites that reported for at least 5 years in both time periods (before the initial sampling and between samplings) were used, 2) in the case of temporal overlaps between the two questionnaires, only information from the second questionnaire was used, 3) the last two years (2023 and 2024) were ignored due to the significantly lower sample size. This resulted in a slightly different number of questionnaires (223-368) for each year between 2001 and 2022 for which information on the cultivation of catch crops was available. From this, the proportion of locations where catch crops were cultivated in a specific year was calculated.

2.4 External data

2.4.1 Land use history

Previous land use or land cover can have a strong influence on soil properties and their current temporal dynamics (Emde et al., 2024) . Data on land use history at the sampling points come from various sources. One source was the initial inventory questionnaire, which already asked whether information on the historical use or cover of the area was available. A distinction was made between cropland, grassland, permanent crops, forest, moorland, heathland, and other uses. Since only some of this data is available to today's farmers, the questionnaire data set contained large gaps and did not go back further than four decades on average. Therefore, various archives and repositories of historical maps and orthophotos were consulted in order to obtain as complete a data set as possible. The aim was to have land use information available for every location for at least 100 years, every 30 years. Continuous time series were generated from these incomplete time series by interpolation, from which approximate dates of land use changes can be derived. More detailed information on the generation of this data set is described by Emde et al. (2024). This report uses only part of this dataset to enable meaningful evaluation: long-term cropland and long-term grassland (no land use changes in the past 136 years), as well as cropland with a grassland history and grassland with an arable history in the past 136 years. Locations with frequent changes between cropland and grassland were excluded, as were those with other historical land uses.

2.4.2 Climate data

Climate conditions are highly relevant for the development of SOC stocks, as they directly influence microbial activity and thus the degradation kinetics of organic matter in the soil on the one hand, and biomass growth and thus the amount of crop and root residues that can be returned to the soil on the other. The weather data used here comprise monthly average temperatures (DWD, 2025a) and monthly totals for precipitation (DWD, 2025b) and sunshine duration (DWD, 2025c). The data were obtained as grid maps with a resolution of 1x1 km and for the period 1970 to 2024 from the Open Data Center of the German Weather Service. Time series for the BZE-LW locations were then extracted from these maps. Global radiation was calculated from sunshine duration according to (Allen et al., 1998) and potential evaporation was estimated according to Turc (Wendling et al., 1991).

2.5 Statistics

Average changes in SOC content, BD_{fine} and SOC stocks were analyzed using a bootstrapping method to enable error estimation and determine significance. For this purpose, the change in a parameter between the initial inventory and the resampling was determined for all available locations. From these n changes, a new sample was generated by drawing n times with replacement, and the mean value was calculated. This process was repeated a total of 5000 times, resulting in 5000 bootstrap mean values of the change. The interval between the 2.5% and 97.5% percentiles of the bootstrap means was defined as the 95% confidence interval (CI95) of the mean change. If this interval of change was completely beyond zero, i.e., exclusively in the positive or negative range, the mean change was interpreted as significant (Ho et al., 2019). The bootstrapping method was chosen because it is nonparametric, does not require normal distribution of the data, and, in addition to significance, confidence intervals of the changes could also be calculated (Çetinkaya-Rundel and Hardin, 2024). By switching from the initial profile pit to the surrounding core drillings (see Chapter 3), the spatial variability of the SOC contents could be determined for both time points. With this uncertainty, a minimum detectable difference (MDD) could be calculated for each site, which is directly proportional to the small-scale variability for a given sample size and allows a statement to be made about the statistical significance of the measured SOC content change. The formula according to (Valk et al., 2000) was used for this purpose:

$$MDD = \sqrt{(Z_\alpha + Z_\beta)^2 \times \frac{\sigma^2}{n}}$$

Where α expresses the statistical significance level (here α=0.05), β is a measure of the probability that a statistical effect can be found (1 - statistical power, here 0.8), and the Z-value indicates how many standard deviations a value is from the mean of a standard normal distribution. With an α of 0.05, Z_α is the 95% percentile of a standard normal distribution and thus 1.96 standard deviations from the mean, while Z_β is 0.84 standard deviations from the mean. The standard deviation of the measured values is included in the formula as σ, and n describes the number of measurement repetitions. An MDD was determined for both the initial BZE (8 soil cores) and the repeat inventory (n=4). The change in SOC content was considered significant if it was greater than both MDD values.

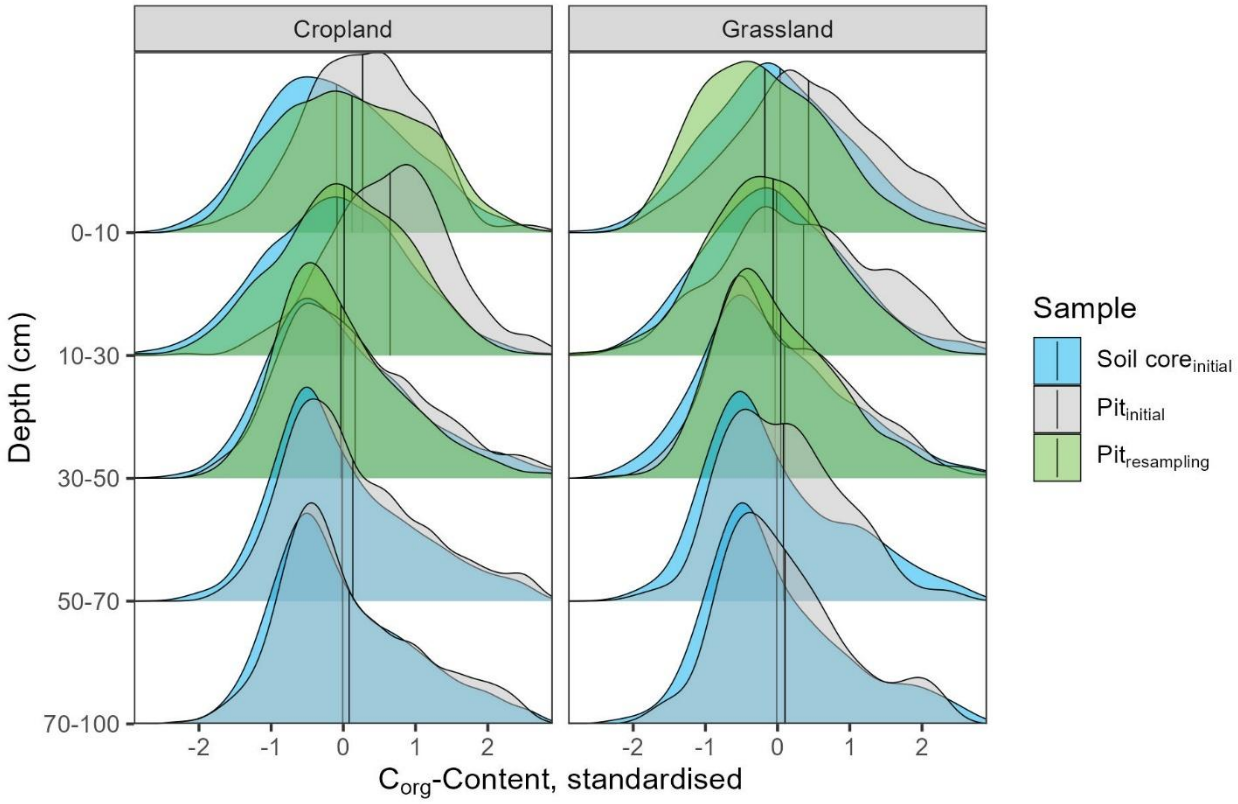
To test whether land use history had a significant effect on the recent change in SOC stocks in 0-30 cm, an analysis of variance (ANOVA) of the changes was performed. The aim was to specifically test whether SOC stocks from long-term cropland or long-term grassland have a significantly different dynamic than those with known land use change (from cropland or grassland) over the past 136 years. The normal distribution of the residuals was checked using QQ plots. Due to the non-normal distribution of the ANOVA residuals, a non-parametric Kruskal-Wallis test was performed with Wilcoxon as a post hoc test.

Due to the reduced size of the data set (see Chapter 3), the limited spatial representation of the sites that have been resampled and analyzed to date, and the fact that only partial management information is available, no global statistical model was calculated in this interim report to explain changes in SOC content and reserves, as well as other soil properties. Only simple correlation analyses (linear regressions) with individual soil properties and changes in climate variables were performed.

3 Comparison of SOC results from the initial profile pit and soil cores

An initial analysis of the changes in SOC content and stocks from the eight federal states sampled to date revealed significant decreases after the first resampling compared to the initial inventory. This was observed regardless of land use. To verify the plausibility of the supposed trends, additional ram core sampling (hereinafter referred to as soil cores) from the initial inventory was used where available. It turned out that i) the deviation between the mean value of the soil cores and the profile pit strongly determined the difference between the initial profile pit and the resampling, and ii) the difference between the resampling and the initial core sampling was on average significantly smaller than the difference between both and the initial profile pit (Fig. 3).

Figure 3 Density function of z-transformed SOC contents (uniformly scaled per site and depth level, with 0 as the mean value of the site across all available measurements) for the data from core drilling and profile pits from the initial inventory, as well as the values from the repeat inventory.

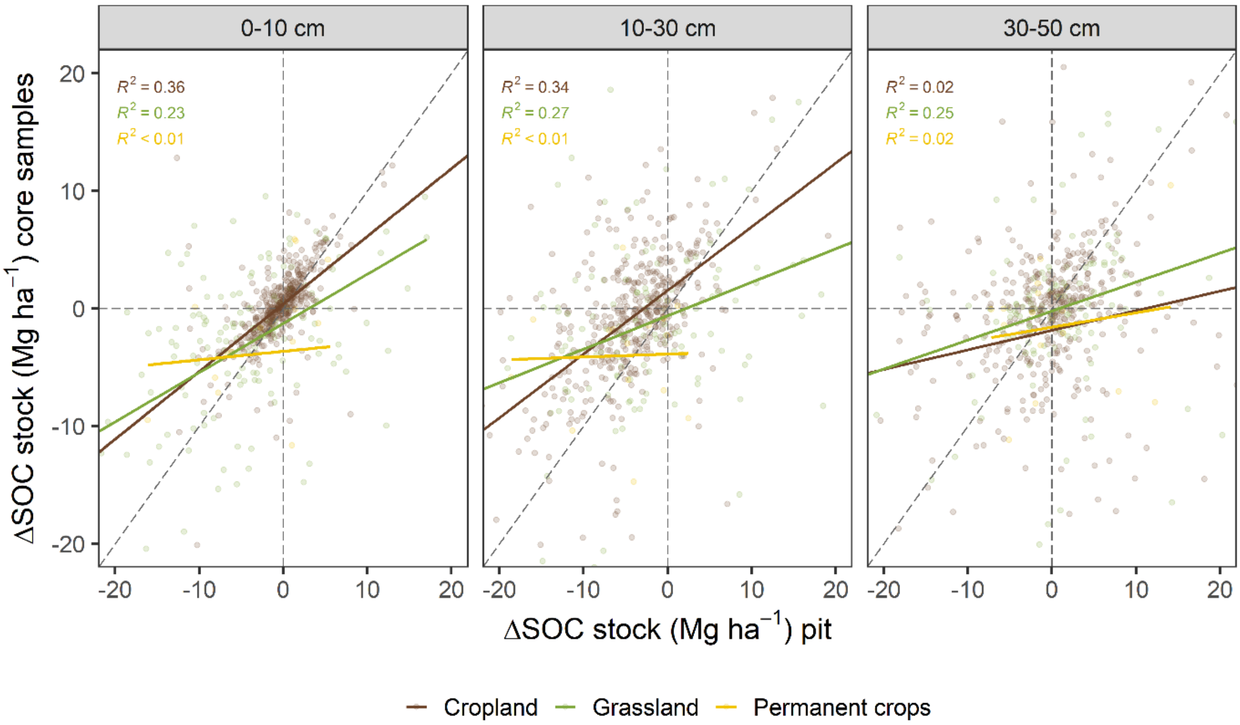


Source: Thünen Institute

In addition, the difference between the initial profile pit and the resampling was most pronounced at precisely those depth levels that had already been identified as problematic during the initial inventory (10-30 cm in cropland land and 0-10 cm in grassland) (Fig. 3). These depth levels are those in which strong gradients in SOC content often occur or which are underlain by significantly SOC-poor depth levels. It seems likely that sampling of the initial profile pit systematically led to slightly lower SOC contents and SOC stocks. One possible explanation is that areas poorer in SOC (appearing lighter in the profile) tended to be omitted or sampled disproportionately.

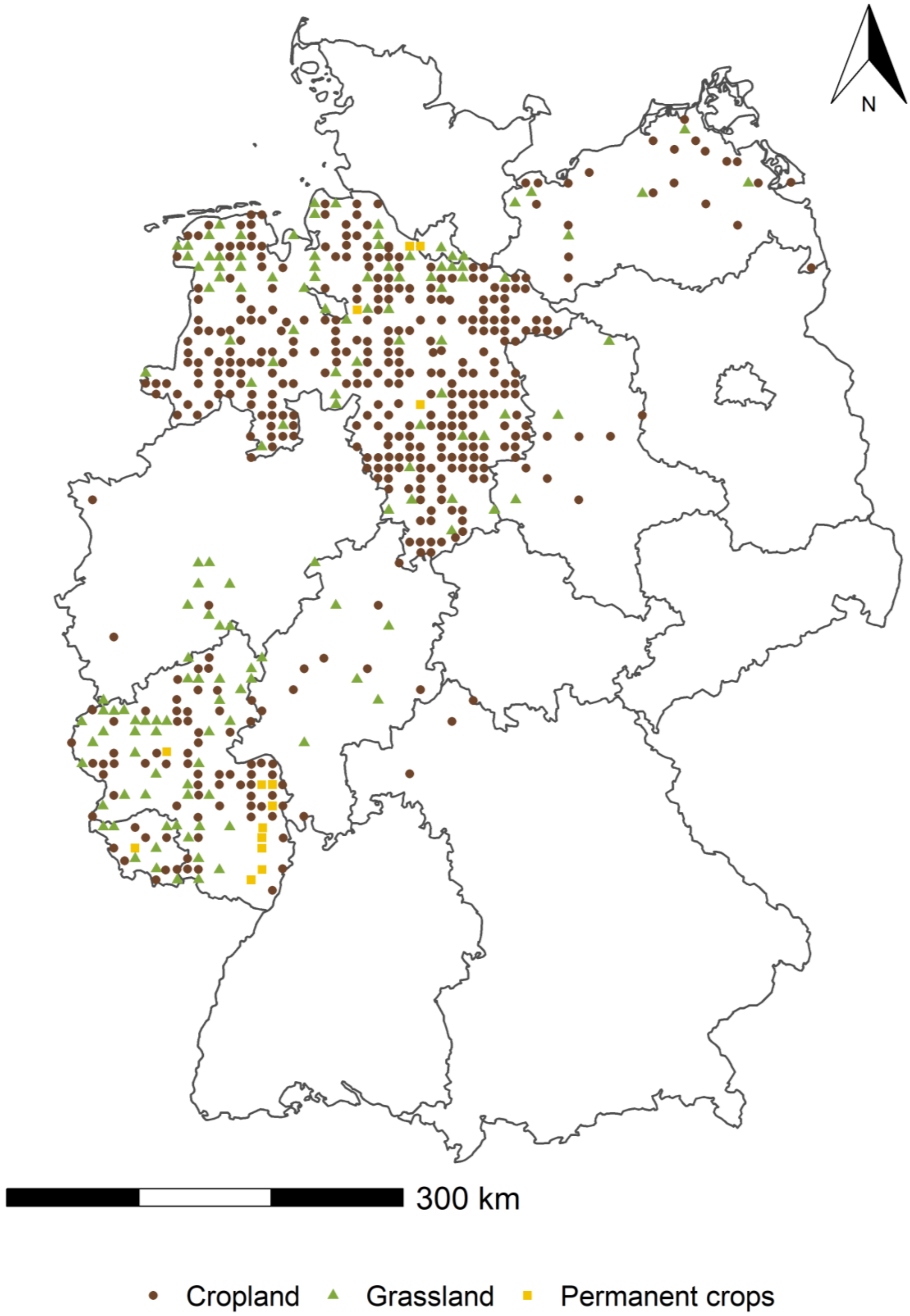
Furthermore, there is a surprisingly low degree of agreement between the SOC changes determined on the basis of the results of the initial profile pit and the initial ram core drilling (Fig. 4). This also leads to the conclusion that the SOC contents of the initial profile pit are a poorer reference than the results from the drill cores. It was therefore decided to remeasure the SOC and N_{tot} contents on some of the drill cores that had not yet been analyzed (four of eight drill cores, three depth levels) and to use the existing results from the core drilling as the initial values for the SOC contents for this report. SOC changes are now reported accordingly for 578 locations for which core drilling from the initial inventory and resampling are currently available (Fig. 4). It is unclear whether or to what extent other chemical soil properties show similar systematic differences between the sampling methods (profile pit or drill cores). Changes in pH values are therefore not addressed in this report, as they have yet to be determined for the drill cores. One advantage of this change is that rates of change can now also be checked for significance on a site-specific basis or assigned an uncertainty value, which allows for a better classification of differences between the two inventory rounds.

Figure 4 Change in SOC stock based on the core drilling plotted against the change in SOC stock based on the initial profile pit with linear regressions and corresponding correlation coefficients (R^2). The dashed diagonal line represents the 1:1 line. The section selected for better visualization (-20 to 20 Mg ha^{-1}) led to the exclusion of 15 sites in 0-10 cm, 51 sites in 10-30 cm, and 66 sites in 30-50 cm. The regressions are not affected by this.



Source: Thünen Institute

Figure 5 **Location of sites that have already been resampled for which data from the initial core drilling and the relevant analysis results from the repeat inventory are available.**



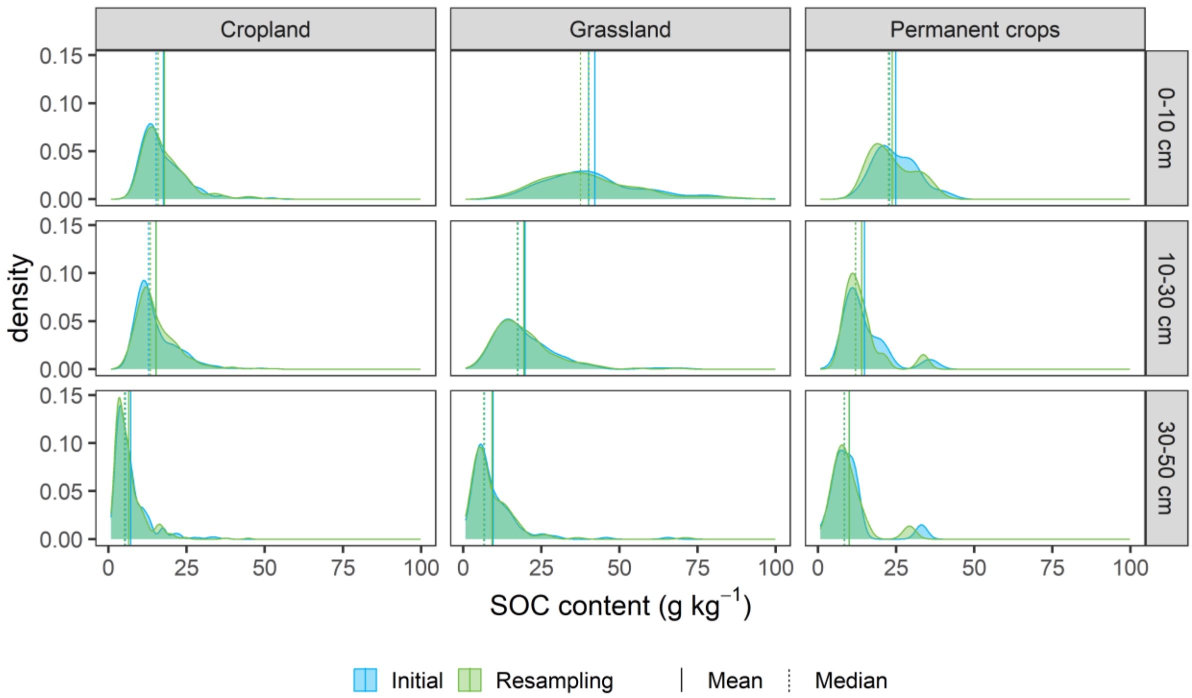
Source: Thünen Institute

4 Results

4.1 Temporal dynamics of organic soil carbon content

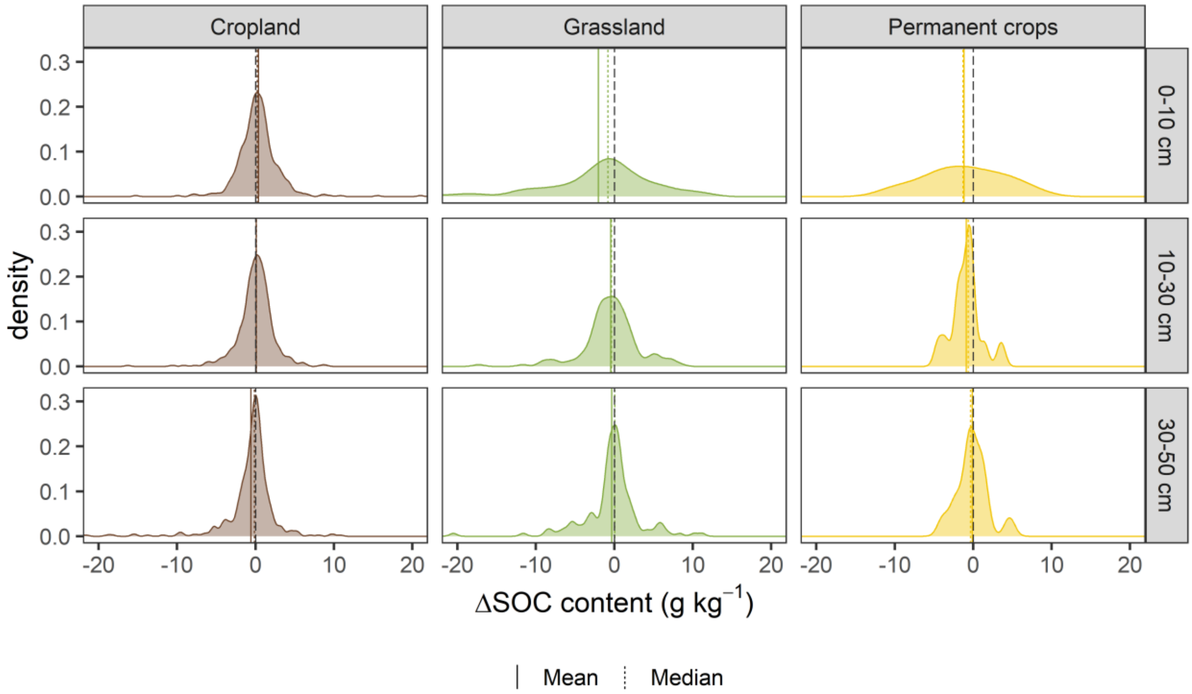
The conversion to SOC contents from the core drilling samples initially resulted in a significantly reduced sample size for the SOC parameter. Of the original 1,000 or so resampled and analyzed sites, an evaluation of SOC content and stock changes could be carried out for a total of 578 sites for which core drilling data had already been collected (see Chapter 3). The fundamentally right-skewed distributions of SOC contents in the three land uses and depth levels and for both inventories are shown in Fig. 6. The change in SOC contents is shown in Fig. 7 and Table A1. These are approximately normally distributed. While the SOC content in the topsoil of cropland (0-10 and 10-30 cm) increased slightly (significantly in 0-10 cm), significant decreases were observed on average in the subsoil (30-50 cm). The most significant overall change in SOC content was observed in the topsoil of grassland soils, especially at a depth of 0-10 cm. A significant decrease in SOC content was observed at this depth for the 140 grassland soils sampled to date. Decreases were also measured on average at the depths below. This was also true for permanent crops, where there was also a tendency toward decreases on average at all depths. However, due to the small sample size of permanent crops, this trend could not be statistically verified.

Figure 6 Distribution of SOC contents from the initial inventory and repeat inventory by depth level and land use with median and mean values.



Source: Thünen Institute

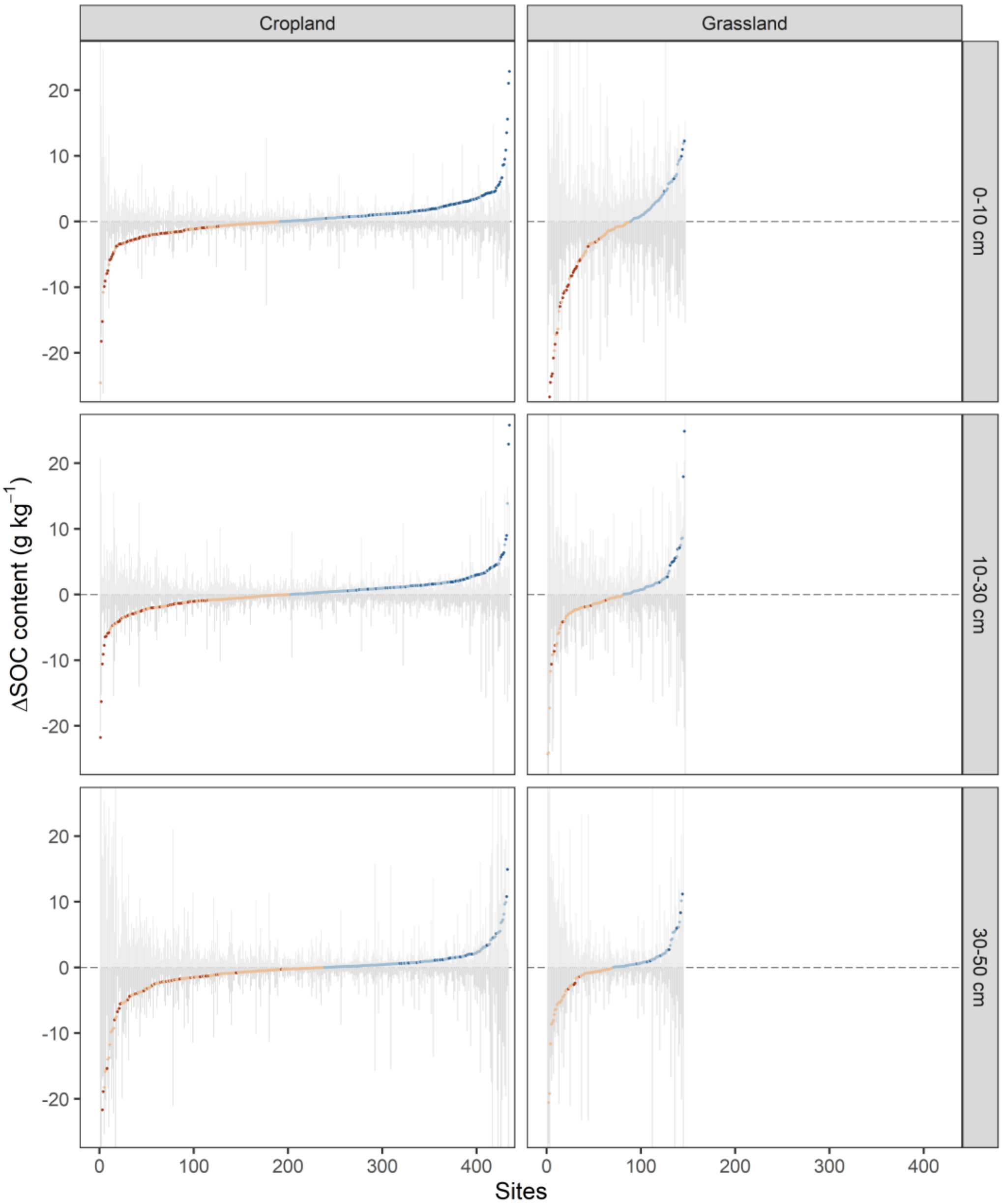
Figure 7 Distribution of changes in SOC content by depth level and land use with mean and median. The black dotted line represents no change (zero line). The section selected for better visualization (-20 to 20 g kg(-1))led to the exclusion of 18 sites in 0-10 cm, 6 sites in 10-30 cm, and 4 sites in 30-50 cm. The representation of the median and mean values are not affected by this.



Source: Thünen Institute

Multiple measurements at each site, and especially after switching to core drilling, made it possible to determine a minimum detectable difference (MDD) for each individual site. This is largely determined by the small-scale variability of SOC at the site and provides information on whether measured differences in SOC content should actually be interpreted as significant temporal trends. Fig. 8 shows both the measured mean change in SOC content and the calculated MDDs for each site (cropland and grassland), sorted by the magnitude of the measured change. Firstly, it is noticeable that among the sampled cropland sites, there were slightly more positive than negative changes in SOC content in 0-10 cm (56%) and 10-30 cm (54%), while this trend reversed slightly in 30-50 cm (45%) (Table 1). In grassland, the opposite was true, with a tendency for more decreases than increases in the topsoil up to 30 cm and a tendency for more increases in the subsoil (30-50 cm). In addition, there were a large number of cropland sites where very small changes in SOC content were observed ~1 g kg^{-1}, which consequently cannot be evaluated as such for the individual site. In grasslands, a significantly smaller proportion of the SOC content changes were very small, while a larger proportion tended to show stronger changes. Nevertheless, in grasslands as a whole, fewer changes than in cropland sites could be confirmed as significantly positive or negative (Fig. 2). SOC content changes were very small, while a larger proportion showed more significant changes. Nevertheless, overall fewer changes could be confirmed as significantly positive or negative in grasslands than in cropland sites (Fig. 8, Table 1). This can be explained by the significantly higher MDD of grassland sites, which also increased with depth. Across all land uses and depths, the proportion of sites with an uncertain trend dominated, although the most significant changes in SOC content were observed at a depth of 0-10 cm.

Figure 8 **Changes in SOC content sorted by size (colored dots) for all cropland and grassland sites at three depth levels with minimum detectable difference (MDD) for the respective site (gray bars). The MDD is a positive value that, depending on the variability at the site, indicates how large a change (amount) in SOC content must be in order to assume a change with statistical certainty. For the figure, the MDD was mirrored into negative values to enable a direct comparison with the losses in SOC content. Negative changes in SOC content are colored red, positive changes blue, and values greater than the MDD are shown in dark colors. Changes within the MDD, and therefore not significantly significant, are shown in light colors. The section -25 to 25 g kg^{-1} selected for better visualization led to the exclusion of 4 grassland sites in 0-10 cm, one cropland and one grassland site in 10-30 cm, and 3 cropland and 2 grassland sites in 30-50 cm.**



Source: Thünen Institute

Table 1 Proportions of positive (increase) and negative (decrease) SOC content changes for each depth level and land use, broken down into those changes that were classified as uncertain, or significantly positive or negative, according to the minimum detectable difference.

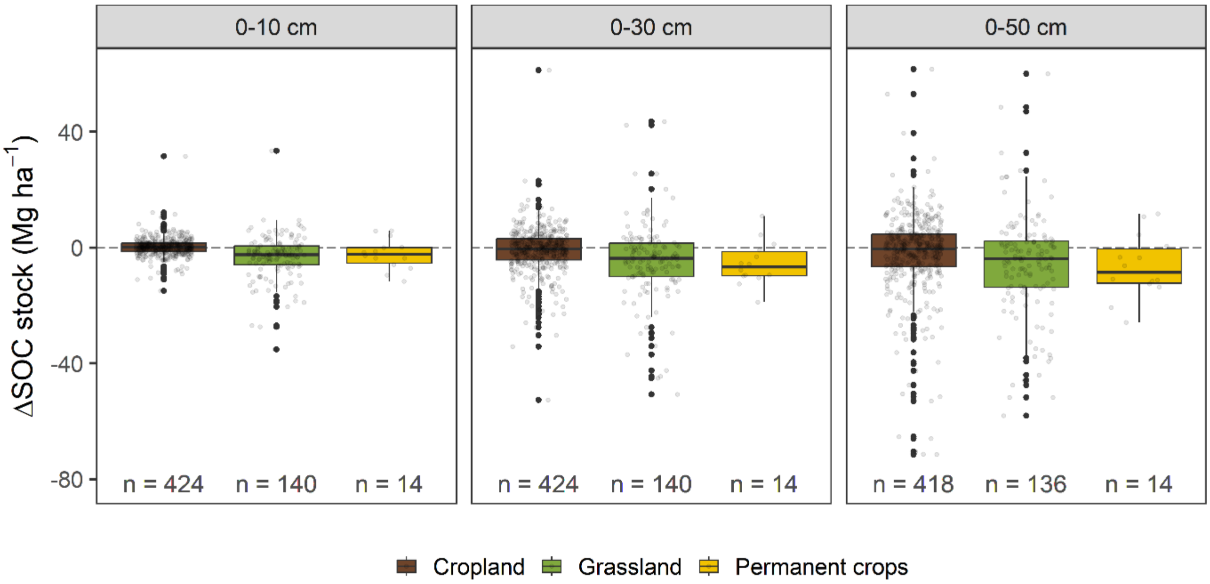
Land use	Depth (cm)	Positive/Negative (%)	Uncertain (%)	Sig. positive (%)	Sig. negative (%)
Cropland	0-10	56/44	60	24	16
	10-30	54/46	72	17	11
	30-50	45/55	84	10	6
Grassland	0-10	40/60	76	14	10
	10-30	45/55	86	8	6
	30-50	52/48	90	6	4
Permanent crops	0-10	40/60	73	16	11
	10-30	13/87	73	16	11
	30-50	40/60	93	4	3

Source: Thünen Institute

4.2 Temporal dynamics of organic soil carbon stocks

The mass-corrected changes in SOC stocks were significant in some cases on cropland. Interestingly, at a depth of 10-30 cm, there was a shift from a tendency toward an increase in SOC content to a significant, albeit slight, loss in SOC stocks (Fig. 9). This can be explained by the decrease in bulk density, which was on average about 0.03 g cm^{-3} (2%) lower in the field at a depth of 10-30 cm than in the initial inventory (Table A4). Cumulatively, and after mass correction, there was a slight but significant decrease in the SOC stock of -0.9 ± 8.2 Mg C ha^{-1} in the top 0-30 cm of the fields and of -2.1 ± 14.4 Mg C ha^{-1} in 0-50 cm (Fig. 9). In grasslands, the loss of reserves in 0-10 cm was particularly pronounced and, similar to the SOC content losses, also significant. Of the changes quantified across the entire soil profile (0-50 cm) of -5.5 ± 18.5 Mg C ha^{-1}, a significant portion was observed in the upper 10 cm (-3.2 ± 7.7 Mg C ha^{-1}. In the entire soil profile of grassland soils (0-50 cm), the differences in SOC stocks were comparable to those in 0-30 cm (-5.0 ± 13.8 Mg C ha^{-1}). For permanent crops, the negative trend in SOC stocks increased with cumulative depth and was also significant for depths of 0-30 cm and 0-50 cm. In all land use classes, there were significant decreases in the mean bulk densities of fine soil (1.9-6.4%) at 10-30 cm and 30-50 cm.

Figure 9 **Box plots (with 1st, 2nd, and 3rd quartiles) of SOC stock changes in the three cumulative depth levels with number of observations (n) for all land uses.**

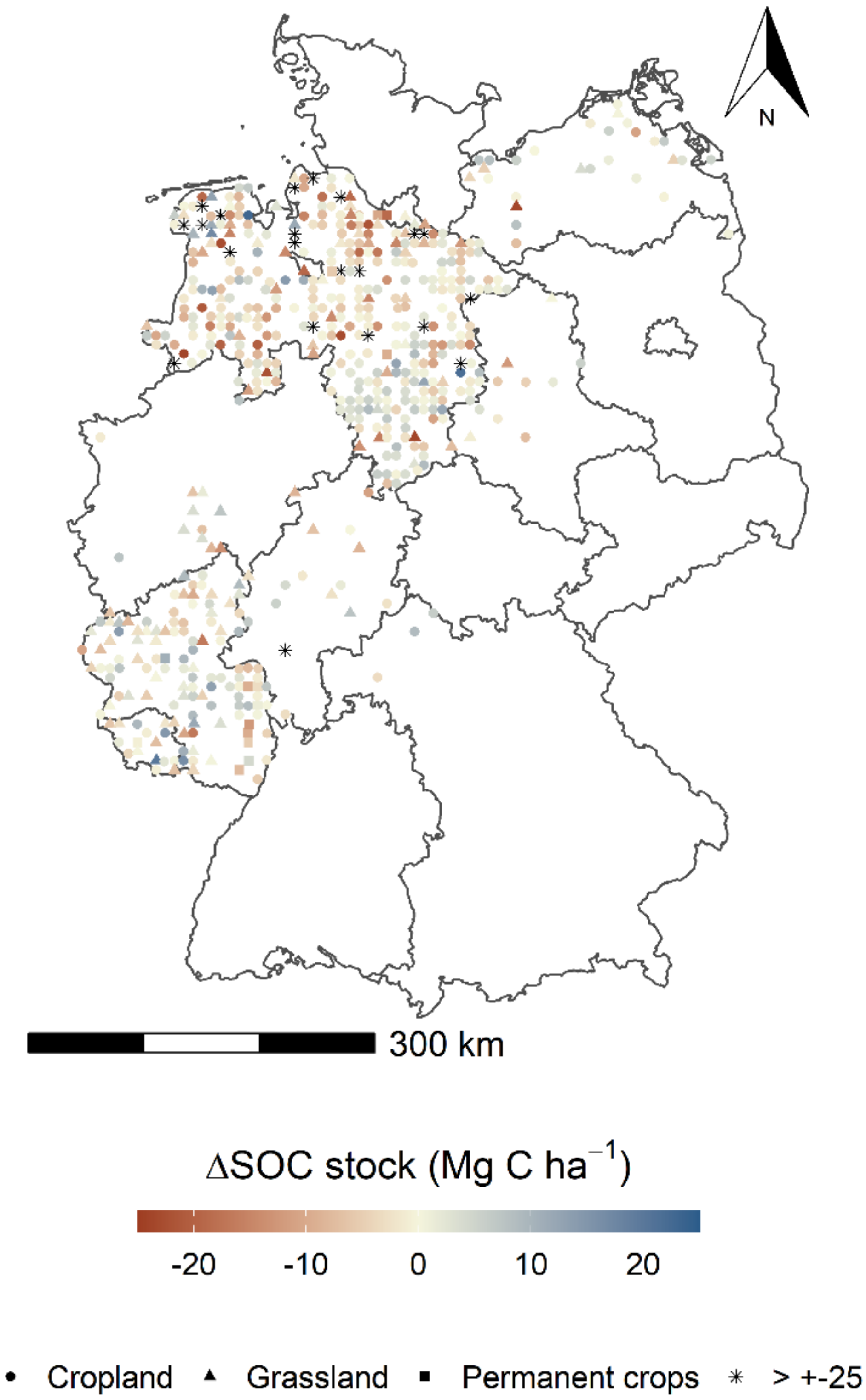


Source: Thünen Institute

Most of the resampled sites with core drilling data were located in the federal states of Lower Saxony, Rhineland-Palatinate, and Saarland, while Mecklenburg-Western Pomerania, North Rhine-Westphalia, Hesse, Saxony-Anhalt, and Bavaria were only sampled to a small extent (Fig. 10). The spatial pattern of the changes is not yet very clear, with the exception that the most severe losses have currently been quantified in Lower Saxony. Similarly, SOC changes above 25 Mg ha^{-1} were found almost exclusively in Lower Saxony.

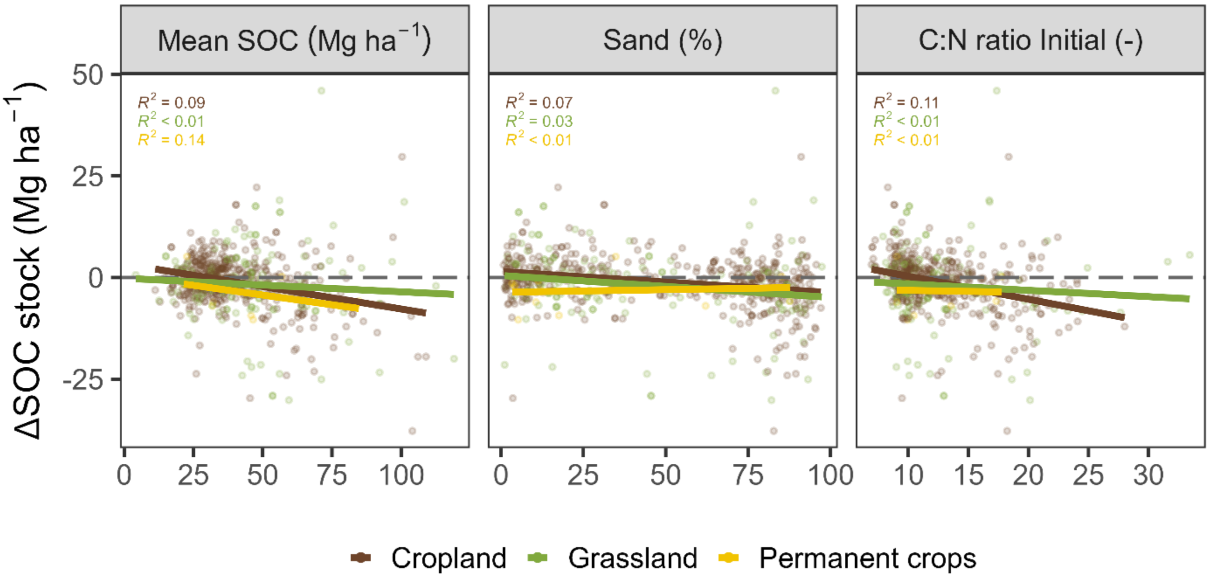
Three key soil properties provide initial indications of which soils experienced particularly high losses of SOC stocks in the 0–30 cm layer. First, weak negative correlations of the SOC stock change with the SOC stock of the site itself (Fig. 11; the higher the SOC stock increases the risk of losses). The SOC stocks of the two inventories were averaged for this purpose in order to exclude statistical artifacts. The sand content was also weakly negatively correlated with the change in SOC stocks (increasing losses with increasing sand content). In particular, a large number of very sandy sites (>80% sand) were found to have very high SOC losses. Ultimately, the C:N ratio was negatively correlated with the change in SOC stocks (the risk of SOC losses increases with a higher C:N ratio). Similar trends were observed for all three land uses. At this point in time, it can therefore be summarized, that sandy soils rich in SOC with wide C:N ratios tended to experience greater losses.

Figure 10 **Spatial distribution of SOC stock changes at a depth of 0-30 cm for all sites resampled to date for which core drilling data were available (n=578). Areas marked with an asterisk have deviations of more than 25 Mg ha[-1)] (n=21, 6 croplands, 15 grasslands).**



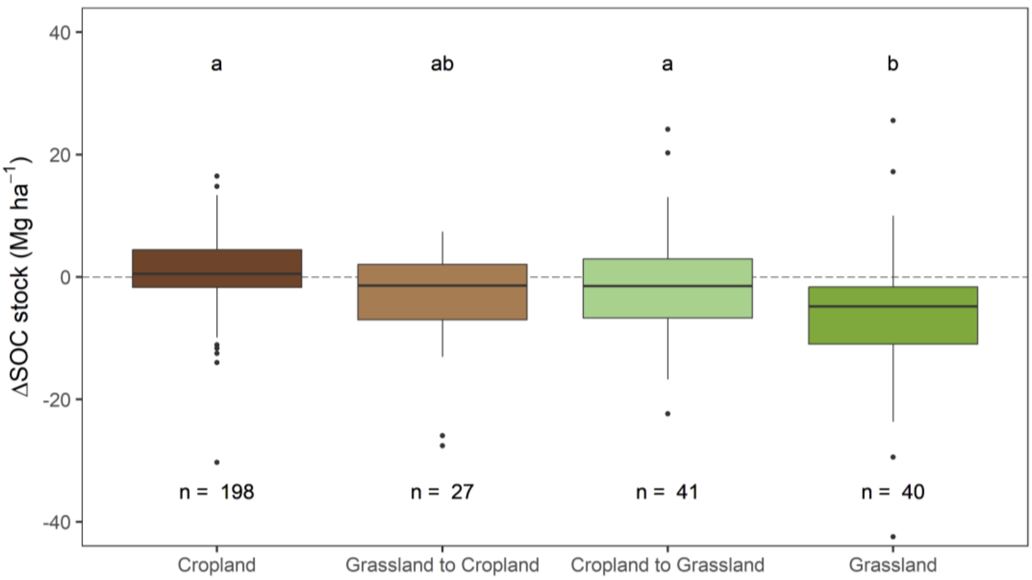
Source: Thünen Institute

Figure 11 **Changes in SOC stocks at a depth of 0-30 cm as a function of the mean SOC stock of the site (mean of both inventories), sand content, and initial C:N ratio for all three land use classes with correlation coefficients (R^2).**



Source: Thünen Institute

Figure 12 **Box plots (with 1st, 2nd, and 3rd quartiles) of the change in SOC stock at a depth of 0-30 cm in cropland (brown) and grassland sites (green), grouped according to land use history (cropland = long-term cropland, grassland to cropland = cropland with grassland history, cropland to grassland = grassland with cropland history, grassland = long-term grassland). Only those sites are shown that had no confirmed grassland rotation in the 10 years prior to the initial sampling, or were characterized by other previous uses (e.g., moor, heath, forest). The land use change is based on the last 136 years according to Emde et al. (2024).**



Source: Thünen Institute

A preliminary evaluation of the land use history showed that previous use as cropland or grassland had a significant influence on the recent dynamics of SOC stocks at a depth of 0-30 cm (Fig. 12). While cropland with a grassland history tended to show SOC losses, the SOC stocks of long-term cropland (no land use change in the last 136 years) tended to be in equilibrium. Conversely, a clear negative trend in SOC stocks was observed for long-term grassland, which differed significantly from grassland with a history of arable use.

4.3 Changes in key environmental and management influences

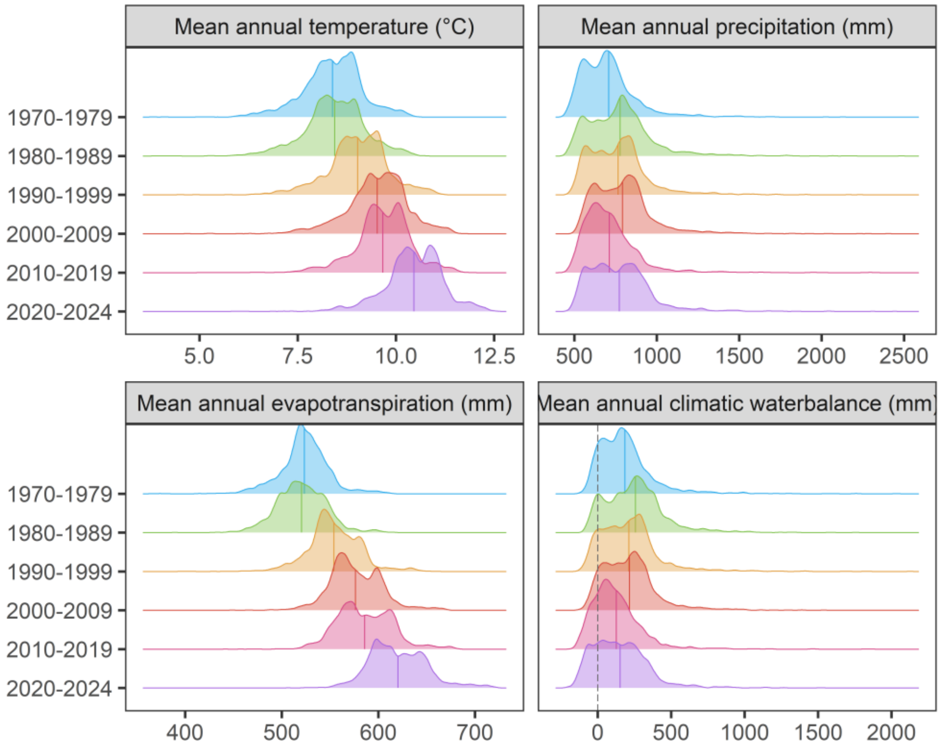
4.3.1 Changes in climatic conditions

Since the 1970s, the mean annual temperature of the air near the ground (2 m above ground level) has risen significantly at the 3104 BZE-LW sites (Fig. 13). While the mean annual temperature in the 1970s was 8.4°C, it has been 10.5°C in the past 5 years. A significant increase in the annual mean temperature has been observed, particularly in the last 15 years, representing a non-linear increase over the past 50 years (Fig. A1). Accordingly, potential evapotranspiration (evaporation) has also increased significantly with each decade. Annual precipitation, on the other hand, has changed little overall, causing the annual climatic water balance to become more negative or smaller. The proportion of potentially arid sites (more potential evaporation than precipitation on average over the calendar decade) has increased from 11% in the 1970s to 23% in the past five years. Cropland sites (26%) are more affected than grassland sites (14%). The spatial distribution of warming is much more homogeneous than the change in the climatic water balance (Fig. A2). The already dry east of Germany has become even drier over the past 50 years. Almost all BZE-LW sites in Brandenburg and Saxony-Anhalt, as well as parts of Mecklenburg-Western Pomerania and Saxony (Fig. A3), have been arid on average over the past 15 years. The proportion of arid sites has also increased significantly in Rhineland-Palatinate, Hesse, and Bavaria. In contrast, the climatic water balance in the far north-west of Germany has become more positive over the past 15 years. It can therefore be assumed that there will be region-specific effects of changed climatic conditions on soil properties.

4.3.2 Cover cropping

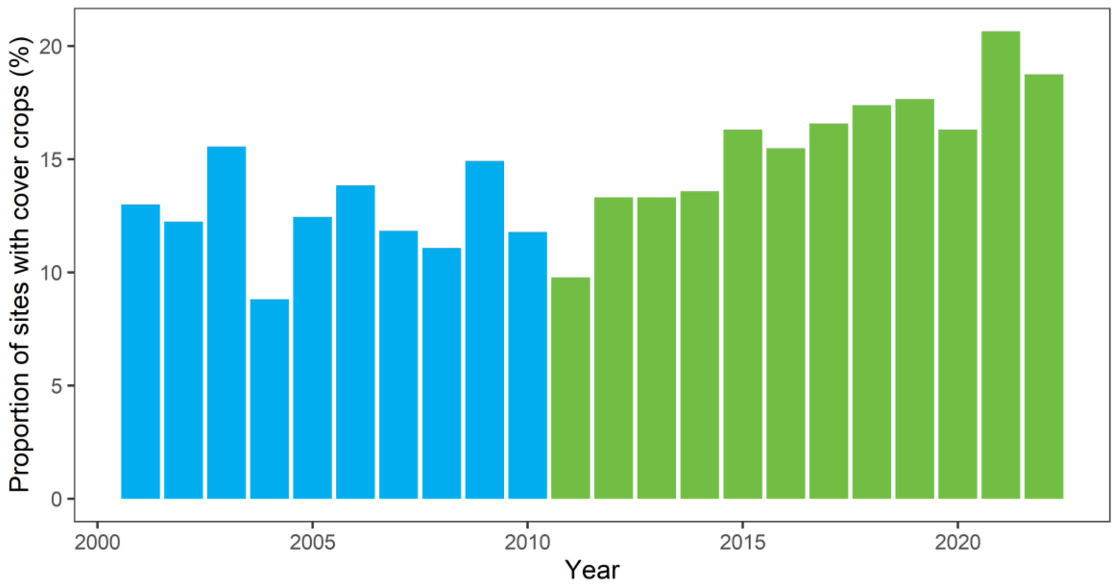
According to an initial evaluation of the two questionnaire data sets, the proportion of cropland sites with catch crops has increased significantly over the past 10 years (Fig. 14). While between 2000 and 2013 the average was around 12% of sites, the data from the repeat inventory questionnaire shows a clear upward trend. The past two years (2023, 2024) were not included in the time series due to insufficient data, but by 2022 the proportion of sites with a cover crop had risen to just under 20%.

Figure 13 **Distribution of mean annual temperature, mean monthly temperature, annual potential evaporation, and annual climatic water balance of all 3104 BZE-LW sites for the last six calendar decades.**



Source: Thünen Institute with data from the Deutscher Wetterdienst (DWD 2025a, b, c)

Figure 14 **Time series showing the proportion of sites with intercropping for each year in the period 2001-2022. Blue = initial inventory questionnaire, green = repeat inventory questionnaire. Where the two questionnaires overlapped (possible in the years 2011-2015), the information from the repeat inventory questionnaire was used for the sake of simplicity.**



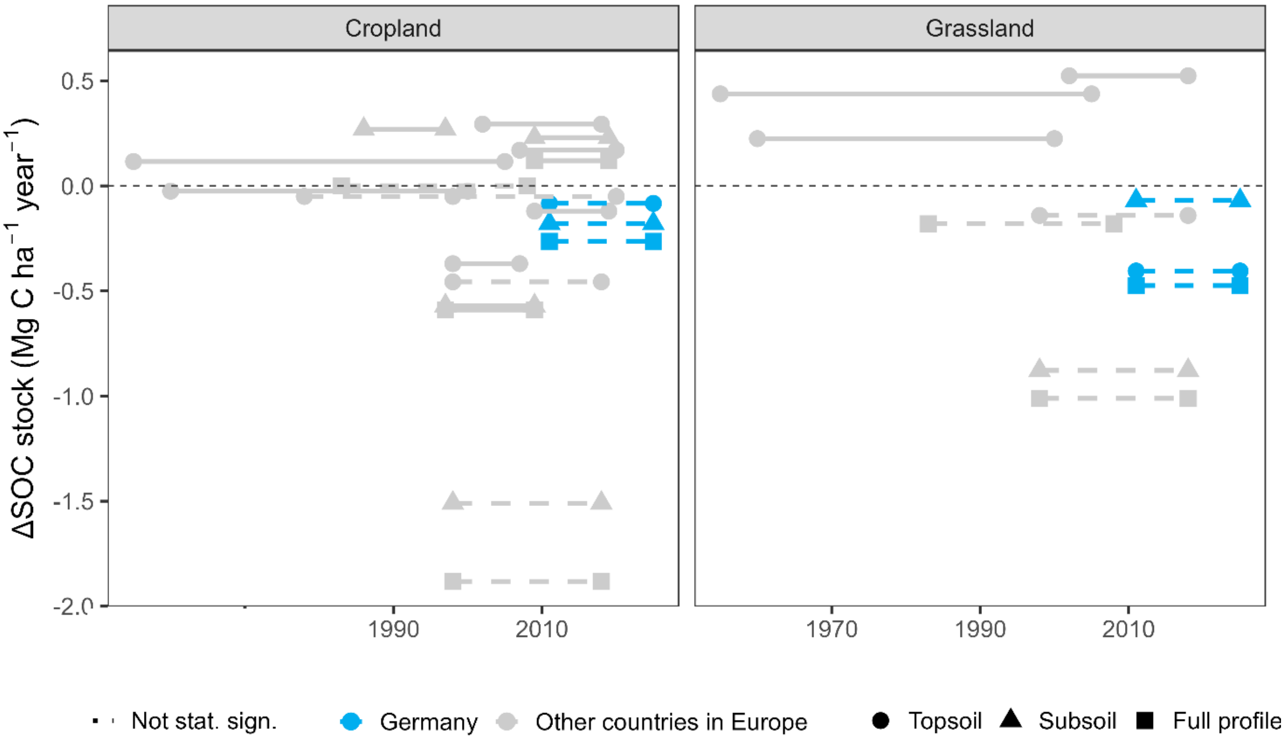
5 Discussion

5.1 Soil carbon dynamics in agricultural soils in Germany

In the BZE-LW cropland sites analyzed repeatedly, only small, albeit in some cases significant changes in SOC content and stocks have been observed. While there was a slight surplus of sites with a positive trend (SOC increase) in the topsoil (0-10 and 10-30 cm), slight losses were observed in the subsoil (30-50 cm). Analysis of the minimum detectable difference (MDD) for SOC content revealed that a large proportion (60%) of the changes observed at site level were below the detection limit (Fig. 8). This means that no reliable statements can be made about changes at these sites. For those sites with very small changes in particular, this can be interpreted as meaning that the positive or negative trend was more likely to be random. Nevertheless, a significant increase in SOC content was observed in the 0-10 cm depth of the cropland soils for 24% of the sites, while only 16% of the sites showed significant SOC losses (Table 1). Even though this was not reflected in the average cumulative SOC stock of cropland soils (Fig. 9), it could be an indication that both increased intercropping and more conservation-oriented, and thus shallower, tillage are having a certain positive effect. According to the Federal Statistical Office, conventional tillage using plows has declined from 53% to 40% in Germany over the past seven years (Destatis, 2025b). Conservation tillage, or no-till farming, ensures at least a redistribution of SOC within the soil profile, i.e., an enrichment in the area of the highest C inputs (close to the surface) and a tendency toward a decrease in the area below (abandoned topsoil) (Meurer et al., 2018). Intercropping has increased significantly over the past decade at the BZE sites already sampled (Fig. 14). This is consistent with statistics on a national scale: according to the Federal Statistical Office, intercropping has increased from just under 1.2 million hectares to just under 2.2 million hectares since 2010 (Destatis, 2024). This increase can be explained primarily by changes in agricultural subsidies and new regulations. With the reform of the Common Agricultural Policy in 2013, the creation of ecological priority areas, including the cultivation of cover crops, was specifically promoted for the first time. In addition, with the entry into force of the new Fertilizer Ordinance (2020), the cultivation of cover crops between winter and summer crops has become mandatory in nitrate-polluted, so-called red areas. The effects of these positive developments in soil management on SOC contents and stocks can therefore only be observed to a limited extent so far.

Despite the slightly positive trends in SOC content and stocks at a depth of 0-10 cm in cropland soils, there have been significant decreases in SOC stocks in all land use classes considered in the depth range relevant for greenhouse gas reporting (0-30 cm) over the past decade. This is comparable to the results from other regions in Europe. Various national inventories (Fig. 15) and the European Commission's Europe-wide soil inventory (LUCAS Soil) currently report negative trends in SOC contents and stocks (De Rosa et al., 2024). This also applies in part to the long-term soil monitoring of the federal states (Höper and Meesenburg, 2021; Wiesmeier et al., 2025). The lack of measurable positive effects of improved soil management on average SOC contents and stocks in cropland soils, as well as the even more pronounced loss of SOC from grassland soils and those under permanent cultivation, can have various causes.

Figure 15 Annual rates of change in average national SOC stocks in various European countries and Germany for cropland and grassland in the respective inventory periods, differentiated by topsoil, subsoil (defined slightly differently depending on the study) and the entire soil profile (if relevant). The data are taken from a previously unpublished literature review and are presented here in modified form (Harbo et al., submitted).



Source: Thünen Institute

1) Increasing cover crop cultivation from 10% to 20% of the annual cultivated area has a relatively small effect on the SOCreserves of all cropland soils. A share of 10% means that, mathematically speaking, every field has a cover crop once every 10 years on average. Doubling this cultivation area is not only a positive development for SOCin the soil, but is also relevant for many soil and ecosystem functions (Shackelford et al., 2019) . Doubling the annual cultivation area means that, on average, a cover crop is currently cultivated twice in 10 years. The average effect of green manure from cover crops on the SOC stock is approximately 0.3 Mg ha^{-1} yr^{-1} with annual cultivation (Poeplau and Don, 2015). However, if only one more cover crop was grown in the past decade, then the expected effect is very small compared to other possible effects on the SOC stock (see following points) and compared to the magnitude of the random sampling error. The random sampling error was estimated at an average of about 3 Mg ha^{-1} when sampling and resampling cropland soils using three soil profiles on the same day (Poeplau et al., 2022). In addition, the proportion of catch crops has not increased sharply over the last decade, but rather gradually. It is therefore likely that the effect of an overall doubling of the area under catch crop cultivation on SOC stocks is still too small to be detectable as such in the repeat inventory of the BZE-LW on a national scale. However, if intercropping is included in a larger statistical model in the future, it is likely that part of the variability in SOC stock changes will be explained by this trend.

2) Climate change is highly likely to have a negative impact on global SOC stocks (García-Palacios et al., 2021). In recent decades, and especially in the current decade, Central Europe has warmed significantly. An increase in the annual mean temperature of 2°C since the 1970s has now been exceeded at all BZE-LW sites

(Fig. 13 and Fig. A1). In the period between the initial and repeat inventories alone, a warming of the air near the ground of about 1°C was measured. It has also been shown that the soil temperature in cropland soils rises more strongly than the air temperature (Dorau et al., 2022). This has consequences for microbial activity and thus the turnover of organic matter in the soil.

According to model calculations and warming experiments in different climate zones, the magnitude of the relative loss of SOC due to warming is approximately 3-5% per °C increase in near-surface air temperature (Peplau et al., 2021; Poeplau and Dechow, 2023; Verbrigghe et al., 2022). With an average initial SOC stock of 65 Mg ha^{-1} initial mean value in 0-30 cm of the cropland sites sampled to date would correspond to approximately 1.9-3.3 Mg ha^{-1}; for grasslands (initial mean value of 89 Mg ha^{-1} this would already be 2.7-4.5 Mg ha^{-1}. In addition, higher evaporation and an accumulation of dry years in many places are leading to a trend toward drier conditions (Fig. A2), which can have a negative impact on yield formation and thus on C inputs. Although the average yields of the most important crops have continued to rise slightly over the past 20 years, interannual yield variability has also increased significantly, and the size of irrigated cropland in Germany has risen from 370,000 hectares in 2009 to around 500,000 hectares in 2019 (Destatis, 2023). In grasslands, weather conditions have a particularly strong influence on biomass development (Liu et al., 2023), and so the dry years of 2018 and 2022 resulted in two years of low yields in grasslands between the two sampling periods (Destatis, 2025a).

In rather dry locations, the permanent decrease in soil moisture can have a negative effect on the mineralization of SOC (Kuka et al., 2025), but in rather wet locations, the opposite can also be the case (Smith et al., 2007; Van Wesemael et al., 2010), as drying leads to increased aeration and thus stimulation of microorganisms. The effects of rapid climate change are complex, and at least the temperature increase is omnipresent to a similar extent. For this reason, the temperature increase, or other climate variables, could not explain the variability of SOCchanges in simple regression analyses (data not shown). This will be similar in more complex statistical models, which is why only the use of process models can isolate the potential climate change signal in SOC dynamics from other influences. However, it is important to carefully check whether these models can correctly represent climate change effects (Hararuk et al., 2015). The fact is that, in many places, improved soil management in the face of advancing climate change can no longer be about enriching SOC, but merely about limiting losses (Don et al., 2024b; Riggers et al., 2021).

3) Changes in the SOC content of the soil occur over long periods of time, which means that past conditions can persist or have a lasting effect for a long time, thereby also influencing current trends (Fig. 12). After extensive research into land use history, it was shown for the initial BZE data set that grassland or arable land use can have an effect lasting several decades (Emde et al., 2024). The new steady state of the SOC stock in cropland soils after grassland use was estimated at around 180 years. In line with this, the present report also showed that fields that had been used as grassland in the past 136 years tended to lose SOC on average, whereas this was not the case for long-term croplands. A reverse trend was observed for grassland sites, which indicates the influence of land use history.

Fundamentally, and viewed over a very long period of time, all of today's cropland soils are highly likely to have a history of higher SOC contents (Sanderman et al., 2017), which may continue to have an impact to this day. For example, losses of SOC in Finnish cropland soils have been linked to deforestation that took place decades ago (Heikkinen et al., 2013). In contrast, there are long-term grasslands that have presumably not been used as cropland due to site characteristics. These site characteristics include, for example, waterlogging and low groundwater levels, which do not allow cultivation as cropland. In fact, permanent grasslands with high losses contain an above-average number of marshes and gley soils (data not shown), which also have elevated SOC stocks due to high groundwater levels (Poeplau et al., 2020). Figure 12 of the land use history shown here should therefore not be misinterpreted to mean that plowing up grassland can lead to a reduction in SOC loss; the opposite is true. Rather, it shows that site characteristics and land use history are closely intertwined and that both have an impact on recent SOC dynamics. SOC dynamics.

In northwestern Germany in particular, there were massive reductions in the groundwater level in the last century in order to convert formerly marshy areas and moors to agricultural use. Even though many of these soils are now classified as mineral soils, some of them are very SOC rich, and their SOC stocks are certainly not yet in equilibrium and therefore tend to decline. These losses are unlikely to be offset by cultivation. Many of these soils are also characterized by wide C:N ratios and a sandy texture and were already highlighted as black sands in the initial BZE-LW (Poeplau et al., 2021; Vos et al., 2018). Accordingly, changes in SOC stocks in all three land use classes tended to correlate negatively with the initial C:N ratio, the mean SOC stock, and the sand content (tendency of SOC to decrease at sites with a wide C:N ratio, high SOC stock, and high sand content). These initial trends are consistent with the results of long-term observations in Lower Saxony, where cropland and grassland sites close to groundwater (sandy gley soils) showed the greatest SOC losses compared to less sandy soils further away from groundwater (Höper and Meesenburg, 2021). The highest losses of SOC in grassland soils shown in Fig. 15 also conceal the SOC -rich soils of the Netherlands, a region bordering Lower Saxony with comparable soil genesis.

However, the high SOC contents of the predominantly northwestern German black humus sands may also have other causes and thus have different effects on the current dynamics. For example, sod cutting was very widespread in Lower Saxony, enriching the very nutrient-poor sandy soils with organic matter (Blume and Leinweber, 2004) . In addition, some of today's cropland was once covered by heathland, which may have left behind very stable organic matter in the soil (Springob and Kirchmann, 2010). A more detailed evaluation of the land use history, together with a characterization of the organic matter, will provide more information about the potential SOC dynamics of these soils in the future.

4) In addition to declining livestock numbers, mineral fertilization in Germany has also been gradually reduced over the past decades. Nitrogen surpluses in the soil have thus fallen from 177 kg per hectare of agricultural land in the 1990s to around 77 kg in the early 2020s (Federal Environment Agency, 2024). Overall, nitrogen inputs into agricultural systems and soils have also been reduced nationwide. These trends can also be reflected in the dynamics of SOC contents and stocks in cropland and grassland soils if the reduced N inputs mean lower yields and thus less biomass input into the soil. Various fertilization experiments on both grassland and cropland soils have shown that the SOC stock is linearly correlated with the amount of nitrogen fertilization and that approximately one kilogram of SOC is built up in the soil per kilogram of mineral nitrogen fertilizer (Kätterer et al., 2012; Poeplau et al., 2018) . Conversely, extensive agricultural production also carries the risk of a shrinking SOC reserve in favor of other positive environmental effects. A preliminary evaluation of 45 grassland questionnaires from the repeat inventory showed an average decrease in nitrogen fertilization (organic and mineral) of 32 kg N (-19%) compared to the initial inventory (data not shown). However, whether a reduction in N fertilization has an effect on humus depends crucially on its yield effectiveness. In the case of the reduction of high N surpluses that are harmful to the environment and climate, it can be assumed that the yield and organic matter effectiveness is low.

The SOC dynamics of a soil are therefore influenced simultaneously by recent soil management, individual previous use or history, and changes in abiotic site characteristics (Heikkinen et al., 2013). A more in-depth analysis of the factors controlling the SOC dynamics of the BZE-LW sites was not possible at this point in time, or rather, it did not make much sense due to the still fragmented data situation. In the currently sampled population, the soils of Lower Saxony play a major role in terms of quantity, which, as described, are strongly influenced by their sometimes very specific history in terms of hydrology and land use. Fig. 10 clearly shows that the most extreme SOC changes also occurred in this region. It therefore remains to be seen whether the results obtained so far will be confirmed for the whole of Germany. The mean values reported here are therefore of limited significance and should not be extrapolated as such. However, the fact that a negative trend in SOC stocks was found for all land uses and across different regions suggests that global warming is already having a negative impact on SOC stocks in agricultural soils in Germany. This has recently been counteracted in cropland soils, primarily through the increased cultivation of catch crops, while in grassland soils, changes in fertilization intensity and organic fertilization may have had an additional negative impact on SOC stocks (Poeplau et al., 2018).

5.2 An unscheduled course correction in the agricultural soil condition survey

A very fundamental difficulty of large-scale soil monitoring over long periods of time is that many soil properties change relatively slowly and therefore relatively little per unit of time. The framework conditions for soil inventories, on the other hand, can change significantly from one iteration to the next. In order to be able to detect the small changes in soil properties with certainty, an exact and, in the best case, unchanging procedure in the field and laboratory is an important theoretical prerequisite, but rarely a reality. Changes in political, financial, organizational, content-related, or analytical conditions all too often lead to changes that can have a more or less significant impact on the quality of time series. Classic examples include changes in analytical methods, contract laboratories, or even individual devices (Even et al., 2025; Wollmann et al., 2025), the not entirely accurate relocation of sites (Heikkinen et al., 2020), variation in the number of sites (Poeplau et al., 2015), or even changes in sampling depth (Jones et al., 2024). Such serious changes should be avoided if possible or, if necessary, mitigated by corrective functions. While the latter is established practice for analytical methods, a directional sampling error can hardly be corrected.

Even though the BZE-LW has always placed great emphasis on consistency and continuity, it is not free from systematic errors. During the evaluation of the initial BZE-LW, it was already established that the two methods used to determine SOC -contents and SOC stocks (profile pits, core drilling) led to different results. This is not surprising. It has already been shown elsewhere that the type of sampling alone can have a significant influence on the result of the analysis (Del Duca et al., 2025; Walter et al., 2016). However, the evaluation of the initial inventory did not reveal which of the two methods is less prone to error, as both approaches are known to have strengths and weaknesses. In addition, only some of the core drilling samples could be processed and measured due to resource constraints.

Furthermore, core drilling is only of limited suitability for determining bulk density and stone content, ii) causes relatively extensive damage to standing crops due to the use of large equipment, iii) requires a greater amount of manpower, and iv) all other parameters were also determined from the profile pit samples, the repeat inventory was also carried out using profile pits. From the outset, care was taken to ensure that a representative sample was taken from each small test pit at the respective depth level. This was achieved by taking a uniformly thick slice of soil material from the profile wall over the entire length of the pit. In the initial inventory, this was also theoretically the case, but with one important restriction: at that time, an attempt was made to carry out coupled sampling of depth levels and diagnostic horizons so that both variants could be evaluated. However, additional samples were only taken at so-called intermediate depth levels when there was a distance of five cm or more between the horizon and depth level boundaries. If, for example, a plow horizon ended at 27 cm and the depth levels of the plow horizon to be sampled were 0-10 and 10-30 cm, the official task was to sample the lower three centimeters of the depth level to the same extent and to mix it with the 10-30 cm sample.

The greatest deviations between the profile pit and core drilling in the field were indeed found precisely in the 10-30 cm depth level. In grassland, it is the 0-10 cm depth level where there is also a strong vertical gradient in the SOC content to the underlying soil material. Under certain circumstances, the inclusion of horizon boundaries in depth-specific sampling may have led to unrepresentative depth samples in some cases. Such an error is ruled out in sampling with drill cores, as sampling was carried out precisely according to depth levels and no selection can be made during drilling as to where exactly the sample material is taken. Due to the fixed positions of the eight drill cores, this is a systematically random sampling (Brus and Saby, 2016) . The evaluation of the repeat inventory now suggests that sampling with drill cores does indeed provide the more stable and accurate SOC contents for the sampled plots. Even though the absolute directed deviation between profile pits and ram core sampling in SOC content in the most affected depth levels was only 1-2 g kg^{-1} i.e., about 0.1-0.2 percentage points SOC (Jacobs et al., 2018), this has a relatively strong impact on the SOC stock and its change. Therefore, this systematic deviation cannot be ignored and must result in an adjustment of the methodology. In the case of the evaluation presented here, it was decided to combine the advantages of both sampling systems of the initial soil inventory (soil profile, drill cores) in order to determine the stocks of organic soil matter. The drill cores from the core drilling were used to record the SOC contents at defined depth levels, while the dry bulk density was recorded at the central soil profile.

As a direct consequence, the number of sites that could be evaluated for this interim report (sites with already analyzed drill cores) decreased, and it became necessary to initiate remeasurements of the samples from the core drilling. As shown in Fig. 5, in which there are only very weak correlations between the SOC changes based on profile pits and core drilling, there are also advantages to taking this time-consuming step . A single profile pit, even in a central position, cannot adequately represent a plot (now 12x12 m) due to known small-scale variability and, per se, introduces a high degree of random uncertainty into the data set. Even a slight positive deviation of the SOC content in the pit from the plot mean already increases the probability of a negative trend in resampling and vice versa (Slessarev et al., 2023). Spatial replication is therefore important even in the smallest plots (Poeplau et al., 2022). Spatial replication with subsequent analysis of all individual samples has the great advantage over a mixed sample in that the small-scale variability at the specific location is known and thus an uncertainty can be specified for each inventory run. This can be used to statistically validate measured changes at the site and thus support the interpretation of observations. It can even be used to develop specific sampling strategies. For example, the present evaluation has shown that the minimum detectable difference (MDD) in grassland soils tends to be higher than in cropland soils. One could conclude from this that the number of samples in grassland soils should be higher than in cropland soils. However, since the differences in MDD between individual sites within each land use are even more extreme than the differences between land uses, this is not necessarily expedient.

6 Outlook

At this stage of the project, no representative picture of changes in soil properties for agricultural soils in Germany has yet emerged. Initial trends have been observed and possible causes identified. In addition to expanding and improving the data set, a main objective in the coming project phase will be to delve deeper into researching the causes and explaining changes in key soil properties. The separation of the influences of recent soil management, climate change, and site history on observed changes in soil properties plays a central role. The systematic use of the collected management data, as well as other external data (e.g., remote sensing products) in process models and statistical approaches will play an important role in this. Only by using a broad methodological spectrum can complex and overlapping spatial patterns be resolved in order to ultimately classify observed changes and incorporate them into political decision-making processes. The second phase of the BZE-LW repeat inventory (until 2030) also presents some particular challenges:

This report has focused heavily on the parameter SOC. This parameter remains of central importance for current reporting requirements. However, a number of other parameters are also being collected that are more or less closely related to SOC and will provide additional insights relevant to practice, policy, and science on the development of agricultural soils. These include pH values, cation exchange capacity, and base saturation, which provide information about the nutrient supply and liming requirements of soils; air capacity of the subsoil and aggregate stability of the topsoil as structural parameters; and the quality of organic matter. The general decline in dry bulk density reported here (Table A4) must also be investigated and understood in more detail. A similar trend was observed for cropland and grassland soils in the French soil inventory (RMQS), but this has also not yet been explained (Munera-Echeverri et al., 2025). Due to the implications for SOC stock calculations, the aforementioned study suggested working with unchanged dry bulk density values in this case. In the next phase of the BZE-LW project, a comparison of different methods for calculating SOC stocks could provide information on the influence of variations in the handling of dry bulk densities on changes in SOC stocks.

The Soil Monitoring Law is an important environmental policy innovation of the European Union, which aims to harmonize soil protection on a continental scale and strengthen it in a legally binding manner. At this point in time, it is uncertain how the Soil Monitoring Law will affect soil monitoring in Germany as a whole, and in particular the repeat inventory of the BZE-LW. Redensification and expansion of the grid, shortening of the sampling interval to six years, new parameters, and land use classes will increase the cost of soil monitoring in Germany, with existing systems in Germany forming an important basis.

In addition to the *Soil Monitoring Law*, two further reporting obligations have recently been introduced for which the BZE-LW can and will provide data: the first is the German adaptation strategy to climate change, which has set concrete, measurable targets for the first time since 2024. One of the targets is to prevent SOC losses from German agricultural soils. An even more ambitious target has been set by the Nature Restoration Law: here, cropland soils should show an upward trend in SOC contents on average.

References

Ad-Hoc-Ag Boden, 2005. Bodenkundliche Kartieranleitung, 5. E.Schweizerbart'sche Verlagsbuchhandlung, Hannover.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. Fao, Rome 300(9), D05109.

Çetinkaya-Rundel, M., Hardin, J., 2024. Bootstrap confidence interval for the mean paired difference., Introduction to modern statistics. OpenIntro.

De Rosa, D., Ballabio, C., Lugato, E., Fasiolo, M., Jones, A., Panagos, P., 2024. Soil organic carbon stocks in European croplands and grasslands: How much have we lost in the past decade? Global Change Biology 30(1), e16992.

Del Duca, S., Tondini, E., Vitali, F., Lumini, E., Garlato, A., Vinci, I., Tagliaferri, E., Brenna, S., Motta, S., Maillet, E., Bispo, A., Orgiazzi, A., Jones, A., Mocali, S., Fantappiè, M., 2025. Comparison of LUCAS and Italian Sampling Procedures for Harmonising Physicochemical and Biological Soil Health Indicators. European Journal of Soil Science 76(3), e70108.

Destatis, 2023. Agrarstrukturerhebung Statistischer Bericht.

Destatis, 2024. Landwirtschaftliche Betriebe mit Zwischenfruchtanbau im Zeitvergleich, https://www.destatis.de/DE/Themen/Branchen-Unternehmen/Landwirtschaft-Forstwirtschaft-Fischerei/Feldfruechte-Gruenland/Tabellen/zwischenfruechte.html.

Destatis, 2025a. Grünland 2025: Erntemengen um 4 % niedriger als 2024, https://www.destatis.de/DE/Themen/Branchen-Unternehmen/Landwirtschaft-Forstwirtschaft-Fischerei/Feldfruechte-Gruenland/aktuell-gruenland1.html.

Destatis, 2025b. Pflugeinsatz verliert in der Landwirtschaft an Bedeutung, https://www.destatis.de/DE/Presse/Pressemitteilungen/2024/05/PD24_212_41.html.

Don, A., Drexler, S., Poeplau, C., 2024a. Indikatoren zur Bewertung von Humusgehalten für die Bodengesundheit. Bodenschutz (1), 8-15.

Don, A., Seidel, F., Leifeld, J., Kätterer, T., Martin, M., Pellerin, S., Emde, D., Seitz, D., Chenu, C., 2024b. Carbon sequestration in soils and climate change mitigation—Definitions and pitfalls. Global Change Biology 30(1), e16983.

Dorau, K., Bamminger, C., Koch, D., Mansfeldt, T., 2022. Evidences of soil warming from long-term trends (1951–2018) in North Rhine-Westphalia, Germany. Climatic Change 170(1), 9.

Drexler, S., Broll, G., Flessa, H., Don, A., 2022. Benchmarking soil organic carbon to support agricultural carbon management: A German case study#. Journal of Plant Nutrition and Soil Science 185(3), 427-440.

DWD, C.D.C., 2025a. Raster der Monatsmittel der Lufttemperatur (2m) für Deutschland, Version v1.0., https://opendata.dwd.de/climate_environment/CDC/grids_germany/monthly/air_temperature_mean/.

DWD, C.D.C., 2025b. Raster der Monatssumme der Niederschlagshöhe für Deutschland, Version v1.0. , https://opendata.dwd.de/climate_environment/CDC/grids_germany/monthly/precipitation/.

DWD, C.D.C., 2025c. Raster der Monatssumme der Sonnenscheindauer für Deutschland, Version v1.0. , https://opendata.dwd.de/climate_environment/CDC/grids_germany/monthly/sunshine_duration/.

Ellert, B.H., Bettany, J.R., 1995. Calculation of organic matter and nutrients stored in soils under contrasting management regimes. Canadian Journal of Soil Science 75(4), 529-538.

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. Global Change Biology 30(8), e17444.

Even, R.J., Machmuller, M.B., Lavallee, J.M., Zelikova, T.J., Cotrufo, M.F., 2025. Large errors in soil carbon measurements attributed to inconsistent sample processing. SOIL 11(1), 17-34.

Freibauer, A., Rounsevell, M.D.A., Smith, P., Verhagen, J., 2004. Carbon sequestration in the agricultural soils of Europe. Geoderma 122(1), 1-23.

Froger, C., Tondini, E., Arrouays, D., Oorts, K., Poeplau, C., Wetterlind, J., Putku, E., Saby, N.P.A., Fantappiè, M., Styc, Q., Chenu, C., Salomez, J., Callewaert, S., Vanwindekens, F.M., Huyghebaert, B., Herinckx, J., Heilek, S., Sofie Harbo, L., De Carvalho Gomes, L., Lázaro-López, A., Antonio Rodriguez, J., Pindral, S., Smreczak, B., Benő, A., Bakacsi, Z., Teuling, K., van Egmond, F., Hutár, V., Pálka, B., Abrahám, D., Bispo, A., 2024. Comparing LUCAS Soil and national systems: Towards a harmonized European Soil monitoring network. Geoderma 449, 117027.

García-Palacios, P., Crowther, T.W., Dacal, M., Hartley, I.P., Reinsch, S., Rinnan, R., Rousk, J., van den Hoogen, J., Ye, J.-S., Bradford, M.A., 2021. Evidence for large microbial-mediated losses of soil carbon under anthropogenic warming. Nature Reviews Earth & Environment 2(7), 507-517.

Hararuk, O., Smith, M.J., Luo, Y., 2015. Microbial models with data-driven parameters predict stronger soil carbon responses to climate change. Global Change Biology 21(6), 2439-2453.

Heikkinen, J., Keskinen, R., Regina, K., Honkanen, H., Nuutinen, V., 2020. Estimation of carbon stocks in boreal cropland soils - methodological considerations. European Journal of Soil Science 72(2), 934-945.

Heikkinen, J., Ketoja, E., Nuutinen, V., Regina, K., 2013. Declining trend of carbon in Finnish cropland soils in 1974–2009. Global change biology 19(5), 1456-1469.

Ho, J., Tumkaya, T., Aryal, S., Choi, H., Claridge-Chang, A., 2019. Moving beyond P values: data analysis with estimation graphics. Nature Methods 16(7), 565-566.

Höper, H., Meesenburg, H., 2021. 30 Jahre Bodendauerbeobachtung in Niedersachsen. Landesamt für Bergbau, Energie und Geologie.

Jacobs, A., Flessa, H., Don, A., Heidkamp, A., Prietz, R., Dechow, R., Gensior, A., Poeplau, C., Riggers, C., Schneider, F., 2018. Landwirtschaftlich genutzte Böden in Deutschland: Ergebnisse der Bodenzustandserhebung. Thünen Report.

Jaconi, A., Don, A., Freibauer, A., 2017. Prediction of soil organic carbon at the country scale: stratification strategies for near-infrared data. European Journal of Soil Science 68(6), 919-929.

Jones, A., Orgiazzi, A., Panagos, P., Scarpa, S., Havenga, C., Van Eynde, E., 2024. LUCAS 2022 Soil Module. JRC Technical Report.

Kuka, K., Schädler, M., Reitz, T., Franko, U., 2025. Evaluating grassland ecosystem responses to management practices and climate change: results from the Global Change Experimental Facility in Bad Lauchstädt (Germany). Plant and Soil.

Liu, C., Siri, M., Li, H., Ren, C., Huang, J., Feng, C., Liu, K., 2023. Drought is threatening plant growth and soil nutrients of grassland ecosystems: A meta-analysis. Ecology and Evolution 13(5), e10092.

Margenot, A.J., Parikh, S.J., Calderón, F.J., 2023. Fourier-transform infrared spectroscopy for soil organic matter analysis. Soil Science Society of America Journal 87(6), 1503-1528.

Meurer, K.H., Haddaway, N.R., Bolinder, M.A., Kätterer, T., 2018. Tillage intensity affects total SOC stocks in boreo-temperate regions only in the topsoil—A systematic review using an ESM approach. Earth-Science Reviews 177, 613-622.

Minasny, B., Malone, B.P., McBratney, A.B., Angers, D.A., Arrouays, D., Chambers, A., Chaplot, V., Chen, Z.-S., Cheng, K., Das, B.S., 2017. Soil carbon 4 per mille. Geoderma 292, 59-86.

Munera-Echeverri, J.-L., Boulonne, L., Arrouays, D., Saby, N., Soler-Dominguez, N., Ratié, C., Jolivet, C., Martin, M.P., 2025. Bulk density and coarse fragment content of the French soil monitoring network for better assessment of changes of soil organic carbon stocks. CATENA 248, 108609.

Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G.P., Smith, P., 2016. Climate-smart soils. Nature 532(7597), 49-57.

Peplau, T., Schroeder, J., Gregorich, E., Poeplau, C., 2021. Long-term geothermal warming reduced stocks of carbon but not nitrogen in a subarctic forest soil. Global Change Biology 27(20), 5341-5355.

Poeplau, C., Bolinder, M.A., Eriksson, J., Lundblad, M., Kätterer, T., 2015. Positive trends in organic carbon storage in Swedish agricultural soils due to unexpected socio-economic drivers. Biogeosciences Discuss. 12(5), 3991-4019.

Poeplau, C., Dechow, R., 2023. The legacy of one hundred years of climate change for organic carbon stocks in global agricultural topsoils. Scientific Reports 13(1), 7483.

Poeplau, C., Don, A., 2015. Carbon sequestration in agricultural soils via cultivation of cover crops–A meta-analysis. Agriculture, Ecosystems & Environment 200, 33-41.

Poeplau, C., Jacobs, A., Don, A., Vos, C., Schneider, F., Wittnebel, M., Tiemeyer, B., Heidkamp, A., Prietz, R., Flessa, H., 2020. Stocks of organic carbon in German agricultural soils—Key results of the first comprehensive inventory. Journal of Plant nutrition and soil science 183(6), 665-681.

Poeplau, C., Jacobs, A., Don, A., Vos, C., Schneider, F., Wittnebel, M., Tiemeyer, B., Heidkamp, A., Prietz, R., Flessa, H., 2021. Stocks of organic carbon in German agricultural soils—Key results of the first comprehensive inventory. n/a(n/a).

Poeplau, C., Prietz, R., Don, A., 2022. Plot-scale variability of organic carbon in temperate agricultural soils—Implications for soil monitoring. Journal of Plant Nutrition and Soil Science 185(3), 403-416.

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.

Poeplau, C., Zopf, D., Greiner, B., Geerts, R., Korvaar, H., Thumm, U., Don, A., Heidkamp, A., Flessa, H., 2018. Why does mineral fertilization increase soil carbon stocks in temperate grasslands? Agriculture, Ecosystems & Environment 265, 144-155.

Riggers, C., Poeplau, C., Don, A., Frühauf, C., Dechow, R., 2021. How much carbon input is required to preserve or increase projected soil organic carbon stocks in German croplands under climate change? Plant and Soil.

Sanderman, J., Hengl, T., Fiske, G.J., 2017. Soil carbon debt of 12,000 years of human land use. Proceedings of the National Academy of Sciences 114(36), 9575-9580.

Sanderman, J., Savage, K., Dangal, S.R.S., 2020. Mid-infrared spectroscopy for prediction of soil health indicators in the United States. Soil Science Society of America Journal 84(1), 251-261.

Schiedung, M., Barré, P., Peoplau, C., 2025. Separating fast from slow cycling soil organic carbon – A multi-method comparison on land use change sites. Geoderma 453, 117154.

Schrumpf, M., Schulze, E., Kaiser, K., Schumacher, J., 2011. How accurately can soil organic carbon stocks and stock changes be quantified by soil inventories? Biogeosciences 8(5), 1193-1212.

Slessarev, E.W., Mayer, A., Kelly, C., Georgiou, K., Pett-Ridge, J., Nuccio, E.E., 2023. Initial soil organic carbon stocks govern changes in soil carbon: Reality or artifact? Global Change Biology 29(5), 1239-1247.

Smith, P., Chapman, S.J., Scott, W.A., Black, H.I., Wattenbach, M., Milne, R., Campbell, C.D., Lilly, A., Ostle, N., Levy, P.E., 2007. Climate change cannot be entirely responsible for soil carbon loss observed in England and Wales, 1978–2003. Global Change Biology 13(12), 2605-2609.

Umweltbundesamt, 2024. Stickstoffeintrag aus der Landwirtschaft und Stickstoffüberschuss, https://www.umweltbundesamt.de/daten/land-forstwirtschaft/stickstoffeintrag-aus-der-landwirtschaft#undefined.

Valk, G.D., Grootenhuis, P.A., van Eijk, J.T., Bouter, L.M., Bertelsmann, F.W., 2000. Methods for assessing diabetic polyneuropathy: validity and reproducibility of the measurement of sensory symptom severity and nerve function tests. Diabetes Res Clin Pract 47(2), 87-95.

Van Wesemael, B., Paustian, K., Meersmans, J., Goidts, E., Barancikova, G., Easter, M., 2010. Agricultural management explains historic changes in regional soil carbon stocks. Proceedings of the National Academy of Sciences 107(33), 14926-14930.

Verbrigghe, N., Leblans, N.I., Sigurdsson, B.D., Vicca, S., Fang, C., Fuchslueger, L., Soong, J.L., Weedon, J.T., Poeplau, C., Ariza-Carricondo, C., 2022. Soil carbon loss in warmed subarctic grasslands is rapid and restricted to topsoil. Biogeosciences Discussions, 1-25.

von Haden, A.C., Yang, W.H., DeLucia, E.H., 2020. Soils' dirty little secret: Depth-based comparisons can be inadequate for quantifying changes in soil organic carbon and other mineral soil properties. Global Change Biology 26(7), 3759-3770.

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. European Journal of Soil Science 70(3), 550-564.

Vos, C., Jaconi, A., Jacobs, A., Don, A., 2018. Hot regions of labile and stable soil organic carbon in Germany–Spatial variability and driving factors. SOIL 4(2), 153-167.

Walker, T.W.N., Kaiser, C., Strasser, F., Herbold, C.W., Leblans, N.I.W., Woebken, D., Janssens, I.A., Sigurdsson, B.D., Richter, A., 2018. Microbial temperature sensitivity and biomass change explain soil carbon loss with warming. Nature Climate Change.

Walter, K., Don, A., Tiemeyer, B., Freibauer, A., 2016. Determining Soil Bulk Density for Carbon Stock Calculations: A Systematic Method Comparison. 80(3), 579-591.

Wendling, U., Schellin, H.-G., Thomä, M., 1991. Bereitstellung von täglichen Informationen zum Wasserhaushalt des Bodens für die Zwecke der agrarmeteorologischen Beratung. Zeitschrift für Meteorologie 41(6), 468-475.

Wiesmeier, M., Burmeister, J., Garcia-Franco, N., Sümmerer, M., 2025. Long-term changes (1986–2016) in soil organic carbon and nitrogen in agricultural soils of Bavaria. Agriculture, Ecosystems & Environment 394, 109874.

Wollmann, I., Klaudy, N., Suter, D., Zimmermann, R., Shavit, N., Hirte, J., 2025. The Development of Carbon Stocks in Topsoil and Subsoil at National Soil Monitoring Sites over 30 Years. Agroscope Science 216.

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Appendix

Table A1: Mean absolute and relative changes in SOC content per depth increment at the sites resampled to date, with the number of sites (n), the upper and lower limits of the 95% confidence interval (CI95) of the absolute changes per depth and land use. The confidence interval was determined using bootstrapping.

Land use	Depth (cm)	n	ΔSOC content (g kg^{-1})	$CI95_{lower\ limit}$ (g kg^{-1})	$CI95_{upper\ limit}$ (g kg^{-1})	ΔSOC content (%)
Cropland	0-10	424	**0.4**	**0.1**	**0.7**	**2.2**
	10-30	424	0.1	-0.2	0.3	0.5
	30-50	418	**-0.6**	**-0.9**	**-0.3**	**-8.6**
Grassland	0-10	140	**-2.0**	**-3.5**	**-0.6**	**-4.8**
	10-30	140	-0.5	-1.2	0.3	-2.4
	30-50	136	-0.3	-1.0	0.3	-3.4
Permanent crops	0	14	-1.2	-3.8	1.3	-4.7
	10-30	14	-0.9	-1.8	0.2	-5.9
	30-50	14	-0.1	-1.1	0.9	-1.1

Source: Thünen Institute

Table A2: Mean absolute and relative change in SOC stocks per depth level of the sites resampled to date, with number of sites (n) and upper and lower limits of the 95% confidence interval (CI95) of the absolute changes per depth and land use. The confidence interval was determined using bootstrapping. Significant changes are shown in bold.

Land use	Depth (cm)	n	ΔSOC stock (Mg ha^{-1})	$CI95_{lower\ limit}$ (Mg ha^{-1})	$CI95_{upper\ limit}$ (Mg ha^{-1})	ΔSOC stock (%)
Cropland	0-10	42	0.3	-0.1	0.6	0.9
	10-30	424	**-1.2**	**-1.8**	**-0.6**	**-3.0**
	30-50	418	**-1.2**	**-2.0**	**-0.4**	**-6.1**
Grassland	0-10	140	**-3.2**	**-4.4**	**-1.9**	**-8.1**
	10-30	140	**-1.8**	**-3.4**	**-0.3**	**-4.0**
	30-50	136	-0.4	-1.9	0.9	-1.7
Permanent crops	0-10	14	-2.2	-4.8	0.5	-7.6
	10-30	14	-3.2	-5.4	-1.2	-7.9
	30-50	14	-1.1	-3.8	1.6	-4.3

Source: Thünen Institute

Table A3: Mean absolute and relative change in cumulative SOC stocks (0-10, 0-30, and 0-50 cm) at sites resampled to date, with number of sites (n) and upper and lower limits of the 95% confidence interval (CI95) for absolute changes by depth increment and land use. The confidence interval was determined using bootstrapping. Significant changes are shown in bold.

Land use	Depth (cm)	n	ΔSOC stock (Mg ha^{-1})	CI95 $_{lower\ group}$ (Mg ha^{-1})	CI95 $_{upper\ group}$ (Mg ha^{-1})	ΔSOC stock (%)
Cropland	0-10	42	0.2	-0.1	0.6	0.9
	0-30	424	**-0.9**	**-1.7**	**-0.1**	**-1.6**
	0-50	418	**-2.1**	**-3.5**	**-0.8**	**-2.7**
Grassland	0-10	140	**-3.2**	**-4.4**	**-1.8**	**-8.1**
	0-30	140	**-5.0**	**-7.3**	**-2.8**	**-5.9**
	0-50	136	**-5.5**	**-8.6**	**-2.4**	**-5.1**
Permanent crops	0-10	14	-2.2	-4.9	0.4	-7.6
	0-30	14	**-5.5**	**-9.2**	**-1.5**	**-7.9**
	0-50	14	**-6.6**	**-12.0**	**-1.0**	**-6.9**

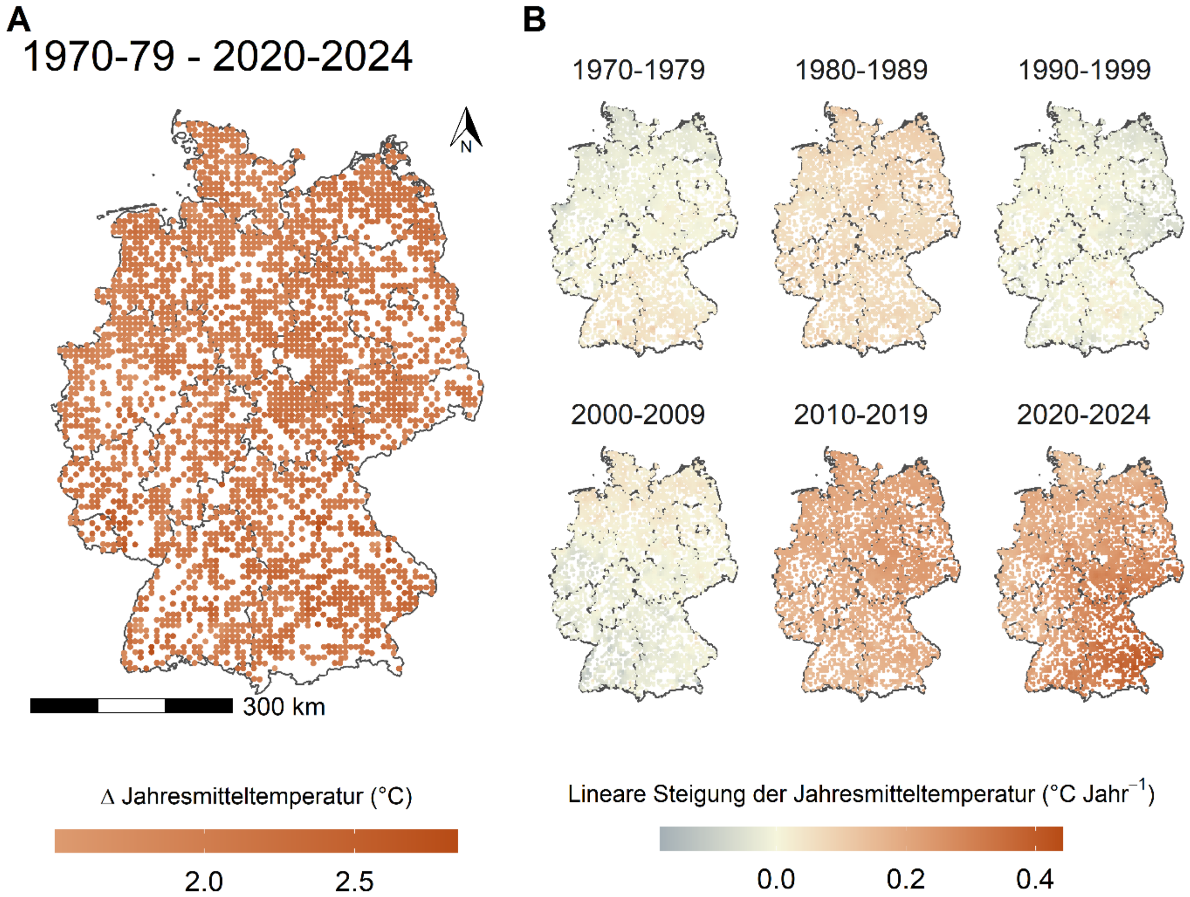
Source: Thünen Institute

Table A4: Mean absolute and relative change in BD at sites resampled to date, with number of sites (n) and upper and lower limits of the 95% confidence interval (CI95) for absolute changes by depth level and land use. The confidence interval was determined using bootstrapping. Significant changes are shown in bold.

Land use	Depth (cm)	n	ΔBD$_{fine}$ (g cm^{-3})	CI95$_{lower\ limit}$ (g cm^{-3})	KI95$_{upper\ layer}$ (g cm^{-3})	ΔBD$_{fine}$ (%)
Field	0-10	424	-0.02	-0.03	0.00	-1.3
	0-30	424	**-0.03**	**-0.04**	**-0.02**	**-2.0**
	0-50	418	**-0.03**	**-0.04**	**-0.02**	**-1.9**
Grassland	0-10	140	0.0	-0.03	0.02	-0.4
	0-30	140	**-0.06**	**-0.08**	**-0.04**	**-4.6**
	0-50	136	**-0.08**	**-0.11**	**-0.05**	**-5.6**
Permanent crops	0	14	-0.03	-0.08	0.03	-2.1
	0-30	14	**-0.09**	**-0.14**	**-0.02**	**-5.9**
	0-50	14	**-0.09**	**-0.15**	**-0.03**	**-6.4**

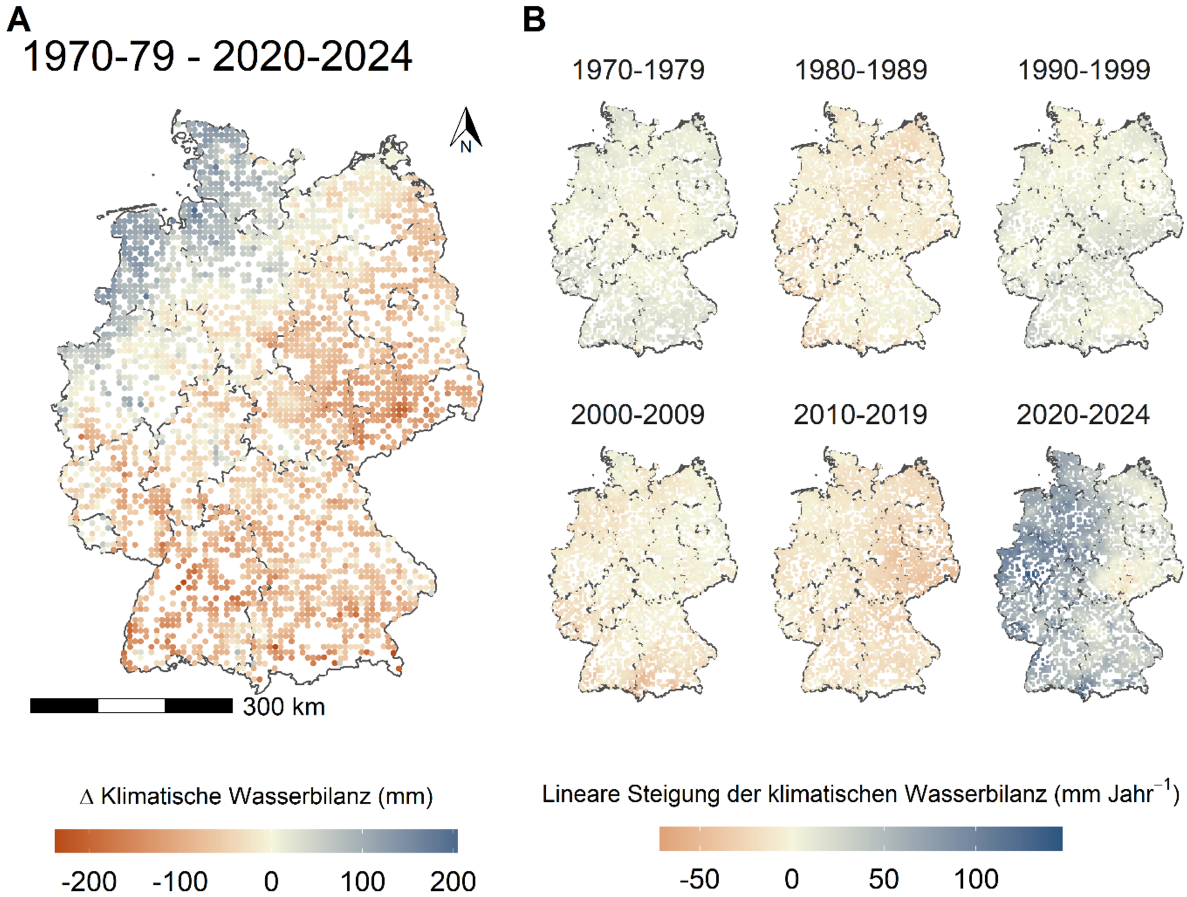
Source: Thünen Institute

Figure A1: **A) Difference in average annual temperature between the periods 1970-79 and 2020-24 for all BZE-LW locations; B) Linear slope of average annual temperature over the last six calendar decades.**



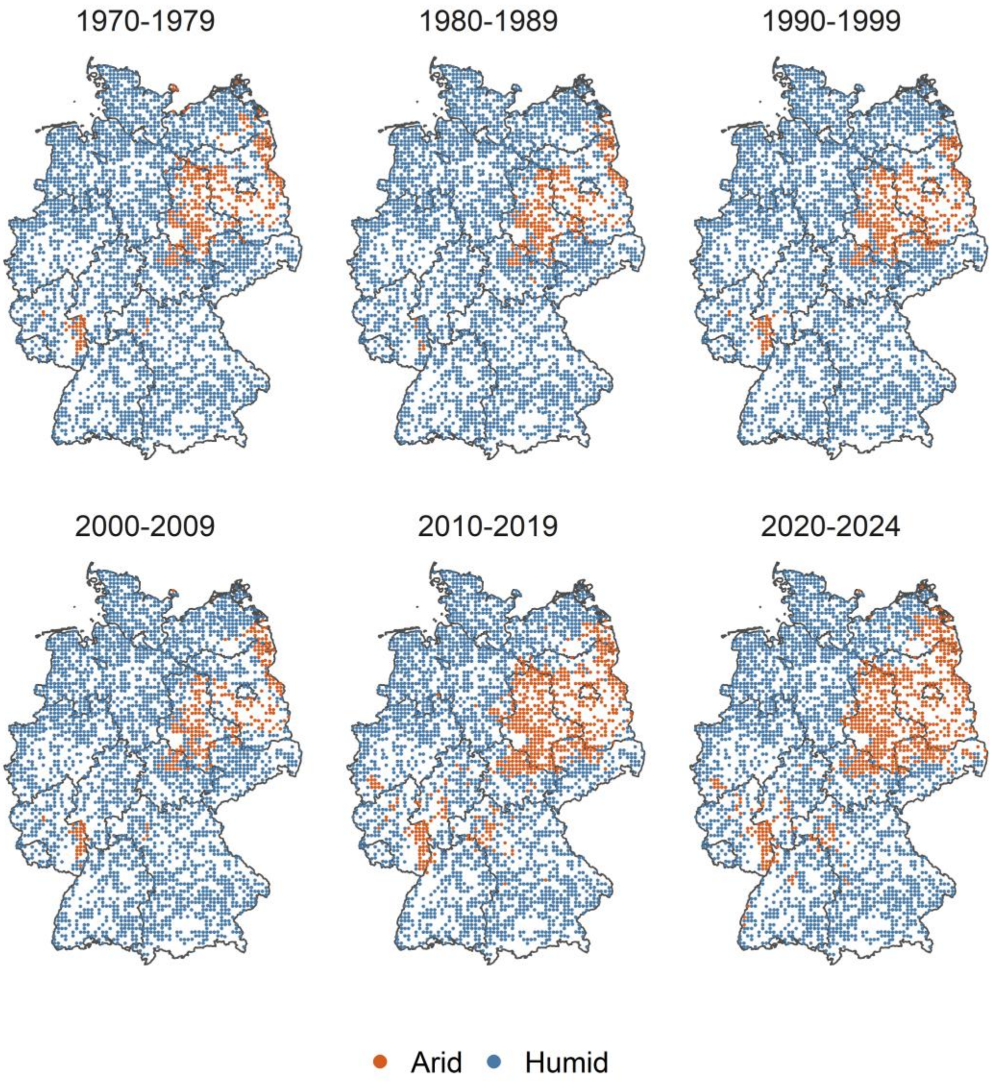
Source: Thünen Institute with data from the Deutscher Wetterdienst (DWD 2025a)

Figure A2: **A) Difference in average annual climatic water balance between the periods 1970-79 and 2020-24 for all BZE-LW sites; B) Linear slope of annual mean temperature over the last six calendar decades.**



Source: Thünen Institute with data from the Deutscher Wetterdienst (DWD 2025a, b, c)

Figure A3: Classification of all sites as potentially arid (negative annual climatic water balance) and humid (positive annual climatic water balance) for the last six calendar decades.



Source: Thünen Institute with data from the Deutscher Wetterdienst (DWD 2025a, b, c)

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