frontiers in Soil Science

TYPE Original Research
PUBLISHED 16 November 2026
DOI 10.3389/fsoil.2026.1991383

Check for updates

OPEN ACCESS

EDITED BY
Carsten W. Mueller,
Technical University of Berlin, Germany

REVIEWED BY
Barbara Kitzler,
Austrian Research Centre for Forests (BFW), Austria
Marcus Schiedung,
Thünen Institute of Biodiversity, Germany

*CORRESPONDENCE
Jens Leifeld
jens.leifeld@cseq.org

RECEIVED 07 September 2026
REVISED 16 October 2026
ACCEPTED 02 November 2026
PUBLISHED 16 November 2026

CITATION
Leifeld J and Rathnayake D (2026) Biochar-treated cropland fields show variable soil organic carbon response but low nitrogen demand for carbon sequestration.
Front. Soil Sci. 6:1991383.
doi: 10.3389/fsoil.2026.1991383

COPYRIGHT
© 2026 Leifeld and Rathnayake. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.

Biochar-treated cropland fields show variable soil organic carbon response but low nitrogen demand for carbon sequestration

Jens Leifeld[1]* and Dilani Rathnayake[1,2]

[1]Agroscope, Climate and Agriculture Group, Zurich, Switzerland, [2]Department of Soil Science, Faculty of Agriculture, University of Peradeniya, Peradeniya, Sri Lanka

Biochar (BC) amendment is a means of increasing soil organic carbon (SOC) and has been explored frequently using high application rates in controlled experiments. Smaller rates and application under on-farm experimental conditions are less studied but considered more realistic. Here, we report results from field-scale BC application on five commercial arable farms in Switzerland with annual doses of 1 t BC/ha over 3–5 years. We analysed SOC and nitrogen changes and soil organic matter thermal stability using high-resolution volumetric soil sampling, including subsoil down to 60 cm for fields split into BC-treated and control. Our analysis revealed three main findings. First, unlike in controlled field experiments with high BC application, using low BC rates at the field level showed no uniform SOC stock increase, but differences were noted between farms, with some controls even outperforming the BC treatment. Second, for fields where SOC increased more than the amount of BC applied relative to the control field, thermal analysis revealed a relative increase not only in the high-temperature region of BC itself (> 450 °C) but also in the thermally more labile fraction below 350 °C. By contrast, the same labile thermal region declined for fields where SOC increased less than expected with BC addition. Finally, SOC accrual with BC required significantly less nitrogen than the same increase without BC, a finding that deserves further attention, as it suggests that SOC sequestration with BC is particularly nitrogen efficient.

KEYWORDS
biochar, field scale, priming, subsoil, thermal stability

1 Introduction

Worldwide, many cropland soils suffer from a decline in soil organic matter (SOM) and, correspondingly, soil organic carbon (SOC) (1, 2). This decline, which may impair important soil functions, such as water storage or climate regulation (3–5), can be counteracted by measures that either increase the organic matter (OM) input to soil or the stability of SOM against decomposition. For the latter, biochar (BC) has proven to be particularly efficient, as it has been shown to have a high intrinsic recalcitrance and sequestration efficiency compared to other organic materials applied in agriculture (6–8). BC is the solid product of controlled pyrolysis, i.e. heating biomass without oxygen at elevated temperatures, and is characterised by high carbon (C) content, aromaticity, and degree of condensation (9). Following the recent European carbon removal and certification

framework (10), the fraction of BC surviving decomposition in soil for commercial BCs with elemental H/C ratios of 0.25 is more than 80% over a century. Therefore, BC application is often considered the most promising agricultural measure for increasing SOC stocks, thereby contributing to climate change mitigation (11, 12).

In line with the hypothesised high BC stability, there is compelling evidence from long-term experiments that BC addition has the potential to strongly increase SOC content (13–15). While this finding is highly reproducible across many studies (11), some research also points towards lower-than-expected increases in SOC following BC application. These observations have been attributed to erosion and possible downward transport of the material, particularly in sandy soils, accelerated decomposition of native SOM (i.e. positive priming), BC decomposition (16–18), and effects of surface oxidation, which can alter BC mobility in soil as well as its interactions with soil minerals (19). Positive priming effects may be related to changing the physico-chemical conditions of the soil induced by BC application and are often short-term (20). However, negative priming—that is, a higher SOC increase than expected from BC addition alone—has also been reported in shorter-term experiments (21), and with multi-annual to centennial addition of biochar or other forms of pyrogenic carbon (22, 23). This process is induced by the sorption of SOM onto BC surfaces (24) as well as by improved soil aggregation (25), both of which lead to co-sequestration of non-pyrogenic C together with BC. These findings revealed that the direction and magnitude of possible priming effects is particularly driven by BC type and soil properties.

A further but largely understudied aspect of BC as a soil carbon sequestration measure is its potentially low co-demand for nitrogen (N). In mineral soils, SOM has a narrow C/N stoichiometry (26), and any SOM increase with regular farming practices, such as cover crops or organic fertilisation, may come at the expense of increasing amounts of N that is co-sequestered, a trade-off that has been phrased as the nitrogen dilemma (27). Because of its inherent stability, the addition of BC may allow C to be sequestered with relatively little N. In their comprehensive meta-analysis, (28) showed that BCs derived from a wide range of feedstocks (crop residues, straw, wood, excreta) had a mean C/N ratio of 115 ± 16 (95% confidence interval), which is far higher than the typical C/N ratio of SOM (10-12; 26). Results from controlled field trials indicate higher soil C/N ratios with BC, suggesting a comparable low N demand for C sequestration compared to other amendments (29, 30). These findings call for a more detailed study of this aspect.

Most of the research on the effects of BC application to soil has been derived from plots in planned parcel-scale field experiments (11). These have the advantage of being controlled, but they may not fully reflect the management conditions and agricultural performance typical of real farms (31). Further, Gross et al. (28) showed that field experiments operated with an average BC application rate of 20 ± 1.9 (95% CI) t/ha, with high rates of up to 100 t/ha, whereas recent research suggests that smaller but more frequent application may serve soil functioning better (32). Smaller but more frequent applications also reflect farm reality more accurately in terms of annual biomass availability and pyrolysis processing rates. Together, these findings have inspired on-farm BC experimentations (33), as well as on-farm soil carbon sequestration studies in general (34), which complement fully controlled small-scale experiments.

In this study, we present SOC and soil N results from low-dose BC application in real farm contexts from the fields of five arable farms in the north of Switzerland over five years. The added amount of 1 t-BC/ha/year corresponds to the annual maximum allowed according to the Swiss CO_2 Ordinance (35) and Swiss fertiliser regulation (36). As outlined above, it also mimics a realistic amount for on-farm pyrolysis, given the limited amount of biomass residues available per hectare and year. With this work, we aim to determine (i) whether low-dose BC application is detectible in soils from on-farm experiments, (ii) whether low-dose BC induces priming effects and changes in SOM stability, and (iii) how BC addition affects the N efficiency of SOC sequestration.

2 Materials and methods

2.1 Experimental site information

The experiments were carried out on the cropland of five different commercial farms (A–E) in the Kanton of Zurich, Switzerland, close to the Flaach municipality. The mean annual precipitation in this region is 966 mm, and the mean annual temperature is 9.9 °C. Farms are situated at approximately 350 m asl.; 47°34′ N, 8°36 E. Farms B–E followed multi-annual crop rotations typical for this region, including winter wheat, silage maize, spelt, sunflower, barley, and grass-clover, whereas farm A is a vegetable grower (outdoor vegetables) with 2–3 crops per year. Farms A and C applied 48 and 27 m^3/ha/year green waste compost, respectively, and farms B, D, and E applied 30, 30, and 88 m^3/ha/year slurry, respectively. All farms also applied mineral fertilisation according to the national fertilisation guidelines (37). Soils of the farms are haplic Cambisols with a loamy texture.

On each of the five farms, one field of 1–2 ha in size was divided into two equal halfs, with one half corresponding to the control treatment (label e.g. as Ac) and the other to a BC treatment (labelled e.g. as Ab). Except for BC application, any other management activity, including crops, organic, and mineral fertilisation or tillage, was identical. BC was applied in pure form and tilled in using a rotary harrow. On each field, 20 sampling points were randomly selected within both the control and BC-treated plots, marked using a high-resolution GPS, and repeatedly sampled over a five-year period. Initial sampling was conducted in March 2017 before the first BC application. Resampling took place in November 2019, one week after the third BC application, and in January 2022, one week after the fifth BC application. Each sampling point was assigned a 2 × 2 m area, which was divided into four 1 × 1 m quadrants. Resampling was conducted within the same 2 × 2 m area but always in a previously unsampled quadrant.

2.2 Biochar supply and characterisation

Wood-based BC produced from mixed pruning residues was obtained from a BC production facility operated by one of the

participating farms (www.a-p-d.ch; pyrolysis unit Biomacon 400, Germany, production temperature >550 °C) and the material was certified according to the European Biochar Certificate (38). EBC certification was considered relevant because it ensures compliance with Swiss regulations for agricultural BC application and requires minimum standards regarding BC quality and stability (39). We chose this material because at the time of the experiment, wood has been the only feedstock allowed for BC production with subsequent application in agriculture in Switzerland. The BC had an organic C content of 83.3%, N content of 0.50%, and H/C and O/C molar ratios of 0.27 and 0.06, respectively (elemental analysis using Eurovector EA, Italy). The specific surface area (N_2) as measured by multipoint BET was 313 m^2/g (NOVA2000e, Quantachrome, USA), and the pH was 8.3. Based on this composition, the total amount of added BC (3, and 5 t BC/ha) corresponded to a total of 4.17 t (0.417 kg/m^2) organic carbon (25 kg N/ha) after five years.

2.3 Soil sampling, soil organic carbon stock assessment

Soil samples were taken using a motor-driven auger (www.bodenproben.ch) equipped with plastic liners (4 cm diameter, 60 cm length). Intact soil cores were separated into three 20-cm increments, brought to the laboratory, dried, weighed, and sieved <2 mm. After weighing the stones, the fine soil bulk density was calculated. Fine soil was ball-milled and measured for soil organic carbon and total nitrogen using dry combustion using the same elemental analyser as above. Samples were pre-treated with HCl following (40) to remove carbonates. The results are expressed as elemental concentrations and SOC stocks over the whole profile using the equivalent soil mass principle (41), where the minimum soil mass over the upper 60 cm per field was used for all replicates of that field. Differences in SOC stocks between 2017 and 2022 were statistically analysed using paired t-tests.

2.4 Soil organic matter thermal stability assessment and auxiliary measurements

As an SOM quality parameter, the thermal stability of the milled fine soil samples was measured using differential scanning calorimetry (DSC) (Netzsch STA 493F3, Germany) for composite samples of each field and sampling event taken from 0–20 cm. Composite samples consisted of 20 field replicates of 50 g each, which were homogenized using a Turbula mixer (Bachofen AG, Switzerland). Thereafter, 20 mg of finely milled sample was weighed into Al_2O_3 crucibles and heated under synthetic air from room temperature to 700 °C at 20K/min. This instrument provides the differential heat flux (W/g) over the entire temperature range. The same non-milled composite samples from each field, treatment, and sampling event were used to determine soil texture (pipette method) and pH (0.01 M $CaCl_2$).

2.5 Estimation of priming effect

To analyse possible priming effects, expected differences in SOC stocks with BC (ΔExp) were compared to measured ones (Equation 1):

$$\Delta Exp = (SOCc_{t3,5} - SOCc_{t0}) + BC_{t3,5} \quad (1)$$

where $SOCc_{t0}$ is the SOC stock of the control fields at the beginning of the experiment (kg/m^2), $SOCc_{t3,5}$ is the corresponding stock after 3 and 5 years, respectively, and $BC_{t3,5}$ the amount of BC added after 3 and 5 years, respectively (kg-C/m^2). Values for ΔExp higher than the measured SOC stock in the BC-treated field indicate negative priming, and values below the measured SOC stock in the BC-treated field indicate positive priming.

2.6 Statistics

Soil organic carbon stocks were analysed using a linear mixed effects model including treatment, sampling year and their interaction as fixed effects. Farm and sampling point nested within farm and treatment were included as random effects:

$$\text{SOC_stock} \sim \text{treatment} \times \text{year} + (1|\text{farm}) + (1|\text{farm}:\text{treatment}:\text{sampling point}) \quad (2)$$

Normality was tested using histograms of residuals, Q-Q plots, and Shapiro Wilk Normality test. Variance homogeneity was tested using residuals vs fitted values, residuals by treatment and sampling year and Levene's test. Since SOC stock data was not normally distributed, data were log-transformed prior to the modelling. Initial differences in SOC stocks between control and BC-treated fields before the first BC application were compared by t-test on log-transformed data. The dependency of ΔExp on initial SOC content was tested using Pearson's correlation coefficient.

3 Results

3.1 Changes in soil organic carbon stocks

Before BC application, SOC concentrations in the topsoil of all studied fields were between 12 and 32 mg/g, and SOC stocks were between 6.9 and 10.7 kg-SOC/m^2 in the upper 60 cm (Table 1). Initial SOC stocks between control and BC-treated fields were not different. Corresponding C/N ratios were between 8.4–11.4. Neither the initial C/N ratios nor the N stocks differed between control and BC-treated fields (Supplementary Table S1).

Over time, SOC stocks significantly increased in three of the farms, whereas they remained almost unchanged for farm A (vegetables) and even declined for farm D, where application commenced just after a three-year ley phase (Figure 1). BC addition did not lead to higher gains or smaller losses in all cases, suggesting interactions between BC addition and SOM decomposition. Indeed, the linear mixed effects model (Equation 2) revealed no significant overall effect of BC application on SOC stocks ($p = 0.944$). Sampling year significantly affected SOC stocks, with higher values observed in 2019 ($p = 0.044$) and 2022 ($p < 0.001$) compared with 2017. A significant treatment × year interaction was detected for 2022 ($p = 0.048$), indicating that temporal SOC dynamics differed between BC and control plots: By 2022, BC showed significantly higher SOC than control (Supplementary Figure S1), although SOC stock increased over time regardless of treatment. Farm-level variability

TABLE 1 Key soil properties of the five sites A–E.

Site	soil pH	% clay	SOC (mg/g; 0–20 cm)			SOC stock (kg/m^2, 0–60 cm eq. soil mass)			p-value
			2017	2019	2022	2017	2019	2022	
Ac	7.3 (0.1)	16.4 (0.1)	15.6 (0.4)	14.3 (0.3)	14.7 (0.2)	8.74 (0.17)	8.73 (0.18)	8.87 (0.19)	0.53
Ab	7.3 (0.1)	16.4 (0.4)	14.6 (0.4)	15.2 (0.4)	16.4 (0.5)	9.15 (0.43)	9.14 (0.30)	9.33 (0.22)	
Bc	7.3 (0.1)	26.7 (0.6)	18.1 (0.3)	19.3 (0.5)	18.3 (0.3)	9.63 (0.24)	10.41 (0.21)	9.72 (0.24)	0.93
Bb	7.3 (0.1)	26.4 (0.4)	16.9 (0.6)	18.9 (0.7)	19.3 (0.6)	9.69 (0.21)	10.56 (0.24)	10.71 (0.32)	
Cc	7.3 (0.1)	18.9 (0.3)	19.2 (0.6)	18.6 (0.5)	22.4 (0.8)	9.54 (0.35)	10.49 (0.31)	11.57 (0.45)	0.85
Cb	7.3 (0.1)	19.8 (0.6)	19.1 (0.7)	20.0 (0.6)	24.0 (1.4)	9.61 (0.40)	10.91 (0.36)	13.68 (0.86)	
Dc	6.8 (0.1)	23.5 (0.8)	26.2 (1.5)	24.3 (0.7)	23.6 (1.0)	10.65 (0.48)	10.07 (0.46)	9.33 (0.52)	0.80
Db	7.0 (0.1)	26.0 (0.6)	32.3 (0.7)	29.5 (0.6)	28.9 (1.4)	10.40 (0.35)	9.64 (0.58)	9.25 (0.29)	
Ec	6.9 (0.1)	16.6 (0.9)	14.0 (0.4)	15.7 (0.4)	18.1 (0.6)	7.32 (0.24)	8.04 (0.38)	8.25 (0.24)	0.34
Eb	6.6 (0.1)	18.2 (0.4)	11.9 (0.6)	15.1 (0.8)	16.6 (0.6)	6.90 (0.33)	9.64 (0.43)	7.66 (0.42)	

Subscripts c and b denote control and biochar treatments, respectively. Standard errors in parenthesis based on n = 3 for pH and clay, and n = 20 for SOC. The last column indicates the p-values for comparisons of SOC stock differences (0–60 cm eq. soil mass) between control and biochar plots before BC application in 2017.

accounted for a substantial portion of the total variance (Supplementary Table S2).

3.2 Measured vs. expected soil organic carbon stock changes

The measured change in SOC stocks of the control fields plus the added amount of BC with the treatment was used to calculate the expected SOC stock change (ΔExp) after three and five years, assuming no interaction between SOM and BC (Equation 1; Figure 2). Most data points are close to the 1:1 line (R^2 = 0.92 for volumetric stocks at 0–20 cm, and R^2 = 0.87 for 0–60 cm equivalent soil mass). For topsoils, the observed effect was smaller than the expected value in six cases, whereas in four cases (farms C3, C5, E3, E5), BC treatment caused an SOC increase that exceeded ΔExp (for 0–60 cm equivalent soil mass, seven and three cases, respectively) (Figure 2).

3.3 Soil organic matter thermal stability

DSC thermograms indicated the highest energy release at temperatures of approximately 345 °C and a shoulder at approximately 520 °C (Figure 3). Pure BC peaked at 519 °C. The peak height at this temperature increased with BC treatment over time in

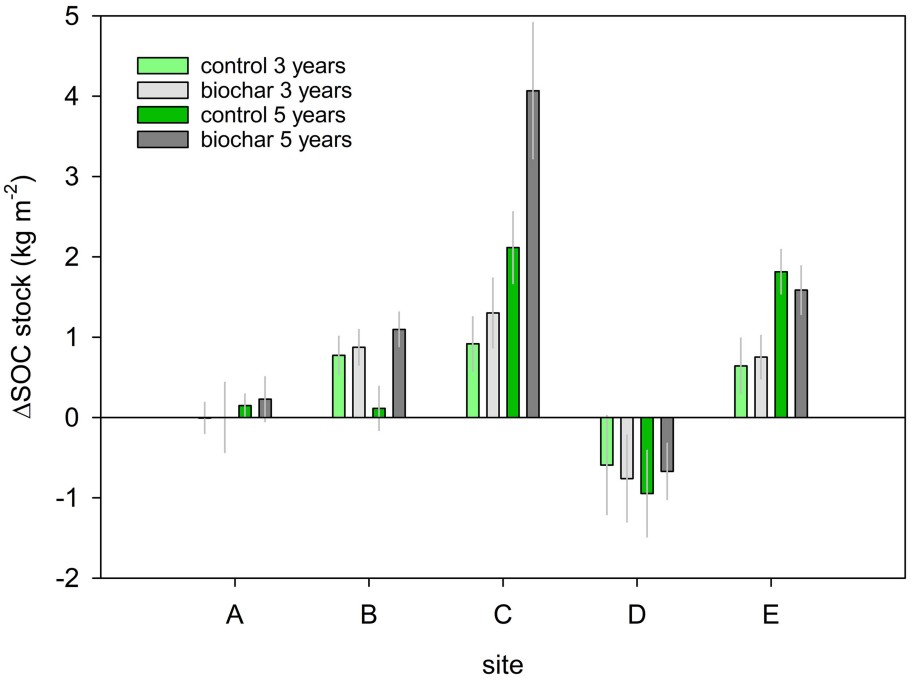


FIGURE 1
Changes in soil organic carbon (SOC) stocks in control and biochar-treated fields after three and five years. Numbers refer to stocks in 0–60 cm equivalent soil mass. Error bars represent the 95% confidence interval.

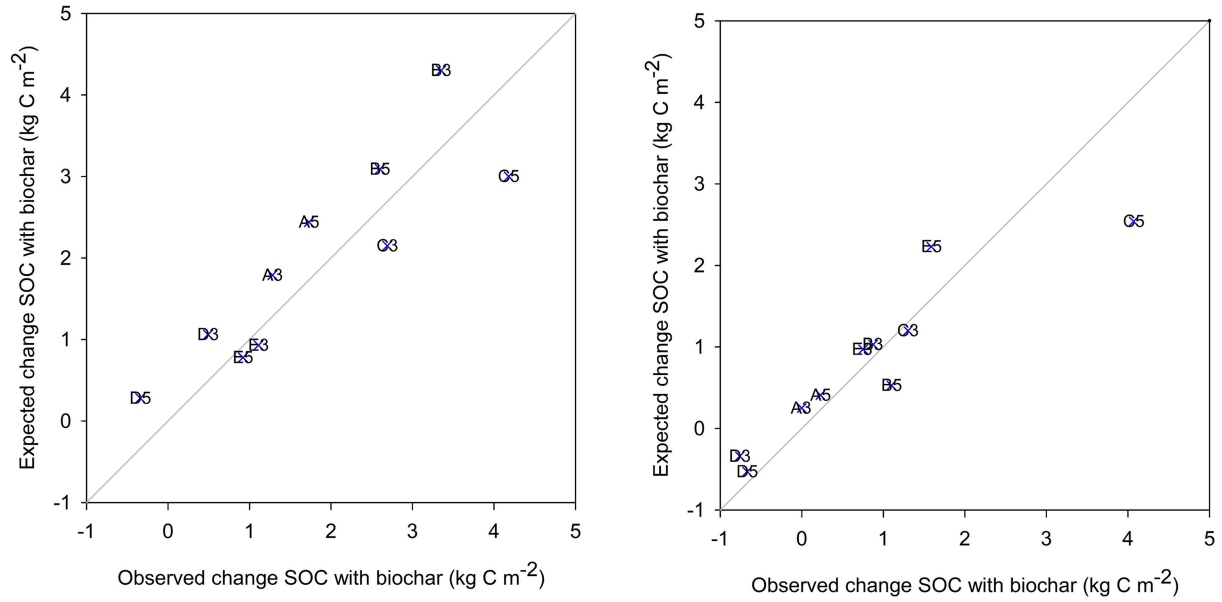


FIGURE 2
Observed vs. expected changes in soil organic carbon (SOC) stocks of the five study sites (A–E) after three (3) and five (5) years. Expected changes are calculated as changes in the control treatment plus the amount of biochar carbon added following Equation 1. The charts report soil volume 0–20 cm (left) and SOC stocks 0–60 cm equivalent soil mass (right).

all five sites (Figure 4). In 2022, when BC was already applied to the fields five times, peak heights were significantly higher compared to 2017 for BC-treated fields ($p<0.01$) but not for control fields ($p=0.15$) (paired t-test) (Supplementary Table S3).

DSC thermograms were grouped following Figure 2 (left) to evaluate whether increases or decreases relative to ΔExp were specific to thermal regions. For the four data points in Figure 2 that revealed a higher than expected increase, which indicated a negative priming (i.e. points below the 1:1 line), the difference in thermograms of BC-treated minus control field samples indicated higher signal intensities both in the lower temperature region below 350 °C as well as in the higher temperature region above 450 °C including the biochar peak region at approximately 520 °C (Figure 5). By contrast, although smaller, increases were also visible for data points at which the SOC increase was below the expected value—indicative of a positive priming—in the higher temperature regions above 450 °C, including the BC peak region; however, they showed substantial losses in the lower temperature region at around 300 °C.

The change in SOC stocks correlated significantly with the change in soil nitrogen stocks (Figure 6). For control treatments, each kg change in SOC corresponded to a 0.10 kg change in N, whereas for BC addition, the corresponding change in N was only 0.06 kg/ha. This difference in N accrual between control and BC

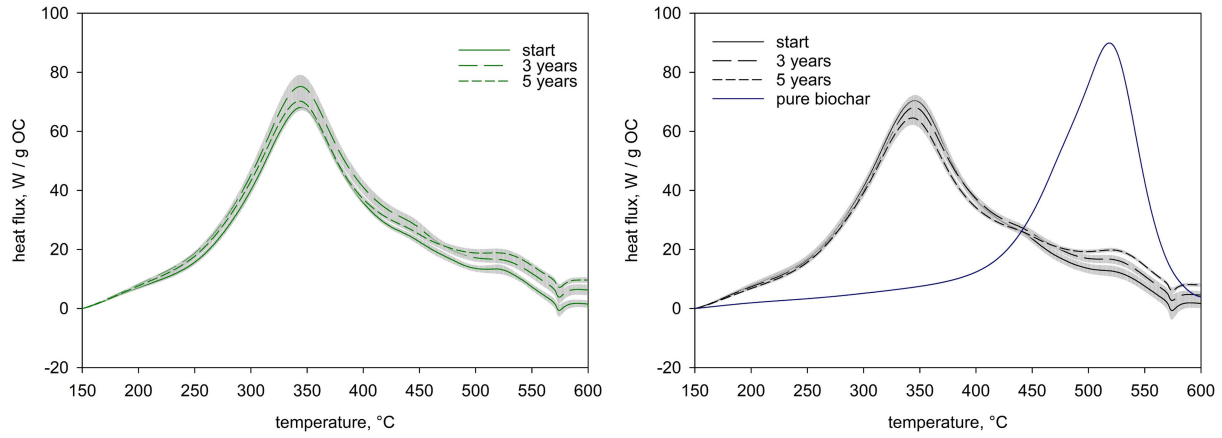


FIGURE 3
Thermograms showing heat fluxes normalised to SOC content of control (left) and biochar-treated (right) fields. The right panel also displays the thermogram of the added biochar. The shaded area shows the standard error (n=5) per treatment. Individual thermograms are displayed in Supplementary Figure S2.

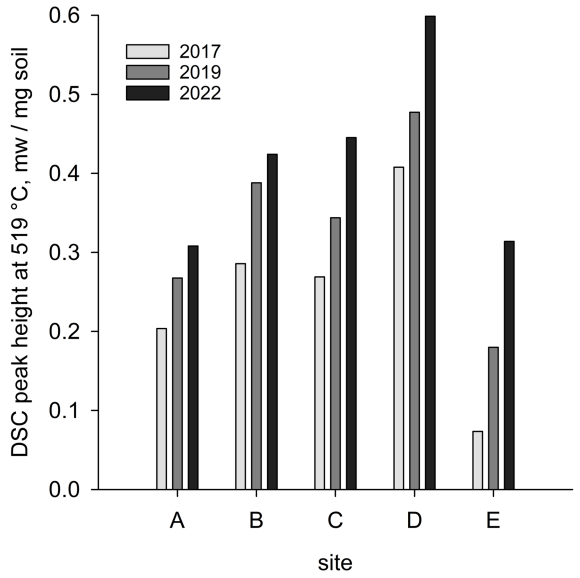


FIGURE 4
Changes in peak heights at 519 °C for biochar-treated fields. The year 2017 indicates the time before the first biochar application.

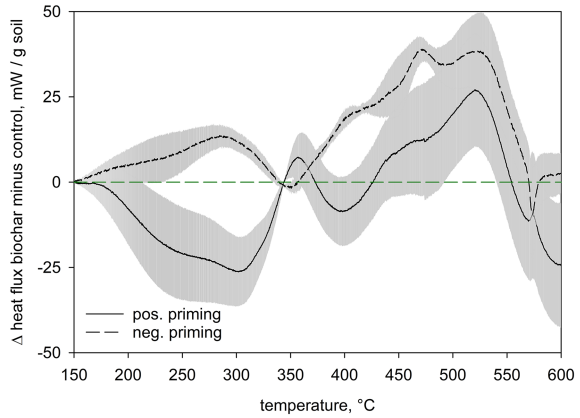


FIGURE 5
Differential thermograms of heat fluxes for biochar-treated fields that exhibit lower (positive priming) and higher (negative priming) than expected changes in SOC stock (0–20 cm). Lines indicate means, whereas shaded areas indicate one standard error. Curves are calculated as the difference in heat flux BC-treated minus control sites as per field after 3 and 5 years, based on the results in the left panel of Figure 2. The shaded area shows the standard error (n=4 and n=6 for negative and positive priming, respectively).

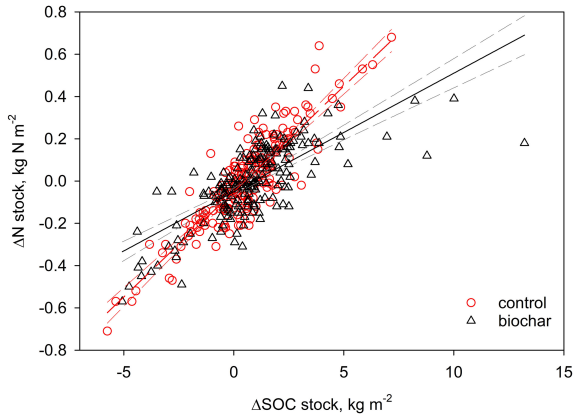


FIGURE 6
Changes in soil nitrogen stocks as a function of changes in SOC stocks (0–60 cm eq. soil mass) for all individual samples collected after 3 and 5 years across the five sites (n = 400). An increase or decline of 1.00 kg SOC corresponds to a change of 0.10 kg N in the control fields (R^2 = 0.77), whereas the corresponding value for N is only 0.06 with biochar treatment (R^2 = 0.53). Regression coefficients (± 1 SE) of linear regression: y0 = -0.050 (0.007), b = 0.100 (0.004) (control); y0 = -0.050 (0.009), b = 0.056 (0.004) (biochar). The dashed lines represent the 95% confidence intervals of the regression line. Black triangles: biochar, red circles: control.

treatments was consistent among sites, and increases in N stocks with BC addition were smallest at farms C and E, i.e., those exhibiting negative priming (Supplementary Table S4).

4 Discussion

4.1 Nitrogen efficiency of carbon sequestration with biochar

One of our research objectives was to study the N efficiency of carbon sequestration with BC, that is, how much N is co-sequestered per unit of additional SOC. Indeed, the most eminent effect of BC application on SOM properties in our study was visible in soil C/N ratios and the differences in N efficiency of carbon sequestration compared to the control fields. Although research on the effects of BC on specific N fractions in soil, notably available N (NO_3, NH_4) (42, 43), is advanced, only a few studies have analysed its effects on the total soil nitrogen pool directly. BC itself is not only a source of C but also of N. The above-cited mean C/N ratio of 115 (28) across many studies converts to an N application of 174 kg N/ha with typical one-time amendments of 20 t BC/ha. Such high rates would, however, occur once but not repeatedly in the same field. In our low-dose experiment, only 25 kg N were applied together with BC over five years, that is, 5 kg/ha/year, a very small share of the fertiliser inputs, which, according to the national fertiliser recommendations (37), is in the range of 150–200 kg N/ha/year for the four arable farms and > 300 kg N/ha/year for the vegetable farm when planted with three crops.

In their meta-analysis, Zhang et al. (44) showed a significant increase in soil total N with BC application but did not relate the results to the accompanying change in SOC. According to a review by Yuan et al. (45), samples disaggregated into soil physical fractions of different sizes and stability show significant increases in both SOC and total N with BC across the evaluated data set. Increases in N are less frequently studied, but they typically exhibit a few percent below the increases in SOC (45), suggesting less N accrual per unit C sequestered than contained in the native SOM stock. However, also their study did not jointly evaluate relationships in the change of both elements.

To the best of our knowledge, our study is the first to measure SOC and soil N changes concurrently and at depths as low as 60 cm under on-farm experimental conditions with low BC doses. For both control and BC-treated fields and consistent for all five farms, we find a close positive relationship between changes in the two

elements after three and five years, confirming that SOC sequestration comes with a nitrogen demand. In the control fields, a one-unit change in SOC was accompanied by, on average, a 0.1-unit change in total N, thereby closely mimicking the soil's C/N average ratios of 9.5. This proportional co-sequestration of N with SOC was consistent among all five control sites and resembles findings from temperate long-term experiments with various organic amendments. For example, Munna and Lal (46) revealed a close linear relationship between sequestration of nitrogen and SOC in a temperate long-term experiment with coefficients being the same for manure and compost. In a long-term field experiment in China (47) observed similar C/N ratios after SOC accrual with different organic amendment combinations. Further, Skadell et al. (48) found no difference in topsoil C/N ratio after long-term application of straw.

In contrast to our control fields, BC addition, on average, led to only a 0.056-unit change in total N per unit SOC, that is, SOC accrual with BC requires 44% less N than by other means, although both control and BC fields received similar amounts of external organic and inorganic N apart from the 5 kg N/ha/year contained in the BC. The lower N accrual per unit SOC with BC was consistent among sites. In a three-year controlled field experiment in Belgium with the application of BC and compost at 10.9 t-C per ha, (29) found a higher N efficiency for C sequestration with BC than with compost in the topsoil (0–25 cm). Similarly, (30) showed higher relative increases in SOC than in soil N (0–15 cm) after applying 20 t of BC over five years in a controlled field experiment in Spain. These studies support our finding that as a carbon sequestration measure, BC presents a higher N efficiency compared to other organic amendments, even those having a wide C/N ratio such as straw.

4.2 Soil organic carbon stock changes

The high-density sampling in this study allowed for the detection of SOC stock changes even after only three and five years of regular low-dose BC application. Soils in the on-farm experiments responded positively to BC addition in the fields of farms B, C, and E, whereas the fields of the two other farms showed little (A) or negative (D) response (Table 1). At the same time, SOC also increased in the control treatments of farms C and E. Overall, there was no significant treatment effect on SOC stocks (Supplementary Table S2), whereas variance component analysis revealed substantial between-farm variability (σ^2=1.56), accounting for approximately 33% of the total variance in SOC stocks. This indicates that differences among farms were a much larger source of SOC variation than BC application, highlighting the challenges of detecting treatment effects under realistic on-farm conditions.

The high increase in SOC of farms C and E can be explained by the substantial amounts of organic fertilisers that added to the regular input of plant residues and by BC in the BC-treated fields. However, vegetable farm A also received compost but responded little to it and BC treatment, confirming that vegetable cropping with little plant residue inputs, longer periods of bare soil, and more frequent soil disturbance is not beneficial for soil carbon storage (49). The SOC decline in farm D was related to the crop rotation, as the first amendment followed a 3-year ley phase during which the SOM was built up, which was commenced by annual crops, resulting in a typical decline (50) that could not be compensated by BC amendment. A comparison of the results of these five farms, which shared the same climate and similar soils, underscores the high context-specific effects of adding the same type and amount of BC on SOC content. This context includes not only differences in soil properties but also management history that partially controls actual SOM dynamics (51). However, due to our measurement set-up, we are unable to draw conclusions regarding why the same BC application resulted in different directions of SOM development in these fields or the mechanisms driving such dynamics.

Data from Gross et al. (28) revealed that, on average over many sites and experiments, only 25% of the added BC was measurable as an increase in SOC stock, indicating leaching, possible BC loss via erosion, decomposition, as well as positive priming of native SOM. In our data set, considering only the amount of BC added to soil would have resulted in a large underestimation of SOC changes in most cases and a much weaker alignment compared to our Figure 2, which considers the parallel SOC stock change without BC addition. This underpins the important role of a proper control experiment to take processes of SOC dynamics that are not related to BC addition quantitatively into account. Calculating the expected SOC stock with BC based on the measured change in SOC in the control treatments plus mathematically adding the amount of BC revealed a close relationship between expected and measured SOC stocks with no bias but some scatter (Figure 2). A 100% alignment would indicate no interaction between native SOM and BC, whereas negative or positive deviations from the 1:1 line point towards negative (i.e. more additional SOC than just added with BC) or positive (i.e. less additional SOC than just added with BC) priming, respectively.

Because we sampled well below the A horizon and the terrain is flat, BC losses from erosion or leaching transport beyond the sampling depth of 60 cm are considered negligible, although they cannot be entirely excluded. In terms of decomposition, BCs with an H/Corg ratio of 0.27, as used in this study, are expected to lose between 6 and 15% carbon over one century according to Woolf et al. (8) and Rodrigues et al. (7), respectively, corresponding to less than 1% over five years. Therefore, our findings tentatively suggest both positive and negative priming effects following BC addition. However, the evidence for priming presented here is indirect, and direct quantification of the direction and magnitude of priming effects requires the use of isotopes (52). In addition to SOM priming, also differences in plant residue inputs via rhizodeposition between controls and BC fields cannot be ruled out. Although farmers did not report any yield effects of BC application, differences in plant residue inputs may nevertheless have occurred and could have influenced SOC stocks.

4.3 Soil organic matter thermal stability

We used DSC to identify changes in SOM quality after BC application. DSC does not allow us to directly infer the chemical composition of SOM, but the different thermal regions correspond to SOM of different ages and stability, both increasing with higher

combustion temperature (53). In terms of composition, thermal signals in lower temperature regions are mostly derived from lipids and polysaccharides (54). As expected, we found an increase in the high-temperature thermal region > 450 °C, which is characteristic of pyrogenic carbon (55, 56), with increasing BC application in all fields. This increase was observed for samples of both groups that we designated as positive and negative priming. However, changes in low-temperature regions differed between the two groups: An overall smaller-than-expected change in SOC storage concurred with a clear decrease in signal height at temperatures < 300 °C whereas that region gained signal intensity for samples where the actual SOC stock change was higher than the expected one. This difference is a clear sign of a changing contribution in thermally labile, non-pyrogenic SOM, mostly lipids and polysaccharides, as a result of BC addition.

4.4 Soil organic matter priming after biochar application

Priming effects after BC addition have been reported frequently in the literature and may have different causes. In the context of our study, negative priming induced by sorption of native dissolved SOM onto the BC surface as well as encapsulation by BC, for example, as discussed by Hagemann et al. (24) or Lu et al. (57), may have occurred, as this would align with our DSC findings where thermally labile SOM increased. Although these studies worked on a small scale over short time periods, accumulation of non-pyrogenic carbon in soils with high BC content has also been observed over 17 years at the field scale (23). Zimmerman et al. (58) analysed the reasons for positive and negative priming after BC addition. In their incubation study, positive priming occurred in soils with a lower SOC content. In our on-farm experiment, however, the initial SOC content was not a significant factor in the estimated magnitude and direction of the supposed priming ($r = -0.43$ and 0.10, $p = 0.48$ and 0.88, after 3 and 5 years, respectively). Instead, farms C and E, which showed evidence of negative priming and a relative accumulation of thermally stable SOM, exhibited the highest N efficiency of SOC sequestration following BC application. This suggests that N-efficient SOC sequestration primarily affects thermally stable SOM, which has been associated with higher activation energy and a more aromatic chemical composition (54). Taken together, our findings suggest that the effects of BC on native SOM are highly site-specific but do not allow the underlying drivers to be disentangled beyond the factors discussed above. This interpretation is in line with that of Fang et al. (59), who showed that the same high-temperature (550 °C) BC added to different soils caused either positive or negative priming, depending on the incubated soil.

5 Conclusion

Although substantial SOC stock increases under high BC application rates have been widely reported in field experiments, relatively few studies have evaluated lower application rates in actual field settings. Results from this study, representing a five-year on-farm experiment using realistic BC application rates resembling actual on-farm biomass availability, and measuring SOC and soil N changes concurrently down to a depth of 60 cm, suggest that even under the same climate and with the same type and amount of BC applied, the direction of SOM development cannot be predicted. Our findings suggest that both positive and negative priming strongly influence SOM dynamics after BC addition. Furthermore, BC adds little N to the soil, highlighting its potential as an N-saving measure for carbon sequestration and, thus, climate change mitigation.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Author contributions

JL: Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Resources, Visualization, Writing – original draft, Writing – review & editing. DR: Formal analysis, Writing – review & editing.

Funding

The author(s) declared that financial support was received for this work and/or its publication. This work received financial support from the Verein AgroCO2ncept Flaachtal agreement 2017_316.

Acknowledgments

The authors thank Robin Giger for his great and reliable support in lab and field work and Hans-Rudolf Oberholzer for initiating collaboration with farmers. The five farmers are gratefully acknowledged for their support and field access.

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that generative AI was not used in the creation of this manuscript.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsoil.2026.1991383/full#supplementary-material

References

1. Prăvălie R, Nita I-A, Patriche C, Niculiță M, Birsan M-V, Roșca B, et al. Global changes in soil organic carbon and implications for land degradation neutrality and climate stability. *Environ Res*. (2021) 201:111580. doi: 10.1016/j.envres.2021.111580

2. Sanderman J, Hengl T, Fiske GJ. Soil carbon debt of 12,000 years of human land use. *Proc Natl Acad Sci*. (2017) 114:9575–80. doi: 10.1073/pnas.1706103114

3. Johannes A, Weisskopf P, Schulin R, Boivin P. Soil structure quality indicators and their limit values. *Ecol Indic*. (2019) 104:686–94. doi: 10.1016/j.ecolind.2019.05.040

4. Beillouin D, Corbeels M, Demenois J, Berre D, Boyer A, Fallot A, et al. A global meta-analysis of soil organic carbon in the Anthropocene. *Nat Commun*. (2023) 14:3700. doi: 10.1038/s41467-023-39338-z

5. Omondi MO, Xia X, Nahayo A, Liu X, Korai PK, Pan G. Quantification of biochar effects on soil hydrological properties using meta-analysis of literature data. *Geoderma*. (2016) 274:28–34. doi: 10.1016/j.geoderma.2016.03.029

6. Keel SG, Budai A, Elsgaard L, Hardy B, Levavasseur F, Zhi L, et al. Efficiency of plant biomass processing pathways for long-term soil carbon storage. *Eur J Soil Sci*. (2025) 76: e70074. doi: 10.1111/ejss.70074

7. Rodrigues L, Budai A, Elsgaard L, Hardy B, Keel SG, Mondini C, et al. The importance of biochar quality and pyrolysis yield for soil carbon sequestration in practice. *Eur J Soil Sci*. (2023) 74:e13396. doi: 10.1111/ejss.13396

8. Woolf D, Lehmann J, Ogle S, Kishimoto-Mo AW, McConkey B, Baldock J. Greenhouse gas inventory model for biochar additions to soil. *Environ Sci Technol*. (2021) 55:14795–805. doi: 10.1021/acs.est.1c02425

9. Amalina F, Razak ASA, Krishnan S, Sulaiman H, Zularisam AW, Nasrullah M. Biochar production techniques utilizing biomass waste-derived materials and environmental applications – a review. *J Hazard Mater Adv*. (2022) 7:100134. doi: 10.1016/j.hazadv.2022.100134

10. EU. Regulation (EU) 2024/3012 of the European Parliament and of the Council of 27 November 2024 establishing a Union certification framework for permanent carbon removals, carbon farming and carbon storage in products. In: Union E, editor. *Document 32024r3012*. Bruxelles: European Commission (2024).

11. Bai X, Huang Y, Ren W, Coyne M, Jacinthe P-A, Tao B, et al. Responses of soil carbon sequestration to climate-smart agriculture practices: a meta-analysis. *Global Change Biol*. (2019) 25:2591–606. doi: 10.1111/gcb.14658

12. Seidel F, Álvaro-Fuentes J, Bolinder MA, Di Bene C, Diacono M, Diaz-Pines E, et al. Feasible carbon sequestration potential in European agricultural mineral soils through improved management. *Eur J Soil Sci*. (2026) 77:e70357. doi: 10.1111/ejss.70357

13. Busch D, Glaser B. Stability of co-composted hydrochar and biochar under field conditions in a temperate soil. *Soil Use Manage*. (2015) 31:251–8. doi: 10.1111/sum.12180

14. Cooper J, Greenberg I, Ludwig B, Hippich L, Fischer D, Glaser B, et al. Effect of biochar and compost on soil properties and organic matter in aggregate size fractions under field conditions. *Agric Ecosyst Environ*. (2020) 295:106882. doi: 10.1016/j.agee.2020.106882

15. Greenberg I, Kaiser M, Polifka S, Wiedner K, Glaser B, Ludwig B. The effect of biochar with biogas digestate or mineral fertilizer on fertility, aggregation and organic carbon content of a sandy soil: results of a temperate field experiment. *J Plant Nutr Soil Sci*. (2019) 182:824–35. doi: 10.1002/jpln.201800496

16. Gross A, Bromm T, Polifka S, Fischer D, Glaser B. Long-term biochar and soil organic carbon stability – evidence from field experiments in Germany. *Sci Total Environ*. (2024) 954:176340. doi: 10.1016/j.scitotenv.2024.176340

17. Hematimatin N, Igaz D, Aydın E, Horák J. Biochar application regulating soil inorganic nitrogen and organic carbon content in cropland in the Central Europe: a seven-year field study. *Biochar*. (2024) 6:14. doi: 10.1007/s42773-024-00307-4

18. Rumpel C. Biochar transport in terrestrial ecosystems. Fate and impacat. In: Lehmann J, Joseph S, editors. *Biochar for Environmental Management: Science, Technology and Implementation*. Routledge, London (2024). p. 18.

19. Wang L, O'Connor D, Rinklebe JR, Ok YS, Tsang DCW, Shen Z, et al. Biochar aging: mechanisms, physicochemical changes, assessment, and implications for field applications. *Environ Sci Technol*. (2020) 54:14797–814. doi: 10.1021/acs.est.0c04033

20. Zhang Y, Dang Y, Wang J, Huang Q, Wang X, Yao L, et al. A synthesis of soil organic carbon mineralization in response to biochar amendment. *Soil Biol Biochem*. (2022) 175:108851. doi: 10.1016/j.soilbio.2022.108851

21. Purakayastha TJ, Bera T, Dey S, Pande P, Kumari S, Bhowmik A. Biochar aided priming of carbon and nutrient availability in three soil orders of India. *Sci Rep*. (2024) 14:8420. doi: 10.1038/s41598-024-56618-w

22. Weng Z, Van Zwieten L, Singh BP, Tavakkoli E, Joseph S, Macdonald LM, et al. Biochar built soil carbon over a decade by stabilizing rhizodeposits. *Nat Clim Change*. (2017) 7:371–6. doi: 10.1038/nclimate3276

23. Kerré B, Bravo CT, Leifeld J, Cornelissen G, Smolders E. Historical soil amendment with charcoal increases sequestration of non-charcoal carbon: a comparison among methods of black carbon quantification. *Eur J Soil Sci*. (2016) 67:324–31. doi: 10.1111/ejss.12338

24. Hagemann N, Joseph S, Schmidt H-P, Kammann CI, Harter J, Borch T, et al. Organic coating on biochar explains its nutrient retention and stimulation of soil fertility. *Nat Commun*. (2017) 8:1089. doi: 10.1038/s41467-017-01123-0

25. Islam MU, Jiang F, Guo Z, Peng X. Does biochar application improve soil aggregation? A meta-analysis. *Soil Tillage Res*. (2021) 209:104926. doi: 10.1016/j.still.2020.104926

26. Batjes NH. Total carbon and nitrogen in the soils of the world. *Eur J Soil Sci*. (1996) 47:151–63. doi: 10.1111/j.1365-2389.1996.tb01386.x

27. van Groenigen JW, van Kessel C, Hungate BA, Oenema O, Powlson DS, van Groenigen KJ. Sequestering soil organic carbon: a nitrogen dilemma. *Environ Sci Technol*. (2017) 51:4738–9. doi: 10.1021/acs.est.7b01427

28. Gross A, Bromm T, Glaser B. Soil organic carbon sequestration after biochar application: a global meta-analysis. *Agronomy*. (2021) 11(12):2474. doi: 10.3390/agronomy11122474

29. D'Hose T, Debode J, De Tender C, Ruysschaert G, Vandecasteele B. Has compost with biochar applied during the process added value over biochar or compost for increasing soil quality in an arable cropping system? *Appl Soil Ecol*. (2020) 156:103706. doi: 10.1016/j.apsoil.2020.103706

30. Moreno LJ, Bastida F, Díaz-López M, Li Y, Zhou Y, López-Mondéjar R, et al. Response of soil chemical properties, enzyme activities and microbial communities to biochar application and climate change in a Mediterranean agroecosystem. *Geoderma*. (2022) 407:115536. doi: 10.1016/j.geoderma.2021.115536

31. Kravchenko AN, Snapp SS, Robertson GP. Field-scale experiments reveal persistent yield gaps in low-input and organic cropping systems. *Proc Natl Acad Sci*. (2017) 114:926–31. doi: 10.1073/pnas.1612311114

32. Zhang J, Li C, Xu M, Dong J, Wang S, Li P, et al. Biochar application rates regulate soil nutrient availability: evidence from an 8-year field study across two soils. *Biochar*. (2026) 8:115. doi: 10.1007/s42773-026-00623-x

33. Bramley RGV, Song X, Colaço AF, Evans KJ, Cook SE. Did someone say "farmer-centric"? Digital tools for spatially distributed on-farm experimentation. *Agron Sustain Dev*. (2022) 42:105. doi: 10.1007/s13593-022-00836-x

34. Bradford MA, Kuebbing SE, Polussa A, Sanderman J, Oldfield EE. Upstream data need to prove soil carbon as a climate solution. *Nat Clim Change*. (2025) 15:1013–6. doi: 10.1038/s41558-025-02429-4

35. Council, S.F. *Ordinance on the Reduction of Carbon Emissions (CO2 Ordinance)*. Bern: Swiss Confederation (2025). p. 154.

36. DüV. *Verordnung Vom 1. November 2023 Über Das Inverkehrbringen Von Düngern (Düngerverordnung, Düv)*. Bern, Schweiz: Der Schweizerische Bundesrat (2023).

37. Richner W, Sinaj S. Grundlagen für die Düngung landwirtschaftlicher Kulturen in der Schweiz. *Agrarforschung*. (2017) 8:1–276.

38. EBC. *European Biochar Certificate - Guidelines for a Sustainable Production of Biochar*. Arbaz, Switzerland: Ithaka Institute (2012–2022). Available online at: https://www.european-biochar.org/en/ (Accessed June 26, 2026).

39. Lebrun Thauront J, Soja G, Schmidt H-P, Abiven S. A critical re-analysis of biochar properties prediction from production parameters and elemental analysis. *GCB Bioenergy*. (2024) 16:e13170. doi: 10.1111/gcbb.13170

40. Agarwal T, Bucheli TD. Adaptation, validation and application of the chemo-thermal oxidation method to quantify black carbon in soils. *Environ pollut*. (2011) 159:532–8. doi: 10.1016/j.envpol.2010.10.012

41. Ellert BH, Bettany JR. Calculation of organic matter and nutrients stored in soils under contrasting management regimes. *Can J Soil Sci*. (1995) 75:529–38. doi: 10.4141/cjss95-075

42. Gao S, DeLuca TH, Cleveland CC. Biochar additions alter phosphorus and nitrogen availability in agricultural ecosystems: a meta-analysis. *Sci Total Environ*. (2019) 654:463–72. doi: 10.1016/j.scitotenv.2018.11.124

43. Nguyen TTN, Xu C-Y, Tahmasbian I, Che R, Xu Z, Zhou X, et al. Effects of biochar on soil available inorganic nitrogen: a review and meta-analysis. *Geoderma*. (2017) 288:79–96. doi: 10.1016/j.geoderma.2016.11.004

44. Zhang L, Jing Y, Chen C, Xiang Y, Rezaei Rashti M, Li Y, et al. Effects of biochar application on soil nitrogen transformation, microbial functional genes, enzyme activity, and plant nitrogen uptake: a meta-analysis of field studies. *GCB Bioenergy*. (2021) 13:1859–73. doi: 10.1111/gcbb.12898

45. Yuan X, Ban G, Luo Y, Wang J, Peng D, Liang R, et al. Biochar effects on aggregation and carbon-nitrogen retention in different-sized aggregates of clay and loam soils: a meta-analysis. *Soil Tillage Res*. (2025) 247:106365. doi: 10.1016/j.still.2024.106365

46. Munna MNH, Lal R. Long-term organic inputs effects on soil carbon and nitrogen sequestration in a temperate agroecosystem. *Soil Use Manage*. (2026) 42:70161. doi: 10.1111/sum.70161

47. Bai J, Zhang S, Huang S, Xu X, Zhao S, Qiu S, et al. Effects of the combined application of organic and chemical nitrogen fertilizer on soil aggregate carbon and nitrogen: a 30-year study. *J Integr Agric*. (2023) 22:3517–34. doi: 10.1016/j.jia.2023.09.012

48. Skadell LE, Schneider F, Bauke SL, Amelung W, Don A. Long-term management effects on depth gradients of 13C, 15N and C/N ratio in agricultural soils. *Geoderma*. (2025) 458:117341. doi: 10.1016/j.geoderma.2025.117341

49. White KE, Brennan EB, Cavigelli MA, Smith RF. Winter cover crops increase readily decomposable soil carbon, but compost drives total soil carbon during eight years of intensive, organic vegetable production in California. *PloS One*. (2020) 15: e0228677. doi: 10.1371/journal.pone.0228677

50. Nyameasem JK, De Los Rios J, Kluß C, Reinsch T, Poyda A, Taube F, et al. Incorporating leys in arable systems as a mitigation strategy to reduce soil organic carbon losses during land-use change. *Front Environ Sci*. (2024) 12. doi: 10.3389/fenvs.2024.1399197

51. Karstens K, Bodirsky BL, Dietrich JP, Dondini M, Heinke J, Kuhnert M, et al. Management-induced changes in soil organic carbon on global croplands. *Biogeosciences*. (2022) 19:5125–49. doi: 10.5194/bg-19-5125-2022

52. Kuzyakov Y, Friedel JK, Stahr K. Review of mechanisms and quantification of priming effects. *Soil Biol Biochem*. (2000) 32:1485–98. doi: 10.1016/s0038-0717(00)00084-5

53. Plante AF, Beaupré SR, Roberts ML, Baisden T. Distribution of radiocarbon ages in soil organic matter by thermal fractionation. *Radiocarbon*. (2013) 55:1077–83. doi: 10.1017/S0033822200058215

54. Sanderman J, Grandy AS. Ramped thermal analysis for isolating biologically meaningful soil organic matter fractions with distinct residence times. *SOIL*. (2020) 6:131–44. doi: 10.5194/soil-6-131-2020

55. Hardy B, Borchard N, Leifeld J. Identification of thermal signature and quantification of charcoal in soil using differential scanning calorimetry and benzene polycarboxylic acid (BPCA) markers. *SOIL*. (2022) 8:451–66. doi: 10.5194/soil-8-451-2022

56. Leifeld J. Thermal stability of black carbon characterised by oxidative differential scanning calorimetry. *Org Geochem*. (2007) 38:112–27. doi: 10.1016/j.orggeochem.2006.08.004

57. Lu W, Ding W, Zhang J, Li Y, Luo J, Bolan N, et al. Biochar suppressed the decomposition of organic carbon in a cultivated sandy loam soil: a negative priming effect. *Soil Biol Biochem*. (2014) 76:12–21. doi: 10.1016/j.soilbio.2014.04.029

58. Zimmerman AR, Gao B, Ahn M-Y. Positive and negative carbon mineralization priming effects among a variety of biochar-amended soils. *Soil Biol Biochem*. (2011) 43:1169–79. doi: 10.1016/j.soilbio.2011.02.005

59. Fang Y, Singh B, Singh BP. Effect of temperature on biochar priming effects and its stability in soils. *Soil Biol Biochem*. (2015) 80:136–45. doi: 10.1016/j.soilbio.2014.10.006