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Effect of sugar beet (*Beta vulgaris* L.) cultivation on soil organic carbon stocks in Germany

Dennis Grunwald[1] | **Christopher Poeplau**[2] | **Heinz-Josef Koch**[1] | **Anna Jacobs**[1]

[1]Institute of Sugar Beet Research, Göttingen, Germany

[2]Thünen Institute of Climate-Smart Agriculture, Braunschweig, Germany

Correspondence

Anna Jacobs, Institute of Sugar Beet Research, Göttingen, Germany.
Email: jacobs@ifz-goettingen.de

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Abstract

Sugar beet is generally seen as detrimental to soil organic carbon (SOC) stocks for multiple reasons although actual data verifying this claim are scarce. In this study, two approaches were combined to examine the effect of sugar beet on SOC from field data in Germany. First, SOC data of the German Agricultural Soil Inventory were used to compare sugar beet sites with similar sites without sugar beet cultivation. Second, a long-term crop rotation trial in Central Germany was evaluated for differences in SOC among crop rotations with and without sugar beet. Further, carbon input into soil from sugar beet residues was compared with wheat as a reference. In the nationwide dataset, lower SOC stocks (−4.6%) were found for sugar beet sites compared with those without. However, a re-sampling of the sites 10 years later showed no (further) SOC loss. In the long-term trial, no negative impact of sugar beet cultivation on SOC was found. From both databases, carbon input from sugar beet crop residues (2 and 2.7 $\mathrm{Mg\,ha^{-1}\,year^{-1}}$, respectively) was much lower than from wheat (3.6 and 5.8 $\mathrm{Mg\,ha^{-1}\,year^{-1}}$, respectively) because of evident differences in the amount of belowground residues. However, this may be counteracted by growing cover crops before sugar beet, as done in the long-term field trial studied. We conclude that sugar beet might have had a negative impact on SOC stocks in the past, yet that this does not necessarily continue in the present on long-term sugar beet fields, possibly because of a current steady SOC state. When growing cover crops, sugar beet cultivation might have no negative effect on SOC at all. In any case, a general loss of SOC because of sugar beet cultivation cannot be assumed.

KEYWORDS

Agricultural Soil Inventory, cover crops, crop residues, crop rotation, MatchIt, winter wheat

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Dennis Grunwald and Christopher Poeplau contributed equally to this work.

1 | INTRODUCTION

Information and transparency on all issues around sustainable development of processing companies are more frequently requested by buyers, consumers, and investors. The latest directive of the European Union (EU) on corporate sustainability reporting (European Parliament, 2022) reflects this request and sets a policy, broadened to small- and medium-sized undertakings, for obligatory reporting of sustainability information. Right now, this directive is not yet transposed to most of the EU countries, including Germany. However, undertakings will need to report their efforts on climate protection issues and their greenhouse gas (GHG) emissions, which fall into three defined categories, called scopes (World Resources Institute and World Business Council, 2004). Since scope 1 and 2 cover the direct emissions and indirect emissions from electricity use, respectively, scope 3 aims at all further emissions along the production chain.

Sugar beet (*Beta vulgaris* L.) contributes 25% of the worldwide sugar production and is the major crop for sugar production in Europe. In Germany, 361,000 ha were under sugar beet cultivation in 2022, and about 3.9 million tonnes of sugar were produced in 2022/2023 (Wirtschaftliche Vereinigung Zucker & Verband der Zuckerindustrie, 2024). Further products of sugar beet processing are bioethanol, biogas, and fertilizer. Four sugar companies are active in Germany, and their scope 3 emissions include the cultivation of sugar beet crops and, with this, possible emissions of greenhouse gases from the soil, which are generated by methane, nitrous oxide, and carbon dioxide (CO_2). The latter are provoked by losses of soil organic carbon (SOC), which is emitted as CO_2 after aerobic mineralization.

Organic C enters the soil by dead organic material of floral and faunal origin. In arable soils, the major C sources are above- and belowground residues of the crops. As part of the natural C cycle, soil organisms feed on this dead organic material and, expressed as simply as possible, exhale mineral gaseous C compounds, such as CO_2 and methane. Further, parts of the organic material pass the digestive tract and are excreted back to the soil, where they remain as more or less stabilized forms of SOC. The mean residence time of SOC strongly depends on the biochemical composition of the organic material as well as site-specific factors controlling decomposition and stabilization of organic matter, such as soil texture, temperature, content of water and oxygen in soil pores, and the availability of further nutrients, for example, mineral N, for soil organisms. With a global sum of approximately 1500 Pg C (excluding permafrost soils), SOC is estimated to be the largest terrestrial C stock (Scharleman et al., 2014). In the context of climate change mitigation, an increase of SOC is considered an important negative GHG emission technology (Minasny et al., 2017) and, vice versa, losses of SOC on a national level need to be reported as a GHG emission following the Paris Agreement (United Nations, 2015). For arable soils, science and practitioners worldwide search for technical solutions to properly account for losses and increases of SOC, especially under site-specific soil management conditions as reviewed by Guo et al. (2023).

The choice of cultivated crops can strongly influence SOC stocks because of differences in the amount and quality of carbon inputs as well as the degree of soil aeration (Mathew et al., 2017). Because of this, crop-specific standard values for losses or increases of organic matter in the soil were established in Germany (VDLUFA, 2014) to attribute 'reproduction needs' of SOC, which might be interpreted as SOC losses, to a crop rotation. This publication attributed the term 'humus-depleting' (humus: dead soil organic matter) to row crops in general and set a minimum value of SOC 'reproduction need' of 0.76 Mg C ha^{-1} (without soil depth indicated), which accounts for 2.79 Mg CO_2 equivalents ha^{-1} and per cultivation year. These values are based on non-retrievable publications from the 1970s (cited as 'Autorenkollektiv 1977' in VDLUFA, 2014). The field trials evaluated in these publications were located in the former GDR (East Germany) and do not represent current cultivation practices nor site conditions that are representative for the whole of Germany. Further, the current state of knowledge (e.g., Prout et al., 2022) attributes site-specific conditions, such as texture, climate, or current SOC content, to be highly relevant for SOC dynamics, which are also not included in the VDLUFA (2014) standard values. Moreover, using these values for the assessment of GHG emissions was never intended. However, since standard values of higher quality are missing so far, some GHG assessment tools for farmers use these values for GHG balancing and advise, because of the SOC depleting effect assigned to sugar beet cultivation, to replace sugar beet with 'humus-increasing' crops for the sake of climate-friendly crop production (Wüstemann et al., 2023).

Beyond the questionable use of outdated and non-site-specific values for a generalized evaluation of SOC gains or losses owing to the cultivation of a single crop, crop-by-crop comparisons and standards generally come along with the imperfection of non-comparable temporal system boundaries since different crops stay for different amounts of months in the field. In the case of spring-sown crops, such as sugar beet, the potential foregoing cultivation of cover crops needs to be included in the assessment, especially if results are to be compared with winter-sown crops, such as winter wheat (*Triticum aestivum L.*), in order to consider similar and comparable timeframes of assessment (Jacobs et al., 2019). In the case of sugar beet, mostly cultivated in rather wide crop rotations (Koch et al., 2018), the variety of further crops grown on the same field over the course of one rotation, including cover crops, is large. This may well affect site-specific SOC dynamics of sugar beet fields and calls for results from controlled long-term trials using common crop rotations or practical fields with a known cultivation history. So far, such data are not present in scientific literature, apart from earlier results from the long-term field trial evaluated here (Grunwald et al., 2021) or older trials with outdated management practices (Götze et al., 2016).

Thus, to enable proper reporting on scope 3 GHG emissions and advice on climate-smart crop production, this study aims at providing reliable values on SOC changes because of sugar beet cultivation for Germany by (i) comparing SOC stocks of crop rotations with and without sugar beet and (ii) assessing C input into soil by sugar beet cultivation in comparison to other crops. To do so, we chose two different approaches using two different datasets: one of a Germany-wide soil survey and one of a long-term field trial in Central Germany. This way, it was further attempted to obtain a representative picture for sugar beet cultivation in Germany as a whole, as an example for temperate, highly productive agricultural regions.

2 | MATERIALS AND METHODS

2.1 | Approach A: Dataset of the German Agricultural Soil Inventory

As the first approach, we used data from the German Agricultural Soil Inventory (German: Bodenzustandserhebung Landwirtschaft, BZE-LW). In this comprehensive survey, 3104 German agricultural soils were sampled in an 8×8 km nationwide grid between 2011 and 2018. The soils at each sampling site were described by pedologists, sampled to a depth of 1 m, and analysed for soil chemical and physical properties. Stocks of SOC were calculated using organic C (OC) content and fine soil stock, the latter being estimated from the thickness of the investigated increment, measured bulk density of the fine soil, as well as the rock fragment fraction. Methodological details of the BZE-LW are described by Jacobs, Flessa, et al. (2018) and Poeplau et al. (2021). Importantly, 10 years of management information of the sites sampled were also obtained by a farmers' survey, including information on crop type, yield, residue management, cover crops, fertilization and tillage regime. These data were converted into C inputs to soil using yield-dependent C allocation coefficients as well as average data on specific C content of organic fertilizers and plant material (Jacobs et al., 2020). A total of 2200 cropland sites were sampled, and a total of 365 sites of those grew sugar beet at least once in the 10 years before sampling. The spatial distribution of the sugar beet sites is shown in Figure 1. As expected, it coincided with the abundance of loess soil and other silty parent materials in Germany. On average, sugar beet was grown 2.2 times within 10 years at each site, that is, roughly every fifth year, fitting to observations by Koch et al. (2018). In 2023, a re-sampling of the BZE-LW sites started. The dataset of the BZE-LW was used in three different ways to estimate potential effects of sugar beet cultivation on SOC stocks. Statistical analysis as described in the following passages was performed using R version 4.4.0.

Firstly, all 365 sugar beet sites were compared with sites in Germany that had similar site conditions but were not under sugar beet cultivation within the 10 years before sampling. We assumed that information on the past 10 years of management was representative for an even longer time series and that we thereby identified soils with typical characteristics because of long-term sugar beet cultivation. To pick sites that were as similar as possible to the sugar beet sites but were not under sugar beet cultivation,

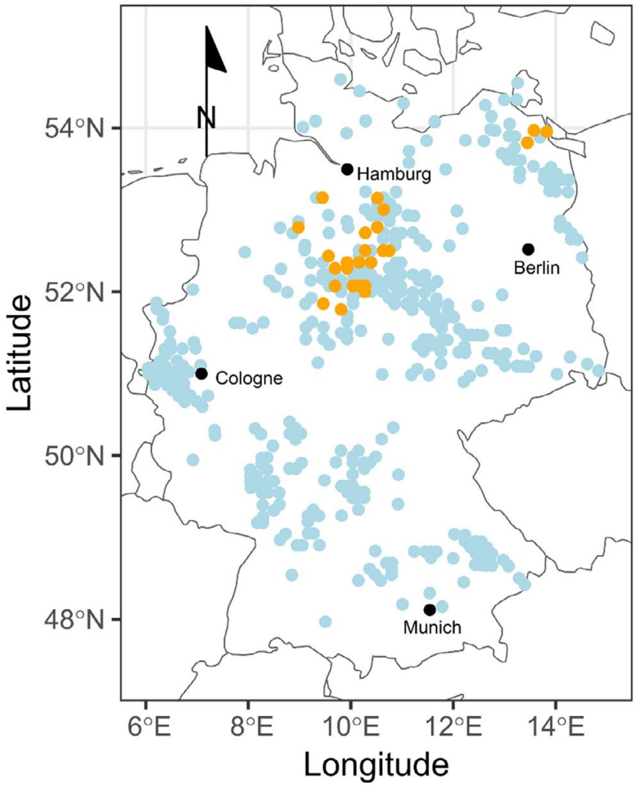

FIGURE 1 Locations with sugar beet cultivation sampled in the first (blue dots; 365 sites; 2011–2018) and the second (orange dots; 25 sites; 2022 onwards) campaign of the German Agricultural Soil Inventory.

we used the 'MatchIt' package (Ho et al., 2011), which contains methods to pre-process observational data for reducing the causal interference of covariates while estimating treatment effects. In this case, nearest-neighbour propensity score matching was used to balance covariates and match each sugar beet site with a site that had a similar propensity score. For propensity scoring, properties relevant for SOC stocks were selected and used in a generalized least squares (gls) regression to identify the most similar sites. As properties, we used C:N ratio, clay content, and pH value of the soil, as well as groundwater level, mean annual precipitation, and soil group (according to the World Reference Base) assigned to the site. This choice of selection factors was in accordance with previous works on the relevance of soil and climate variables for SOC stocks (Drexler et al., 2022; Poeplau et al., 2021), and the Akaike Information Criterion was used to identify the best model and avoid overfitting. The SOC stock comparison was restricted to a depth of 0–30 cm because of a high variability of subsoil SOC stocks (Poeplau et al., 2021).

Secondly, SOC stock trends between the two sampling campaigns at the sugar beet sites were identified. This was done to test potential SOC losses because of sugar beet cultivation during approximately the last decade. The resampling campaign of the BZE-LW started in the end of 2022 and is still ongoing. During this campaign, the initial sampling plots (12 × 12 m) are relocated exactly and are resampled using four small soil pits around the central pit of the initial sampling campaign. Resampling is conducted at least 10 years after initial sampling and to a depth of 50 cm. However, in this study we evaluated only the trend of the 0–30 cm topsoil increment. The methodology of SOC stock estimation remained the same as described in Jacobs, Flessa, et al. (2018). The fine soil stock at each site was assumed to be constant. To date, 25 of the sugar beet sites were resampled and had a confirmed sugar beet cultivation between the first and second sampling (Figure 1). For these sites, we compared SOC stocks of both campaigns by a paired *t*-test and set the level of significance to $\alpha = 5\%$.

Thirdly, calculated C inputs to soil because of sugar beet cultivation were compared with the mean C input across all main crops of the 730 selected sites ($n = 7099$) and of winter wheat on the selected sites ($n = 2527$) as a reference crop of the highest economic importance in Germany. The specific n given is the multiplication of sites and harvest years reported in the farmers' survey. The C input was evaluated regarding quantity and origin (shoots, roots, and organic fertilizers) following Jacobs et al. (2020) to get a rough estimate of the SOC formation potential. The survey revealed that exogenous organic amendments were applied on croplands in 42% of the reported site years, consisting of 98% animal-derived organic materials (including farmyard manure, slurry, and similar), and contributed 12% to the total C input.

2.2 | Approach B: Dataset of long-term field trial

For the second approach, SOC data from a long-term crop rotation trial located near Harste in Lower Saxony, Germany (51°36′24.4″N 9°51′49.0″E) were used. The soil of this trial was classified as a Stagnic Luvisol with a silty loam texture (14% sand, 76% silt, 10% clay) and a pH value of 6.8 in the top 0–30 cm. Long-term (1991–2020) mean annual precipitation was 624 mm, and mean annual temperature was 9.5°C (DWD 2021). The experiment started in 2006, comparing eight different crop rotations, with each crop rotation element cultivated every year in three complete blocks (field replications). Crop residues were generally left on the field, and tillage was mostly carried out with a cultivator to a depth of around 15 cm. Mineral fertilization and plant protection were adapted to crop rotation and growing conditions and were aimed at optimal plant growth without restrictions owing to nutrient shortage or disease pressure. The SOC content in 0–20 cm depth in 2005, before the start of the experiment, ranged from 12.5 to 12.9 $\mathrm{g\,C\,kg^{-1}}$ soil.

For this study, soil samples from plots assigned to four different crop rotation treatments were evaluated:

(i) Monoculture of winter wheat
(ii) Monoculture of silage maize (*Zea mays* L.)
(iii) Winter oilseed rape (*Brassica napus* L.)—winter wheat—winter wheat
(iv) (Cover crop mustard (*Sinapis alba* L.))—sugar beet—winter wheat—winter wheat

The silage maize monoculture was started in 2010. Soil sampling took place in March 2008 and in August 2020 on the same plots (three replicates for each rotation). In both years, four undisturbed soil samples were taken per plot, in March 2008 by hand from 0 to 10, 10 to 20, 20 to 30, and 30 to 45 cm, while in August 2020 samples were taken from 0 to 30 and 30 to 60 cm by drill pipe. In the case of silage maize monoculture, no samples were taken in March 2008, but in March 2010, shortly before the first sowing of maize on the plots, in 0–30 and 30–60 cm soil depth. In all cases, soil bulk density was determined by drying and weighing the samples, and subsamples for SOC analysis were taken from the soil cores. The total soil C content for the 2020 samples was analysed by dry combustion (FlashEA 1112, Thermo Fisher Scientific, Waltham, USA), corresponding to SOC because of the absence of notable amounts of carbonates. For all samples in 2008 and the

2010 samples from the silage maize monoculture plots only, OC content was determined by a different device of dry combustion (NA 1500N, Fisons Instruments, Glasgow, UK).

Stocks of SOC were then calculated for equal soil masses (Ellert & Bettany, 1995) for the topsoil (0–30 cm) and the subsoil (30–60 cm). To do so, the maximum soil mass of 0–30 cm (both sampling dates) and 30–60 cm soil depth (for the 2020 sampling only) was used. For the 2008/2010 samplings, the range of soil masses in 0–30 cm was 4080–4460 Mg ha^{-1}, and for the 2020 sampling, 4020–4937 Mg ha^{-1}; thus, all 0–30 cm samples were adjusted to the maximum value of 4937 Mg ha^{-1}. The C content used for mathematical calculation of soil masses lower than the maximum was taken from 30 to 60 cm soil depth for the 2020 and 2010 samplings and from 30 to 45 cm for the 2008 sampling because of differences in data availability. Thus, there might be slightly lower SOC stocks resulting from the 2020 and 2010 compared with the 2008 sampling date by a dilution resulting from the use of lower C contents in the deeper subsoil horizon (2010/2020: 6.0 ± 1.5 g C kg^{-1} soil in 30–60 cm and 2008: 7.9 ± 3.4 g C kg^{-1} soil in 30–45 cm in average of all treatments). However, differences were below the standard deviation, and we considered this difference in subsoil sampling as negligible for the outcomes of this study. For the 30–60 cm soil depth in 2020, soil mass ranged between 4097 and 5221 Mg ha^{-1} and was thus adjusted to 5221 Mg ha^{-1}. During this sampling campaign, no measurements below 60 cm were conducted, and we assumed the 30–60 cm C content to be representative for the soil depth below for soil mass-based compensation.

Aboveground and belowground plant residue C input was calculated for each plot for the period from 2008 (2010 in the case of silage maize monoculture) to 2019, that is, the timeframe between the two sampling dates. Aboveground crop residue biomass of winter wheat and sugar beet was determined by manual harvest each year, and C content was determined by dry combustion as described above (the mean value was 44.4% C for wheat and 38.0% for sugar beet). For oilseed rape, maize, and mustard, these data were not analysed as a routine, and respective assumptions were necessary: (i) For oilseed rape straw and aboveground mustard biomass, C contents were only determined from 2019 onwards. As an approximation for oilseed rape, the average C content of oilseed rape straw (43.4%) from the so-far measured years (2019–2023) was multiplied with measured straw biomass of each year. Regarding mustard, the mean annual aboveground C input from 2019 to 2023 was averaged (1.24 Mg C ha^{-1}) and used for each year. (ii) Maize stubble biomass was measured twice, in 2010 and 2023, and average C input of these years (0.6 Mg C ha^{-1}) was taken into account. Further, the C input from the stubble biomass of wheat and oilseed rape was calculated following the protocol of Jacobs et al. (2020) and added to the straw input. Belowground C input as sum of root and rhizodeposition C input was estimated for each crop, year and plot following Jacobs et al. (2020) as well. From this total calculated belowground input, 75% was assumed to occur in the top 30 cm and thus to be relevant for this study, following Fan et al. (2016).

Statistical analyses were performed with R version 4.1.1. Differences in SOC stocks and concentrations between crop rotations in single soil depths, as well as in aboveground, belowground, and total C input, were analysed by a linear mixed model (package 'lme4'; Bates et al., 2015) with crop rotation as fixed and field replication as a random effect. Residuals of the models were checked for homoscedasticity by Levene's test as well as graphically and for normal distribution by the Shapiro–Wilk test as well as graphically. When the factor crop rotation was significant ($\alpha = 5\%$), mean values were compared by calculating estimated marginal means (package 'emmeans'; Lenth, 2024).

3 | RESULTS

3.1 | Topsoil organic carbon contents and stocks of sugar beet sites and reference sites

3.1.1 | Approach A

On average, sites with sugar beet cultivation had a topsoil (0–30 cm) OC content of 13.3 g kg^{-1}, which was significantly lower than the SOC content of the reference sites without sugar beet cultivation (14.3 g kg^{-1}, $p = .01$) (Table 1). Equally significant ($p = .03$), SOC stocks of topsoil (0–30 cm) were 2.6 Mg ha^{-1} lower on sugar beet sites. Figure 2 depicts the density, as the frequency distribution, of SOC content of both groups. Their very similar frequency distributions revealed that the statistical matching algorithm was successful and that the treatment (sugar beet cultivation) caused a slight but systematic downward shift in SOC contents.

TABLE 1 Contents and stocks of soil organic carbon (SOC) in 0–30 cm of sites with sugar beet cultivation ($n = 365$) and on reference sites without sugar beet cultivation ($n = 365$). Data retrieved from the First German Agricultural Soil Inventory (2011–2018). Comparison was undertaken by matching sugar beet and reference sites of similar conditions.

Site	SOC content (g kg^{-1})	SOC stock (Mg ha^{-1})
Sugar beet	13.3 (5.2)	53.4 (16.7)
Reference	14.3 (5.2)	56.0 (16.8)

Note: Mean values and standard deviation.

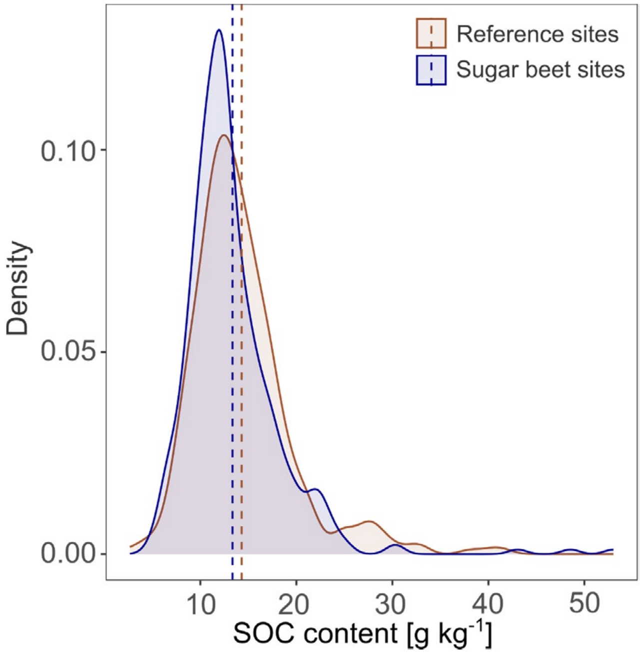

FIGURE 2 Frequency distribution expressed as a density function (unitless, with the integral of the function being 1) of soil organic carbon (SOC) content in 0–30 cm of sites with ($n = 365$) and matched sites without (reference, $n = 365$) sugar beet cultivation. Dotted vertical lines indicate the mean SOC content. Data were retrieved from the First German Agricultural Soil Inventory (2011–2018).

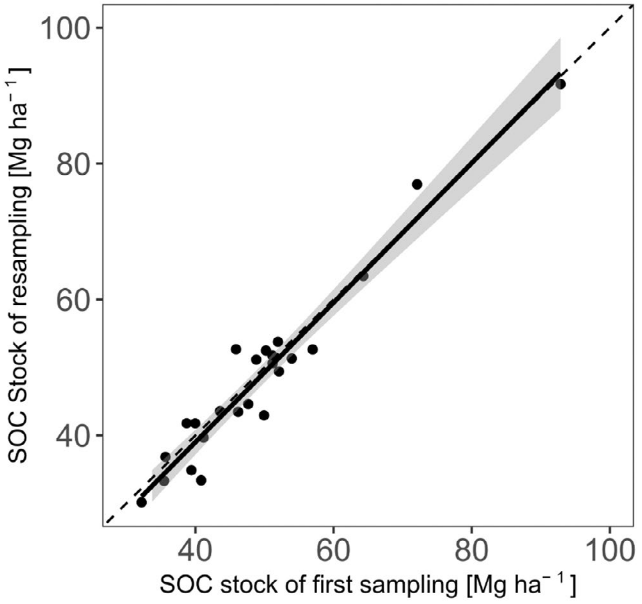

FIGURE 3 Stocks of soil organic carbon (SOC) in 0–30 cm on sites with sugar beet cultivation ($n = 25$) of the initial (2011–2018) compared with the resampling campaign (started in 2022) of the German Agricultural Soil Inventory. Dashed line depicts the 1:1 line; solid line depicts the linear regression with a 95% confidence interval. The time between both sampling dates was a minimum of 10 years.

TABLE 2 Contents and stocks of soil organic carbon (SOC) in 0–30 cm across different crop rotations (M, mustard as a cover crop; SB, sugar beet; SM, silage maize; WR, winter oilseed rape; WW, winter wheat), Harste, Lower Saxony, in 2008 (2010 in the case of SM monoculture) and in August 2020. Stocks were calculated to an equal soil mass of 4937 Mg ha^{-1}.

Crop rotation	SOC March 2008	SOC August 2020	Difference 2008–2020
	SOC content [g C kg^{-1} soil]		
WW monoculture	11.9 (0.8)	11.4 (0.8)^{ab}	−0.6 (0.6)
SM monoculture	11.3 (0.3)*	10.2 (0.4)^{a}	−1.1 (0.6)
WR—WW—WW	12.3 (1.1)	11.7 (1.1)^{b}	−0.5 (0.7)
M—SB—WW—WW	12.4 (0.8)	12.0 (0.5)^{b}	−0.4 (0.4)
	SOC stock [Mg C ha^{-1}]		
WW monoculture	58.9 (4.0)	56.2 (4.1)^{ab}	−2.7 (2.9)
SM monoculture	55.9 (1.3)*	50.4 (2.2)^{a}	−5.5 (3.2)
WR—WW—WW	60.5 (5.5)	58.0 (5.5)^{b}	−2.5 (3.7)
M—SB—WW—WW	61.2 (4.1)	59.2 (2.5)^{b}	−2.1 (2.1)

Note: Means ($n = 3$) and standard deviations in brackets. Different letters indicate significant differences ($p \leq .05$) across crop rotations. Differences in 2008 and in the development of SOC values between 2008 and 2020 were non-significant (in both cases excluding SM monoculture).

*Starting value was taken in March 2010 when SM monoculture was established.

3.1.2 | Approach B

At both sampling dates, all crop rotations in the long-term trial as well as the winter wheat monoculture were similar in SOC stock in 0–30 cm depth (Table 2). At the 2020 sampling, the rotation mustard (cover crop)—sugar beet—winter wheat—winter wheat showed the highest mean SOC stock in 0–30 cm (59.2 Mg C ha^{-1}) compared with the other rotations. The significantly lowest SOC stock was observed for the silage maize monoculture (50.4 t C ha^{-1}). In the subsoil (30–60 cm), no significant differences were found (data not shown), yet numerically the lowest values were for the rotation with sugar beet (29.3 Mg C ha^{-1}) and the highest values were for the winter wheat monoculture (33.4 Mg C ha^{-1}).

3.2 | Change in soil organic carbon stocks over time

3.2.1 | Approach A

The 25 sugar beet sites that were resampled so far did not reveal a clear trend in SOC stocks (Figure 3), with the regression being in perfect agreement with the 1:1 line. Overall, only a slightly significant loss of SOC was detected (-1.4 ± 3.3 Mg ha^{-1}, $p = .04$). It can thus be inferred that SOC stocks at sugar beet sites were relatively stable.

3.2.2 | Approach B

All studied treatments lost SOC over the study period from 2008 (2010 for silage maize monoculture) to 2020. For both rotations as well as the winter wheat monoculture, the loss was similar with 2.1–2.7 Mg C ha^{-1} and 0.4–0.6 g C kg^{-1} soil, while the silage maize monoculture lost numerically higher amounts (5.5 Mg C ha^{-1} and 1.1 g C kg^{-1} soil) in a shorter time (10 compared with 12 years; Table 2).

3.3 | Annual carbon inputs to the soil

3.3.1 | Approach A

Sugar beet cultivation had much lower mean total C input per cultivation period to the soil (2.6 ± 1.6 Mg C ha^{-1}) than winter wheat (4.2 ± 1.7 Mg C ha^{-1}) and all crops combined (3.9 ± 1.8 Mg C ha^{-1}) (Table 3). The relative C input differences of sugar beet to winter wheat and all crops were thus −37% and −32%, respectively. This difference was fully attributed to the lower root-derived belowground C input (Table 3). In 99% of cases, sugar beet leaves were left in the field, while wheat straw only remained in the field in 68% of all cases.

3.3.2 | Approach B

Annual aboveground C input by sugar beet leaves and tops was 2.3 Mg C ha^{-1}, while the input by straw of winter wheat and of winter oilseed rape averaged at 4.1 Mg C ha^{-1} (Table 4). The remaining silage maize stubbles and mustard biomass were estimated (see above) to provide 0.6 and 1.2 Mg C ha^{-1} annually, respectively. Calculated belowground input was similar for winter wheat, winter oilseed rape, and silage maize (1.6–1.8 Mg C ha^{-1} year^{-1}), while sugar beet and mustard provided less (0.3–0.6 Mg C ha^{-1} year^{-1}). Total annual input varied strongly between the main crops, with 2.2 and 2.7 Mg C ha^{-1} for silage maize and sugar beet, respectively, and 5.8 Mg C ha^{-1} for both winter wheat and winter oilseed rape.

Aboveground C input as a total of the entire crop rotation over 12 years of field trial (silage maize monoculture: 10 years) ranged from 13.6 to 51.2 Mg C ha^{-1} for the different crop rotations and was highest for winter wheat monoculture and lowest for silage maize monoculture (Table 5). The rotation mustard (cover crop)—sugar beet—winter wheat—winter wheat summed up to a medium C input of 46.4 Mg C ha^{-1}, which was numerically, yet not significantly, lower than the rotation winter oilseed rape—winter wheat—winter wheat and the winter wheat monoculture. Belowground C input calculated from yield data was clearly lowest for the rotation with sugar beet with 16.6 Mg C ha^{-1}, while the winter wheat monoculture and rotation with winter oilseed rape ranged between 20.0 and 21.1 Mg C ha^{-1}. In summary, the rotation with sugar beet and maize monoculture provided 8–9 and 45–46 Mg ha^{-1} less C input to the soil, respectively, than the wheat monoculture and the oilseed rape rotation in the time periods considered.

TABLE 3 Carbon input (Mg ha^{-1}) to soil per cultivation period owing to the cultivation of sugar beet, winter wheat, and all crops within the matched dataset. Data were retrieved from the First German Agricultural Soil Inventory (2011–2018) and included the multiplication of sites and harvests of the main crop (specific n). Sugar beet cultivation ($n = 803$) was compared with winter wheat as a reference crop ($n = 2527$), as well as all crops together ($n = 7099$) for the selected sites. Aboveground input is the sum of harvest residues and stubble; belowground input is the sum of root biomass and rhizodeposition; organic fertilizer includes cover crops cultivated as green manure.

	Total	Belowground	Aboveground	
Crop	C input (Mg ha^{-1})			Organic fertilizer
Sugar beet	2.6 (1.6)	0.4 (0.1)	1.7 (0.8)	0.6 (1.4)
Winter wheat	4.2 (1.7)	1.8 (0.3)	1.8 (1.0)	0.6 (1.2)
All crops	3.9 (1.8)	1.6 (0.7)	1.7 (1.1)	0.6 (1.2)

Note: Mean values and standard deviation in brackets.

TABLE 4 Mean above- and belowground C input per vegetation period (Mg ha^{-1}) in the study period (2008–2019) for the different crops in the studied crop rotations in the long-term trial in Harste, Lower Saxony, with measured data for aboveground residues and calculated data for belowground residues (see Methods section).

Crop	Total	Aboveground	Belowground
	C input (Mg ha^{-1})		
Sugar beet	2.7 (0.7)	2.3 (0.7)	0.3 (0.1)
Winter wheat	5.8 (0.9)	4.1 (0.3)	1.7 (0.3)
Winter oilseed rape	5.8 (0.8)	4.1 (0.3)	1.8 (0.4)
Silage maize	2.2 (0.2)	0.6	1.6 (0.2)
Mustard (cover crop)	1.8	1.2	0.6

Note: Mean values ($n = 12$ for oilseed rape and sugar beet, 42 for silage maize belowground and total input, and 108 for winter wheat) and standard deviation in brackets, except for silage maize aboveground input and mustard which are estimated from other data. Owing to the strongly different replication numbers and differences in data acquisition, no statistical analysis was conducted.

TABLE 5 Sum of long-term (2008–2019; silage maize (SM) monoculture: 2010–2019) above- and belowground C input (Mg ha^{-1}) for the long-term crop rotation trial, Harste, Lower Saxony (M, mustard cover crop; SB, sugar beet; WR, winter oilseed rape; WW, winter wheat).

Crop rotation	Grown crops	Aboveground	Belowground	Total
		C input (Mg ha^{-1})		
WW monoculture	12 × WW	51.2 (1.8)	20.0 (0.2)^{b}	71.2 (2.0)^{b}
SM monoculture*	10 × SM	6.0 (0.0)*	15.1 (0.5)*	26.2 (0.7)*
WR—WW—WW	8 × WW, 4 × WR	51.0 (1.9)	21.1 (0.5)^{c}	72.1 (2.4)^{b}
M—SB—WW—WW	8 × WW, 4 × M + SB	46.4 (1.8)	16.6 (0.3)^{a}	63.1 (1.8)^{a}

Note: Mean values and standard deviation in brackets ($n = 3$). Different letters indicate significant differences ($p \le .05$).

*Excluded from statistics since cultivated for 10 years only.

4 | DISCUSSION

4.1 | Changes in contents and stocks of soil organic carbon owing to sugar beet cultivation

The BZE-LW dataset of the first sampling campaign (2010–2018) revealed slightly lower SOC contents and stocks (0–30 cm soil depth) on sites that were cultivated with sugar beet at least once within the previous years (a maximum of 10 years was reported): The difference compared with sites of similar conditions but without sugar beet cultivation was 1 g kg^{-1} and 2.6 Mg ha^{-1}, respectively. Since further management-induced drivers of SOC dynamics, such as cover crop cultivation, diversity of crop rotation, frequency of sugar beet within the rotation, harvest residue return, and organic fertilization, were not included in this evaluation, the difference of 2.6 Mg ha^{-1} in SOC stock might not fully be attributable to sugar beet cultivation. Moreover, it is not possible to mirror this difference to a timely denominator to gain a value for SOC loss per hectare and year as it is needed for a GHG balance. However, those sugar beet sites that were already sampled during the second campaign and still had sugar beet in the rotation showed only very moderate loss of SOC (−1.4 Mg ha^{-1}), especially when compared with all sites resampled so far that exceeded a loss of 5 Mg ha^{-1} ($p < .001$; data not shown). Average SOC losses of similar magnitude have been observed in several European countries and could be attributed to diverse drivers, including past land use change, climate change, drainage, and yield-optimized crop breeding (Gubler et al., 2019; Smith et al., 2007). However, the smaller-than-average SOC loss at long-term sugar beet sites might indicate that the cultivation of sugar beet as such does not cause any further SOC losses. This is in line with the general understanding of SOC dynamics, which is strongest directly after a given management change but levels off into a new steady state after a certain time (Stewart et al., 2007). In Germany, sugar beet is broadly cultivated since the mid of the 19th century (Verband der Hessisch-Pfälzischen Zuckerrübenanbauer, 2011; Wirtschaftliche Vereinigung Zucker & Verein der Zuckerindustrie, 2024), and we assume that most sites are approximately in steady state by now or have only a moderately negative baseline owing to other environmental drivers. This is, however, not implemented in the logic of the classical humus balance, which assumes an equal annual loss of SOC because of sugar beet cultivation, regardless of any potential foregoing losses or other modifying factors. A major part of the observed moderate SOC losses of the sugar beet sites can most likely be attributed to climate change (see below; Poeplau & Dechow, 2023).

Data evaluated from the long-term crop rotation trial in South Lower Saxony confirmed that a higher reduction of SOC under crop rotations with sugar beet (accompanied by mustard as a cover crop in this case) compared with rotations without sugar beet cannot be expected. Losses of SOC stock (0–30 cm) were found for all crop rotations and were even lowest (loss of 2.1 Mg ha^{-1} in 2008–2020, averaged to 0.18 Mg ha^{-1}year^{-1}) for the one with sugar beet, although differences to the other crop rotation and the wheat monoculture were far from being significant. The overall loss of SOC on the study site indicated that SOC at this site is not in a steady state. This might be attributable to management changes before the start of the experiment, in this case most likely the cessation of manure application in the 1970s. Further, climate change might play a certain role in such SOC losses: Poeplau and Dechow (2023) estimated the average climate-change-driven SOC loss for the temperate zone (Cfb) to be about 0.08 Mg C ha^{-1}year^{-1} during the past 50 years. Moreover, the timepoint of sampling may have played a role: while the samples in 2008 and 2010 were taken in spring, the 2020 sampling took place in late summer. As Wuest (2014) showed, there is a considerable temporal variation of SOC within one field, partially of a seasonal nature. Also, because of methodical differences between the sampling dates regarding the sampling process below 30 cm (see section 2), values for 2020 might generally be lower than for 2008, not reflecting the actual development. Nonetheless, even if all these factors had an effect in our study, the bias would be the same for all treatments and would not affect the central finding of the lack of a sugar beet effect in the long-term trial.

In general, effects of sugar beet cultivation reducing SOC could include: (i) very low root residue biomass and therefore low C input to the soil (see below), (ii) nitrogen-rich leaves as harvest residues, which can be assumed to mineralize very quickly, plus aeration of soil during harvest supporting mineralization, (iii) SOC removal from the field by harvest erosion as soil sticks to beets and is delivered to the factory, (iv) SOC losses by soil erosion during bare fallow in winter before sugar beet cultivation and the first weeks after sowing when the soil is uncovered. Despite the possibly high importance of these factors in determining the impact of sugar beet cultivation on SOC and thus the need for quantification, data availability on all of these aspects is scarce.

For C input to the soil from harvest residues, we offer values within this study and discuss them below in a separate chapter. Pre-winter mineralization of sugar beet aboveground harvest residues might arise from nitrogen-rich leaves and the uppermost bit (crown) of the beet, which is rich in labile carbohydrates (Hoffmann, 2011). Leaves and crown residues are generally left in the field during harvest, and currently, there is no technical opportunity to remove them. Field trial data from the studied long-term trial indicated a very high nitrogen content (about 1.8% N of the dry matter) and a narrow C:N ratio (about 22) of these aboveground residues (not shown). Thus, they might mineralize shortly after harvest without contributing to the long-term SOC stock. Essich et al. (2020) measured CO_2 and nitrous oxide emissions during winter after sugar beet harvest and showed a strong positive impact of leaves on gaseous emissions, and thus mineralization of organic material. Overall, however, information on pre-winter mineralization and possible effects on mineralization or further stabilization of older soil organic material for the sake of balancing input and losses of organic material by sugar beet leaves is more than scarce and needs experimental clarification.

Concerning soil losses via sugar beet harvest, Saggau et al. (2024) published data of a field study in Lower Saxony, Germany. Multiplied by the SOC content of the sites they sampled, a SOC loss of 0.003–0.464 Mg ha^{-1} per sugar beet harvest was attributed. The most important driving factor for soil eroded via harvest was the soil water content (Saggau et al., 2024). Thus, this source of SOC depletion is to be minimized by harvesting under dry soil conditions. In addition, storing harvested beets at the field margin and cleaning during the loading on trucks is known to further significantly reduce harvest soil loss, especially if the clamps had been covered (Koch, 1996). Occurrence and quantity of erosion events induced by wind and water are not documented so far in Germany, and no realistic estimation on respective SOC losses can be drawn.

4.2 | Residue carbon inputs by different crops

The evaluation of C input to soil out of the dataset of the first BZE-LW clearly indicated that sugar beet cultivation resulted in a lower C input (2.0 Mg ha^{-1} per cultivation period when ignoring the averaged C input by organic fertilizers) than winter wheat (3.2 Mg ha^{-1}), representing the most frequently grown crop in Germany (Table 1). The crop rotation trial evaluation resulted in estimated yearly C inputs of 2.7 Mg ha^{-1} for sugar beet and 5.8 Mg ha^{-1} for winter wheat. This general difference between BZE-LW and crop rotation trials might be owing to the ideal conditions created in an experimental field, with small plots and sufficiently available labour, resulting in higher yields and amounts of crop residues in the trial than on average in practical fields, or owing to uncertainties in the allocation factors (Jacobs et al., 2020), representing rather average growing conditions not necessarily found in every field. Regarding winter wheat, the difference was even more striking than for sugar beet, which might be owing to the mentioned reasons but also because of a certain share of fields in the BZW-LW dataset on which straw was removed from the field (32%), considerably lowering the average C input from wheat.

The difference between both crops can mainly be attributed to the very low amount of C bound within belowground organic residues of sugar beet (0.4 and 0.5 Mg ha^{-1} estimated from BZE-LW and from the crop rotation trial data, respectively, both including C input from rhizodeposition). For belowground residues from sugar beet, the standard value used was a share of 3.3% of total sugar beet biomass C (Jacobs et al., 2020). It might be questioned if this value was realistic since there are very few studies on root development and belowground biomass of sugar beet (Bolinder et al., 2015; Grunwald & Koch, 2024), although root-derived C input is regarded as one major source for SOC (Yang et al., 2023). Moreover, root plasticity may obscure the relation between yield and root biomass for all crops in general (e.g., Arnhold et al., 2023; Grunwald & Koch, 2024).

Literature offers very few values of single-field experiments regarding belowground C input by sugar beet for comparison. Schnittmann (2017) stated a rough mean of 2% of the beet fresh matter to be lost during harvest in the soil owing to beet breakage with a dependence on soil water content at harvest. Further, Grunwald and Koch (2024) measured a mean of about 200 kg dry matter ha^{-1} (0–60 cm) of fibrous roots in two field experiments in Lower Saxony. Assuming broad means of 80 Mg ha^{-1} fresh matter beet yield, 23% dry matter content of the beet, and 45% C content of the beet dry matter, these two studies sum up to about 0.25 Mg C input per hectare and sugar beet harvest (0.16 Mg ha^{-1} by broken beets plus 0.09 Mg ha^{-1} from fibrous roots). Adding a standard value of 31% of the belowground biomass C input as rhizodeposition taken from Pausch and Kuzyakov (2018) results in a sum of 0.33 Mg C ha^{-1} as annual belowground C input from sugar beet cultivation. Therefore, we conclude that the results we gained by the standard values from Jacobs et al. (2020) appear realistic. However, regarding reliability and usability in a broader context, especially under different growing conditions, the values would strongly benefit from verification by more field data, particularly concerning a possible overestimation.

Concerning the C input from aboveground residues, BZE-LW dataset results (1.7 Mg ha^{-1}) were retrieved by a C allocation factor as a fixed share of 2.2% from the beet yield C. However, to the best of our knowledge gained from sugar beet field experiments all over Germany, leaf biomass at harvest may be just weakly positively related to the beet yield (see also Hoffmann & Kenter, 2018). Results shown here for the long-term field trial (2.3 Mg ha^{-1}), based on measured values, point to a similar value, though. From these two datasets, we concluded that an aboveground C input after sugar beet harvest of around 2 Mg ha^{-1} might be realistic. However, the difference in belowground C inputs between different crops is considered of much higher importance than the aboveground residues since roots are generally more effective in SOC build-up per unit biomass (Poeplau et al., 2021). While the difference between sugar beet and other crops in this regard is very clear from our data and is likely the most striking issue in terms of SOC dynamics in sugar beet fields, the uncertainty of these numbers is clearly higher than for aboveground residues and needs to be addressed in future research.

Comparing winter cereals (about 10 months in the field) and sugar beet (about 6 months in the field) ignores the fact that sugar beet, as a spring crop, offers the opportunity of cultivating a cover crop during the foregoing winter months. Within the crop rotation trial of this study, mustard as a cover crop came along with a C input of 1.8 Mg ha^{-1}. Overall, the effect of cover crops on soil organic matter by C input should be included in assessments such as GHG emissions accounting. As a mean value, Poeplau and Don (2015) proposed a yearly SOC increase of 0.32 Mg ha^{-1} year^{-1} within the first 50 years of cover crop cultivation. To avoid uneven biased comparisons, an evaluation of the entire crop rotation is an effective means (Jacobs, Koch, & Märländer, 2018). For the long-term crop rotation trial, we summed the C input for the duration between both dates of SOC measurement and reached 63.1 Mg ha^{-1} C input over 12 years by the mustard—sugar beet—winter wheat—winter wheat rotation. In comparison, the 'rotation' of the largest C input, the winter wheat monoculture, reached 71.2 Mg ha^{-1}, while the one of the lowest C input, the silage maize monoculture, cumulated to 26.2 Mg ha^{-1} (10 years of study only). The strong differences between the silage maize monoculture and the other treatments were, although only partially significant, reflected in the topsoil SOC stock measured in 2020, while all crop rotations with wheat showed similar SOC stocks. Thus, when we consider sugar beet a 'low C input crop', cultivating sugar beet preceded by a cover crop of a high biomass and in rotation with a cereal seems reasonable in terms of SOC maintenance. Choosing a cover crop of even higher C inputs than mustard could even amplify this effect since the range of cover crops strongly differs in C input provision (Grunwald et al., 2023). Finally, soils under long-term sugar beet rotations may thus even become C sinks when winter fallows are consistently replaced by a cover crop.

5 | CONCLUSIONS

Based on the datasets evaluated within this study, a general and recent loss of SOC attributed to the cultivation of sugar beet, in particular when preceded by a cover crop, is not supported. Long-term cultivation of sugar beet appeared to have lowered SOC stocks of German agricultural soils to some extent, with low root-derived C inputs as a likely major source of such negative effects. However, in recent years, sugar beet is most often cultivated in combination with a cover crop, which may compensate for low C inputs by sugar beet and potentially even lead to SOC accumulation (relative to a baseline) at long-term sugar beet cultivation sites owing to an increase in C input. It is therefore not recommended to assign fixed values of SOC loss to sugar beet cultivation in GHG calculation tools as well as for corporate sustainability reporting. This holds true for any other crop. An important way forward is to use process-based SOC models taking the current state of a given site's SOC stock as well as pedoclimatic conditions into account. To feed such models, more accurate data on above- and belowground C inputs are needed. Fixed, yield-derived estimates of above- and belowground biomass residues appear particularly problematic in the case of sugar beet and should be refined in future studies.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

ORCID

Dennis Grunwald https://orcid.org/0000-0002-2621-2971
Christopher Poeplau https://orcid.org/0000-0003-3108-8810
Anna Jacobs https://orcid.org/0009-0006-6744-0694

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