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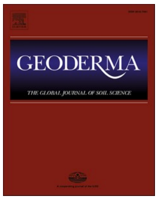

Carbon sequestration potential in hedgerow soils: Results from 23 sites in Germany

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ABSTRACT

Carbon dioxide removal strategies are becoming increasingly important as a fundamental component of comprehensive climate policies. One strategy to increase carbon (C) sinks is the integration of hedgerows into agricultural landscapes. Besides additional C storage in above-ground and below-ground hedgerow biomass, the establishment of hedgerows has the potential to increase soil organic carbon (SOC) stocks. However, empirical data regarding the magnitude of SOC accrual with hedgerow establishment are still limited. We sampled 23 sites across Germany in a paired-plot approach with the aim of estimating SOC stock change with hedgerow establishment on cropland. At 21 sites, SOC stocks were higher beneath hedgerows than in the reference cropland. On average, SOC stock accrual was 29 ± 22 Mg ha^{-1} (36 ± 49 %) in 0–100 cm soil depth. SOC stocks were significantly different in both topsoil and subsoil. Subsoils below 30 cm depth contributed 41 % (12 ± 17 Mg C ha^{-1}) of the total SOC stock change, stressing the importance of subsoil SOC for the total SOC stocks of hedgerow systems. The positive effect of hedgerows on SOC stocks extended laterally beyond the hedgerow area itself. SOC stock in the grassy hedgerow edge also increased significantly by 22 ± 22 Mg C ha^{-1} (28 ± 30 %) and SOC stock in the cropland directly adjacent to the hedgerow were 9 ± 19 Mg C ha^{-1} (12 ± 25 %) higher than in the reference cropland. Particularly high C stock differences between hedgerows and reference cropland soils were found in old hedgerows (>200 years) planted on hedgebanks, which are typically found in northern Germany. Our study confirmed that SOC stocks increase with hedgerow establishment on cropland throughout the whole soil profile. If hedgerows were to be established on 3 % of Germany's cropland area, SOC stocks would increase by 13 Tg C equivalent 48 Mio. t CO_2, highlighting that hedgerows are a promising and multi-functional climate change mitigation option.

1. Introduction

To meet climate change mitigation targets, in addition to rapid emission reductions, negative emission technologies, i.e. the capture and removal of greenhouse gases from the atmosphere, are required (IPCC, 2023). Biological negative emission technologies, also called nature-based solutions, are intended to achieve atmospheric carbon dioxide (CO_2) removal by deliberately enhancing land or ocean carbon (C) sinks. There has been an increasing focus in recent years on the creation of such C sinks to mitigate climate change because climate change is increasingly difficult to combat. Nature-based solutions include measures such as reforestation, improved forest management, C sequestration in soils, peatland restoration and coastal blue C management (IPCC, 2023). A measure to enhance C sinks and achieve additional environmental benefits that is increasingly being discussed is the establishment of hedgerows. The UK Climate Change Committee lists their establishment as a key measure in the land-use sector to achieve net zero and has set a goal to expand hedgerows in the UK by 20 % by 2035 and by 40 % by 2050 (Committee on Climate Change, 2020). This would require the planting of 193,000 km of hedgerows in the UK by 2050 (Biffi et al., 2022). Other countries, such as Germany and Ireland, have also mentioned hedgerows as a measure to achieve net zero in the land-use sector (BMUV, 2023; Government of Ireland, 2022). Accordingly, in many European countries, various incentive programmes for the establishment of hedgerows in the context of climate change mitigation are emerging, initiated both by private sector actors within C farming schemes and on the initiative of local governments (e.g. Ministerium für Klimaschutz, 2023; SPW Wallonie, 2023).

Hedgerows are a traditional agroforestry system that are widely distributed within agricultural systems in the temperate climate zone.

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Hedgerows are defined as managed, linear structures composed of perennial shrubs or shrubs and trees adjacent to agricultural fields (Drexler et al., 2021). They vary greatly regarding their species composition, management practices and intensities, and dimensions such as width and height. Often dating back centuries, they were originally established to mark out fields, fence in livestock, and provide a source of food, fuel and timber (Baudry et al., 2000; Burel, 1996). The integration of hedgerows into agricultural landscapes offers multiple benefits. Hedgerows are pivotal for biodiversity in agricultural landscapes by providing and connecting habitats and offer an effective way of reducing soil erosion at the slope scale (Clark et al., 2022; Montgomery et al., 2020). In addition, hedgerows can contribute to climate change adaptation by improving flood control, preventing soil erosion and altering microclimates (Böhm et al., 2014; Cleugh et al., 2002; Sánchez et al., 2010; Wallace et al., 2021). Creating synergies between climate change mitigation and other socio-environmental targets, such as biodiversity loss, is an important prerequisite for high-quality nature-based solutions (Waring et al., 2023) and therefore hedgerows have recently been rediscovered as a long-known example of a nature-based solution that serves such multiple targets (Collier, 2021).

The establishment of hedgerows in agricultural landscapes can help mitigate climate change since hedgerows store more C than grassland and cropland. Around 80 % of additional C is stored in the perennial hedgerow biomass (Biffi et al., 2023; Drexler et al., 2021). However, it has also been shown that SOC stocks are increased due to more above-ground and below-ground C input through litter and rhizodeposition, as well as favourable microclimatic conditions and less soil disturbance (Cardinael et al., 2018; Drexler et al., 2021; Mayer et al., 2022). The expected difference in SOC stocks, and therefore also the climate change mitigation potential, is larger with hedgerow establishment on cropland. Lesaint et al. (2023) studied 25 hedgerow sites in France and found that SOC was 15 % higher on average in systems with hedgerows compared with cropland, grassland and their mixture without hedgerows. The greatest differences in SOC stocks were found for the cropland reference. However, the samples were not taken from directly beneath the hedgerows but adjacent to the hedgerow, and may not reflect the hedgerows' full effect. Although the findings of Biffi et al. (2022) indicate that there is also a high C sequestration potential with hedgerow establishment on grassland not only in the biomass, but in the soil as well, we thus focused on a comparison between hedgerow and cropland soils in this study. Furthermore, besides the larger SOC stock difference, the greatest synergies with the establishment of hedgerows, e.g. in relation to biodiversity and erosion control, are also expected with hedgerow establishment in cropland regions that currently also have the lowest hedgerow densities (Golicz et al., 2021; Kay et al., 2019). The difference in SOC stocks between hedgerows and cropland has been examined in a recent study by Wenzel et al. (2023). They sampled 54 hedgerow sites in Austria and found significant differences in SOC stocks between hedgerows and adjacent cultivated soils only in topsoils (0–20 cm), but not in subsoils (20–40 cm). This is in contrast to other studies that have found differing SOC stocks throughout the soil profile to 90 and 100 cm depth (Chiartas et al., 2022; Viaud and Kunnemann, 2021). However, the control land-use types sampled by Chiartas et al. (2022) were mostly furrow-irrigated tomato/wheat/sunflower rotations, which may not be comparable with central European cropland. The study by Viaud and Kunnemann (2021) involved a mixture of cropland (maize, wheat, rapeseed, oat) and grassland. This mixture of land-use as reference may affect the magnitude of the hedgerow effect, which is expected to be larger with establishment on cropland (Drexler et al., 2021). Thus, although recent empirical studies have provided valuable data on the C sequestration potential with hedgerow establishment, there are still limited empirical data on hedgerow SOC stocks, particularly with regard to the whole profile depth, over a large range of croplands differing in land management, and including SOC stocks measured directly beneath the hedgerows. Missing data, insufficient sampling depth and differing land use or land management could lead to considerable underestimates or overestimates of the climate change mitigation benefits of hedgerows.

To assess the C sequestration potential of hedgerow establishment on temperate cropland, we conducted a field sampling campaign at 23 sites in Germany with a variety of hedgerows and site conditions. Our aim was to get representative estimates of the C sequestration potential in hedgerow soils for Germany as an exemplary region for hedgerows in the temperate climate zone. We hypothesised that: (1) total SOC stocks beneath hedgerows are higher than cropland SOC stocks, (2) hedgerow SOC stocks increase throughout the soil profile, (3) SOC stocks are not only increased directly beneath the hedgerow, but also along a transect from hedgerow to cropland, and (4) the variability in SOC stock change can be related to environmental parameters, such as soil texture and climate, as well as hedgerow characteristics, such as age, dimensions and vegetation. Based on the results, a further aim was to estimate the C sequestration potential in hedgerow soils on the scale of Germany in order to quantify the climate change mitigation potential of the establishment of new hedgerows.

2. Material and methods

2.1. Study sites

To investigate the effects of hedgerow establishment on cropland, we sampled 23 sites across Germany in a paired-plot approach (Fig. 1). SOC stocks beneath hedgerows were compared with the SOC stocks of reference cropland plots at a distance of 30 m from the hedgerow, which was considered as a baseline. Increases in SOC stocks are always reported relative to the reference plot and are given per hectare of hedgerow. The sites had to meet the following criteria: (1) hedgerow definition: only traditional hedgerows consisting of shrubs or a combination of shrubs and trees were sampled; tree rows and modern agroforestry systems were excluded; (2) relief: the terrain at the sites had to be relatively flat to avoid the effects of water erosion that may influence SOC stocks, excluding both embankments and other hilly topography, and there should be no ditches near the hedgerow as periodic water logging can affect SOC stocks; (3) reference: a possible reference cropland plot had to be directly adjacent to the hedgerow and comparable with the hedgerow plot in terms of soil type and soil texture as important predictors of SOC stocks; this was ensured by scanning the site conditions using a hand auger to 1 m soil depth prior to sampling; (4) hedgerow age: the hedgerow had to have been established at least 15 years prior to sampling, as afforestation studies have shown that it may take years until changes in SOC can be detected (Poeplau et al., 2011). Hedgerow age and the land-use history of the reference cropland were reported by the hedgerow owners. Additionally, old maps dating back to the beginning of the 20th century and aerial images were analysed to determine the year of hedgerow establishment and to exclude sites with land-use changes on the reference cropland in recent decades.

Meeting these criteria, the sites were selected to represent a diversity of hedgerow characteristics and pedoclimatic conditions within Germany covering different (1) hedgerow ages, (2) hedgerow heights and widths, (3) climates and (4) soil textures. Hedgerow age ranged from 15 to over 200 years, with 10 hedgerows aged between 15 and 30 years old, nine hedgerows over 30 years old, and three hedgerows more than 200 years old. The hedgerow at site ND was established at least 20 years prior to sampling, but it was not possible to obtain the exact hedgerow

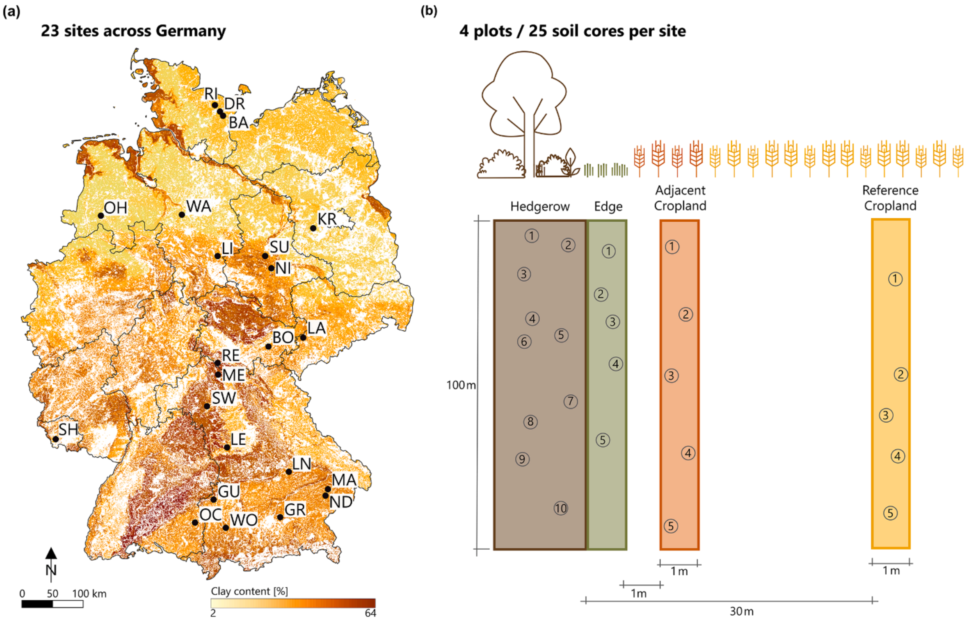

Fig. 1. (a) Location of the 23 sampled sites across Germany, background map representing the topsoil clay content for agricultural areas adapted from Gebauer et al. (2022), and (b) sampling scheme: each site was sampled using a paired-plot approach consisting of a hedgerow plot and a reference cropland plot 30 m from the hedgerow. Additionally, the hedgerow edge and an adjacent cropland plot 1 m away from the hedgerow edge were sampled. Soil organic carbon stocks were determined on randomly selected subplots within each plot by soil coring.

age. To cover different hedgerow types, we selected hedgerows differing in width and height. Hedgerow height was 9 m on average across all sites, ranging from 4 to 15 m. Hedgerow width was 7 m on average, ranging from 2 to 17 m. Hedgerow width was measured in the field and was defined as the midpoint between maximum crown width and minimum stem width. The lower and narrower hedgerows consisted only of shrubs, while the taller and wider hedgerows had a high proportion of trees. Most hedgerows were diverse in species composition (Table S.1). The species found most often throughout the hedgerows were blackthorn (*Prunus spinosa;* present in 16 out of 23 hedgerows) and hazel (*Corylus avellana*; present in 10 out of 23 hedgerows). Besides species composition, vegetation density [%] was assessed by visually estimating the number of trees and shrubs, as well as their coverage per unit of ground area. To characterise the site, a soil pit to 100 cm soil depth was dug close to the hedgerow at each site, and the soil profile was described including soil type and soil texture. Average topsoil clay content ranged from 2.5 % to 37.5 %. Mean annual precipitation (MAP) and mean annual temperature (MAT) were extracted from 1*1 km grid data available from Germany's National Meteorological Service (DWD), as a multi-annual mean for the period 1991–2020 (DWD Climate Data Center, 2021a, 2021b). MAP ranged from 515 to 984 mm yr^{-1} and MAT ranged from 8.5 to 10.7 °C (Table 1). Information on cropland

Table 1
Site and hedgerow characteristics of the study sites. MAT: mean annual temperature, MAP: mean annual precipitation, WRB: World Reference Base for Soil Resources.

Site	Latitude	Longitude	Site characteristics					Hedgerow characteristics			
			MAT [°C]	MAP [mm]	WRB soil group	Average clay content [%]	Average sand content [%]	Hedgerow orientation	Maximum height [m]	Average width [m]	Age [years]
BA	54.074	10.609	9.1	760	Anthrosol	21	34	N-S	15	4	>200
BO	50.681	11.613	8.9	630	Cambisol	21	34	N-S	6	2	55
DR	54.143	10.536	9.1	770	Anthrosol	21	34	W-E	15	3	>200
GR	48.173	11.790	9.2	960	Leptosol	14.5	11.5	N-S	11	9	27
GU	48.445	10.329	8.9	820	Luvisol	14.5	11.5	N-S	13	6	25
KR	52.398	12.749	9.9	560	Cambisol	2.5	80	N-S	7	11	28
LN	50.797	12.421	9.3	720	Cambisol	2.5	80	N-S	8	5	25
LA	48.839	12.006	9.3	640	Cambisol	23.5	19	N-S	12	13	25
LE	49.211	10.635	8.7	670	Planosol	10	65	W-E	6	6	50
LI	52.020	10.451	9.8	660	Luvisol	14.5	11.5	N-S	5	7	39
MA	48.561	12.859	9.3	790	Planosol	23.5	19	N-S	7	6	20
ME	50.279	10.446	8.9	590	Vertisol	37.5	10	N-S	5	6	15
ND	48.470	12.802	9.2	830	Planosol	23.5	19	N-S	13	7	/
NI	51.829	11.723	10.1	520	Chernozem	10	13.5	N-S	4	1	80
OC	48.108	9.922	8.5	940	Planosol	14.5	11.5	N-S	13	10	26
OH	52.588	7.644	10.1	780	Podzol	2.5	92.5	N-S	14	4	42
RE	50.451	10.436	8.8	660	Luvisol	21	9	N-S	6	8	16
RI	54.232	10.410	9.2	750	Anthrosol	21	34	W-E	4	3	>200
SH	49.288	6.7915	10.7	750	Cambisol	10	65	N-S	10	17	60
SW	49.816	10.189	9.9	590	Anthrosol	21	9	N-S	15	8	31
SU	52.013	11.582	10	520	Chernozem	14.5	11.5	N-S	4	11	40
WA	52.625	9.5951	10.1	690	Fluvisol	21	34	N-S	5	2	55
WO	48.031	10.594	8.6	980	Leptosol	21	34	W-E	6	7	25

management, including organic fertilisation and crop rotation, was assessed via a farmer questionnaire for each reference cropland plot (Table S.2).

2.2. Soil sampling

The sites were sampled in either 2020 or 2021. At each site, the reference cropland plot was established 30 m from the hedgerow (Fig. 1b) to ensure the comparability of soil properties while avoiding the influence of the hedgerow on the reference cropland plot. The reference cropland plot was established on one random side of the hedgerow. In order to capture the full potential C sequestration effect of hedgerow establishment in the soil, we investigated soils not only directly beneath the hedgerow, but also along a transect from the hedgerow to the cropland. Therefore, the hedgerow edge (“edge” plot), which consists mostly of grassy vegetation in the transition area from the hedgerow to the cropland, and a plot 1 m away from the hedgerow edge (“adjacent cropland” plot) were sampled (Fig. 1b). All plots covered a length of 100 m. The hedgerow and hedgerow edge plots each covered the entire hedgerow/hedgerow edge width. The adjacent and reference cropland plots had a width of 1 m (Fig. 1b). Within each plot, subplots were randomly selected for soil sampling. Five subplots were selected within each hedgerow edge, adjacent cropland and reference cropland plot (Fig. 1b). Within each hedgerow plot, 10 subplots were selected, as the expected variability within hedgerow plots was assumed to be higher compared with the hedgerow edge and cropland plots due to differing vegetation densities and types. Soil cores with a diameter of 6 cm were taken to a soil depth of 100 cm using a machine-driven soil auger in each subplot after aboveground vegetation and litter had been removed. The soil cores were cut into six depth increments: 0–5 cm, 5–10 cm, 10–30 cm, 30–50 cm, 50–70 cm and 70–100 cm. At two sites with shallow soils (GR, WO), the soil was sampled down to bedrock at a depth of 50 cm. If compaction or stretching of the soil core occurred, the difference between the core length and borehole depth was allocated to the entire core and the depth increments were corrected in situ accordingly (Walter et al., 2016).

2.3. Sample preparation and soil organic carbon analysis

All soil samples were stored at 4 °C until further analysis, subsequently dried at 60 °C until constant mass was reached, and then weighed. Visible living roots and rocks were removed and the soil sieved to ≤ 2 mm. Rock and root weights were recorded to determine fine soil mass. An aliquot of fine soil was milled for subsequent analysis. Total C and total nitrogen (N) content were determined by dry combustion on the milled aliquot using an elemental analyser (LECO TruMac CN). Soil samples with a C/N ratio > 13 or inverse depth gradients (increasing C content or C/N ratio with depth within a soil core) were assumed to contain carbonates. For these samples, aliquots were combusted for 16 h in a muffle furnace at 400 °C. The remaining C fraction was defined as total inorganic C and was subsequently measured again with the elemental analyser. SOC content was then calculated by subtracting the total inorganic C content from the total C content of these samples. For the other samples, total C content was assumed to equal total organic C content. Plausibility checks were performed for all the values obtained (SOC and N content, dry weight, rock fragment content). In total 3,456 soil samples were obtained and analysed. In exceptional cases of presumed measurement errors (n = 61), the mean value of the remaining soil cores in the respective subplot and depth increment of the site was used to replace this value.

2.4. Calculations and statistics

Data analysis and visualisation were performed in R v4.3.0 (R Core Team, 2023), including the use of the packages *lme4* (Bates et al., 2015), *lmerTest* (Kuznetsova et al., 2017) and *emmeans* (Lenth, 2023). SOC stock in each depth increment i ($SOCstock_i$[Mg ha^{-1}]) was calculated in accordance with Poeplau et al. (2017) via fine soil stock FSS_i[Mg ha^{-1}]:

$$FSS_i = \frac{\left(M_{sample_i} - M_{rock\,fragments_i} - M_{plant\,fragments_i}\right)}{Area_{core}} * 100 \tag{1}$$

$$SOCstock_i = FSS_i * \frac{SOCcontent_i}{1000} \tag{2}$$

where M_{sample_i} is the total dry mass of the sample [g], $M_{rockfragments_i}$ and $M_{plantfragments_i}$ are the masses of rock and plant fragments >2 mm [g] respectively, $SOCcontent_i$ is the SOC content of the fine soil [g kg^{-1}], all for the respective depth increment i, and $Area_{core}$ is the surface area of the soil core [cm^2].

To account for differences in bulk density between the subplots, it is necessary to correct SOC stocks for equivalent soil masses (ESM, e.g. Ellert and Bettany, 1995). Therefore, the mineral fine soil mass ($MFSS_i$[Mg ha^{-1}]) for each depth increment i was first calculated according to Eq. (3). MFSS excludes soil organic matter, derived from SOC via the van Bemmelens factor of 1.742 (Rovira et al., 2015).

$$MFSS_i = FSS_i * \left(1 - 1.724 * \frac{SOCcontent_i}{1000}\right) \tag{3}$$

where FSS_i is the fine soil stock [Mg ha^{-1}] calculated according to Eq. (2), and $SOCcontent_i$ is the SOC content of the fine soil [g kg^{-1}], both for the respective depth increment i. The reference MFSS ($MFSS_{reference_i}$ [Mg ha^{-1}]) for each site was calculated as the mean MFSS of all cores of the reference cropland plot at the respective site, with which all other plots at the respective sites were compared.

Corrected SOC stocks ($SOCstock_{corr}$ [Mg ha^{-1}]) were calculated for the ESM depths 0–30 cm and 0–100 cm, referred to below as “soil depth”. Additionally, we calculated SOC stocks for the ESM depth 0–50 cm, which is a sampling depth often used (e.g. Biffi et al., 2022). The SOC stock of each soil core was therefore adjusted to the reference MFSS ($MFSS_{reference}$) on the basis of a linear relationship between MFSS and SOC stocks in accordance with Wendt and Hauser (2013) using Eq. (4):

$$SOCstock_{corr} = \sum_{0}^{j} SOCstock_i - \left(\frac{SOCcontent_{j\ or\ j+1}}{1000} * \left(\sum_{0}^{j} MFSS_i - \sum_{0}^{j} MFSS_{reference_i}\right)\right) \tag{4}$$

where j refers to the deepest increment of the respective ESM depth. For the ESM depths of 0–30 cm and 0–50 cm, a depth increment below the respective ESM was sampled. Therefore, in the case of extrapolation ($MFSS_{reference} > MFSS$), we thus did not use the SOC content of the deepest depth increment ($SOCcontent_j$); instead the actually measured SOC content of the depth increment directly below the respective ESM depth ($SOCcontent_{j+1}$) was used. The SOC stock for the ESM depth of 30–100 cm was calculated as the difference between the ESM corrected SOC stock 0–100 cm and 0–30 cm.

Estimates of C stocks and C stock change with hedgerow establishment were all given on an area basis (Mg C per full ha of hedgerow). Differences in SOC stock ($\Delta SOCstock$) and SOC content ($\Delta SOCcontent$)

between plots were assessed by calculating the absolute difference (in Mg ha^{-1}) and the relative difference (according to Eq. (5):

$$\Delta SOCstock/content_i[\%] = \frac{SOC_{hedgerow/edge/adjacent\_cropland_i} - SOC_{reference\_cropland_i}}{SOC_{reference\_cropland_i}} \times 100 \tag{5}$$

where $SOC_{hedgerow/edge/adjacent\_cropland_i}$ is the SOC stock or content of the hedgerow, the hedgerow edge or adjacent cropland plot, and $SOC_{reference\_cropland_i}$ is the SOC stock or content of the reference cropland plot, for the respective depth increment i or, in the case of SOC stock, for the respective ESM depth.

Average annual total organic C input ($C_{input_{average}}$ [Mg ha^{-1} yr^{-1}]) of the reference cropland was calculated as a possible explanatory variable for the SOC stock differences between cropland and hedgerow plots according to Eq. (6):

$$C_{input_{average}} = \frac{\sum_1^t C_{input_{above}} + C_{input_{below}} + C_{input_{covercrops}} + C_{input_{organic}}}{t} \tag{6}$$

where $C_{input_{above}}$ [Mg ha^{-1} yr^{-1}] is the above-ground and $C_{input_{below}}$[Mg ha^{-1} yr^{-1}] the below-ground organic C input, $C_{input_{covercrops}}$[Mg ha^{-1} yr^{-1}] is the organic C input via cover crops, $C_{input_{organic}}$ [Mg ha^{-1} yr^{-1}] is the organic C input via organic fertiliser, and t are the reported years. The different C inputs were calculated according to Jacobs et al. (2020) based on crop-specific allocation factors of organic C (Eq. S.1–S.3). $C_{input_{average}}$ was calculated only for sites where information on crops, related yield, straw removal, organic fertilisation and cover crops was available on a yearly basis for the last 10 years via the farmer questionnaire ($n = 18$, Table S.2).

Results are presented as arithmetic means per plot of the independent sites. When presenting the results per site, arithmetic means of field replicates (i.e. subplots) are reported. All errors given in the text along with mean values are standard deviations. To evaluate whether SOC stocks and topsoil C/N ratios differed significantly between plots (i.e. land use), random intercept models with restricted maximum likelihood estimation were fitted with the SOC stock or topsoil C/N ratio of the individual soil cores as dependent variable, plot as fixed effect, and site as random effect to account for the paired data. Plot was nested within site to account for within-plot variability. Separate models were fitted for the different soil depths (0–30 cm, 0–50 cm, 30–100 cm, 0–100 cm). Residual plots were used to check for the model assumptions of linearity, normality of the residuals, and homoscedasticity. SOC stocks were log-transformed to meet the model assumptions. Estimated marginal means with Tukey adjustment of SOC stocks at the different soil depths and for C/N ratios were then used for pairwise comparisons between treatments and to derive p-values. Significance for all analyses was assessed at a 95 % confidence level. To identify factors influencing the hedgerow effect on SOC stocks between sites, the same random intercept modelling approach as described above was used, including only observations of the hedgerow and reference cropland plots. Separate models were fitted for the different soil depths 0–30 cm and 0–100 cm. Possible explanatory variables (hedgerow age class, clay content, sand content, MAP, MAT, vegetation density, hedgerow height and hedgerow width) were included as additional fixed effects, allowing for interaction with plot. Correlations between predictor variables were examined to avoid multicollinearity. Due to missing information on exact hedgerow age, site ND was removed from this analysis. C input of the reference cropland was only available for 19 sites. Thus, a separate model was fitted to assess the influence of the C input of the reference cropland on the hedgerow's effect on SOC stocks. We simplified the models via a backward step-wise model selection based on Akaike's information criterion (AIC); therefore models were fitted with maximum likelihood estimation. The significance of the fixed effects was assessed from the t-statistics, and additionally F-tests were conducted, both using Satterthwaite approximation (Luke, 2017). The same approach was used to test whether the orientation of the cropland towards the hedgerow affects ΔSOC stocks between the adjacent cropland/hedgerow edge and the reference cropland. Orientation of the cropland towards the hedgerow was therefore classified into "north", "east" and "west", depending on the orientation of the reference cropland towards the hedgerow (Table S.2). Two separate models were fitted: for ΔSOC stock adjacent cropland-reference cropland hedgerow height and edge width, and for ΔSOC stock hedgerow edge-reference cropland edge type were added as additional fixed effects, allowing for interaction with plot. Hedgerow edge type was classified into two classes ("diffuse" and "grassy"), with "diffuse" defining edges with varying width and vegetation, and edge type "grassy" defining hedgerow edges that were clearly delineated from the hedgerow and cropland and had grass vegetation (Fig. S.1, Table S.2).

3. Results

3.1. SOC stock change with hedgerow establishment on cropland

SOC stocks were on average 36 ± 49 % higher beneath hedgerows than in the reference cropland in 0–100 cm soil depth (Fig. 2). This equals a mean average increase in SOC stock of 29 ± 22 Mg C ha^{-1}. For 21 out of 23 sites, the mean SOC stock in 0–100 cm soil depth was higher beneath the hedgerow compared with that of the reference cropland, for two sites a negative effect on SOC stocks was observed. Total SOC stocks in 0–100 cm soil depth in the hedgerow plots varied greatly, between 45 Mg C ha^{-1} at site KR and 220 Mg C ha^{-1} at site WA. Average hedgerow SOC stock across all sites was 115 ± 46 Mg C ha^{-1}. The average SOC stock of the reference cropland was 86 ± 30 Mg C ha^{-1}. The mean SOC stock between the hedgerow edge and the reference cropland was significantly different ($p < 0.001$), with a mean increase of 22 ± 22 Mg C ha^{-1} (28 ± 30 %). No significant difference was found between SOC stocks of the hedgerow edge and the hedgerow ($p = 0.81$) (Fig. 2). The SOC stock of the adjacent cropland was on average 9 ± 19 Mg C ha^{-1} (12 ± 25 %) higher than the SOC stock of the reference SOC stock. This mean difference was not significant ($p = 0.24$), but 16 out of 23 sites showed higher SOC stocks in the cropland adjacent to the hedgerow compared with the reference.

The quality of soil organic matter also changed with hedgerow establishment. Average topsoil (0–30 cm) C/N ratio was highest in the hedgerow at 10.5 ± 1.4 compared with 9.5 ± 1.7 in the reference cropland ($p < 0.001$). However, although a continuous increasing trend was observed for SOC stocks from the reference cropland towards the hedgerow, no significant differences were found in the topsoil C/N ratio between the reference cropland and the adjacent cropland (C/N 9.5 ± 1.6, $p = 1.00$) or between the reference cropland and the hedgerow edge (C/N 9.9 ± 1.5, $p = 0.28$) (Fig. S.2). Accordingly, hedgerow ΔSOC stock was positive and simultaneously a positive ΔC/N ratio was found for most sites, whereas for the hedgerow edge and adjacent cropland an increase in SOC stock was not always associated with an increase in the C/N ratio (Fig. 3).

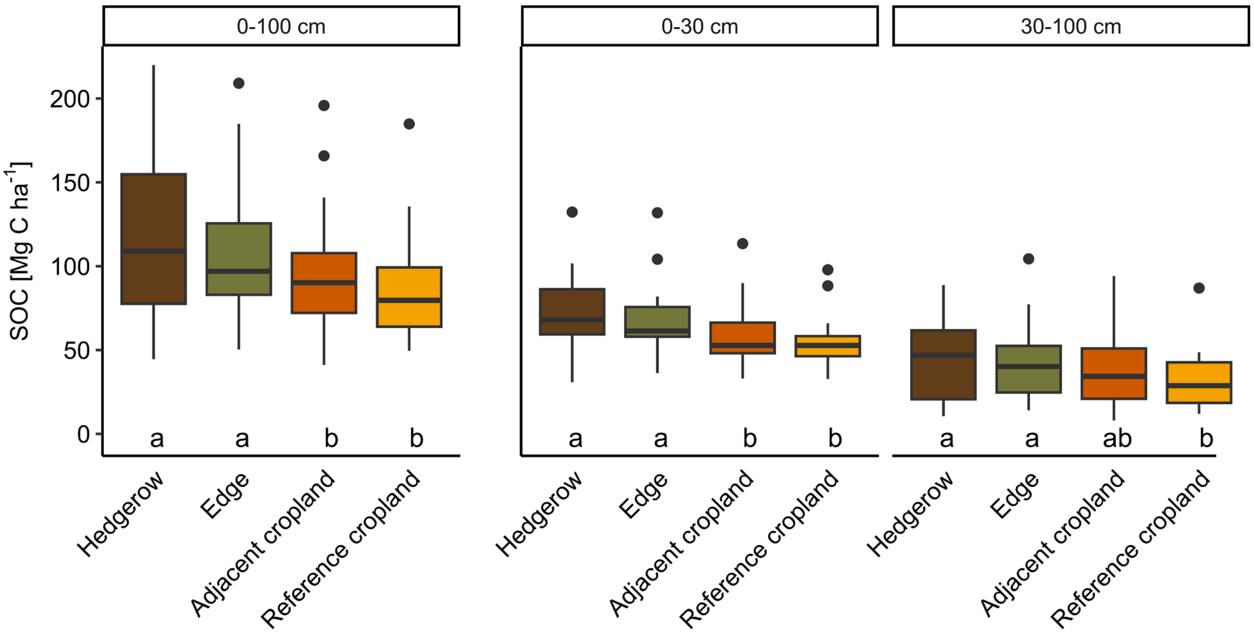

Fig. 2. SOC stocks for the different depth increments for the hedgerow, hedgerow edge, adjacent cropland and reference cropland plots (n = 23 sites). Different letters indicate significant differences between plots for the respective depth increment based on estimated marginal means ($p < 0.05$).

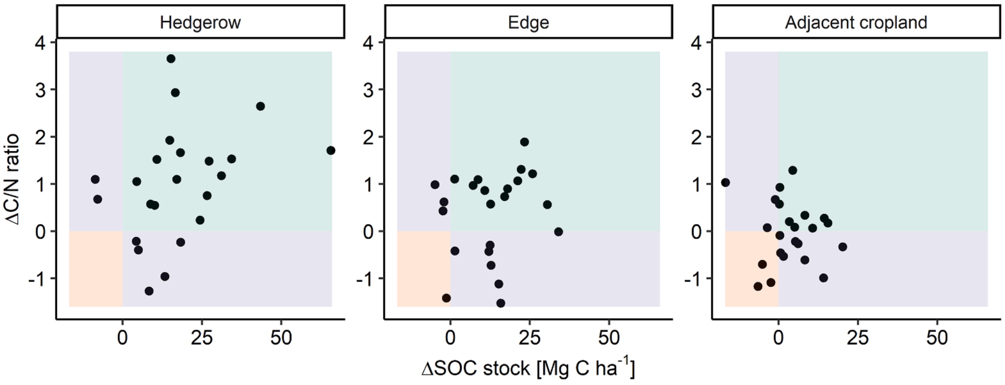

Fig. 3. Difference in soil organic carbon stock (Δ SOC) and C/N ratio between the treatment plots (hedgerow, hedgerow edge and adjacent cropland) and the reference cropland in 0–30 cm soil depth for individual sites. The green-shaded area (top right) indicates an increase in both SOC and C/N ratio, the red-shaded area (bottom left) indicates a decrease in both SOC and C/N ratio, and purple-shaded areas (top left, bottom right) indicate an increase or decrease in one of the two variables.

3.2. *Depth gradient of SOC change*

SOC stocks between the hedgerow and reference cropland were significantly different for all soil depths (Fig. 2). The average SOC stock difference between hedgerow and the reference cropland was 30 ± 43 % (17 ± 16 Mg C ha^{-1}, $p < 0.001$) in the topsoil (0–30 cm), and 39 ± 61 % (12 ± 17 Mg C ha^{-1}, $p < 0.01$) in the subsoil (30–100 cm), with a high variability between sites (Fig. S.3). Thus, 41 % of total SOC stock change from hedgerow establishment occurred below 30 cm soil depth. In 0–50 cm soil depth the SOC stock difference between the hedgerow and the reference cropland was 36 ± 45 % (23 ± 22 Mg C ha^{-1}, $p < 0.001$) (Fig. S.4). SOC stocks between adjacent cropland and reference cropland plots were not significantly different for all soil depths (Fig. 2). The differences in SOC stocks between the hedgerow edge and the reference cropland were significantly different for all soil depths, but no significant differences were found regarding SOC stocks between the hedgerow and hedgerow edge for any depth (Fig. 2). Differences in SOC contents between the reference cropland and the treatment plots (hedgerow, hedgerow edge and adjacent cropland) generally decreased with increasing depth, except for the 30–50 cm depth increment, which had greater differences in SOC content than the 10–30 cm depth increment (Fig. 4).

3.3. *Temporal dynamics and other drivers for SOC change*

The influence of possible explanatory variables for the hedgerow effect on SOC stocks was assessed by random intercept models fitted for the soil depths 0–30 cm and 0–100 cm. Model estimates of the final model showed a significant interactive effect of hedgerow age class and plot (hedgerow/reference cropland) on SOC stocks in 0–100 cm soil depth (Table 2, Fig. S.6). This effect was driven by the three old hedgerows (>200 years; sites BA, RI and DR). Disregarding the three older sites, no significant effect of age class was found (data not shown). SOC stock in 0–100 cm soil depth of the hedgerows and reference croplands was significantly different for all age classes, with the youngest hedgerow being 15 years old (Fig. S.7). However, hedgerow age had no significant effect on topsoil SOC stocks (0–30 cm) (Table 2, Fig. 5).

Using the stock-change method, we calculated an average C

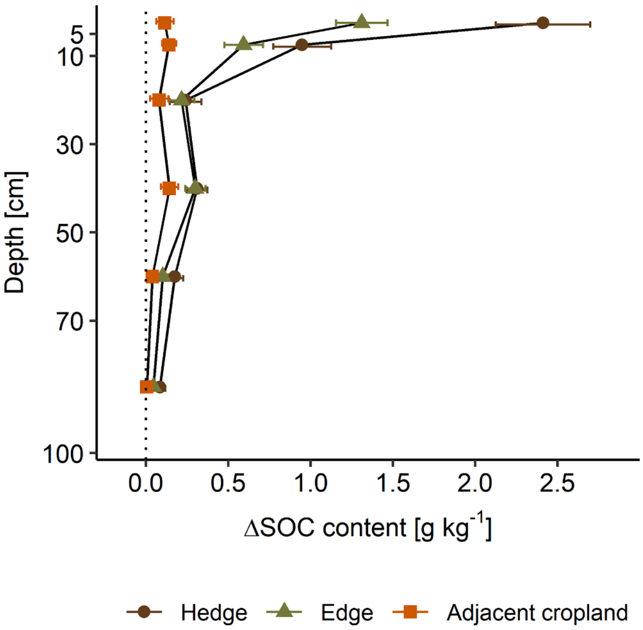

Fig. 4. Vertical distribution of differences in SOC content between hedgerow, hedgerow edge, adjacent cropland plot and reference cropland plot. The points indicate the mean across all sites (n = 23), error bars indicate the standard error of the mean.

sequestration rate of 0.65 ± 0.55 Mg ha^{-1} yr^{-1} in 0–100 cm soil depth and 0.42 ± 0.32 Mg ha^{-1} yr^{-1} in 0–30 cm soil depth, as the absolute difference between the hedgerow and reference plot per site divided by the number of years since the hedgerow was planted and assuming a linear sequestration. Only 19 of the 23 sites were included in the mean value; for one site (ND) the age of the hedgerow was unknown. For the three sites where the hedgerows were > 200 years old, it was assumed that a new SOC equilibrium had been reached at least several decades ago and that the C sequestration rate would thus be reduced over the full time period.

A significant interactive effect between plot and sand content was found for the 0–100 cm SOC stock model, with a lower SOC stock difference with a higher sand content (Table 2). Sand content also lowered the AIC for the 0–30 cm SOC stock model, but this effect was not significant at a 95 % confidence level. For the topsoil (0–30 cm) SOC stock model, significant interactive effects were also found between plot and width, height and vegetation density (Table 2). The SOC stock difference was lower with increased hedgerow width, and higher with increased hedgerow height and vegetation density (Fig. 5).

Differences in SOC stock between the hedgerow edge and the reference cropland were higher on average in grassy edges than with more diffuse edges, and with an orientation north or east of the hedgerow compared with west (Fig. S.8). However, these effects were not significant. Furthermore, cropland orientation did not significantly affect SOC stocks between the reference cropland and the adjacent cropland, although differences in SOC stock were slightly higher on average with the cropland being north or east of the hedgerow compared with west (Fig. S.9). No significant effect of edge width or hedgerow height on SOC stocks was found between the reference cropland and the adjacent cropland.

4. Discussion

4.1. Average SOC change estimates and variability between sites

This study identified an average relative SOC stock increase of 36 ± 49 % within 0–100 cm soil depth with hedgerow establishment on cropland. This SOC stock increase aligns well with the recent study for

Table 2

Results of the mixed-effect models of the effects of hedgerow age, clay content, sand content, MAP, MAT, hedgerow height, hedgerow width and vegetation density and their interaction with treatment (reference cropland/hedgerow plot) on SOC stocks in 0–100 cm soil depth and in 0–30 cm soil depth. Site was included as a random effect: SOC_stock ~ plot*age_class + plot*clay_content + plot*sand_content + plot*MAP + plot*MAT + plot*height + plot*width + plot*vegetation_density + (1 + site | plot). SOC stocks were log transformed for analysis Estimates, standard errors (SE), t-statistics and *p*-values are given for all variables included in the final model (based on AIC).

	Variable	Estimate	SE	t-statistics	*p*-value
SOC stock 0–100 cm	(Intercept)	4.592	0.170	23.987	<0.001 ***
	Hedgerow_plot	0.385	0.105	3.666	<0.01 **
	Age_class_>30	0.209	0.132	1.585	0.124
	Age_class_>200	−0.087	0.198	−0.440	0.663
	Sand_content	−0.003	0.002	−1.434	0.162
	Width	−0.026	0.017	−1.538	0.135
	Hedgerow_plot*Age_class_>30	−0.011	0.081	−0.136	0.893
	Hedgerow_plot*Age_class_>200	0.606	0.122	4.961	<0.001 ***
	Hedgerow_plot*Sand_content	−0.003	0.001	−2.300	0.031 *
	Hedgerow_plot*Width	−0.012	0.010	−1.173	0.253
$R^2_{marginal} = 0.476$, $R^2_{conditional} = 0.858$[1]					
SOC stock 0–30 cm	(Intercept)	4.845	0.355	13.649	<0.001 ***
	Hedgerow_plot	−0.241	0.233	−1.037	0.311
	Sand_content	−0.002	0.002	−1.095	0.283
	Height	−0.010	0.013	−0.780	0.441
	Width	−0.008	0.013	−0.647	0.523
	Vegetation_density	−0.010	0.004	−2.277	0.030 *
	Hedgerow_plot*Sand_content	−0.002	0.001	−1.338	0.194
	Hedgerow_plot *Height	0.032	0.009	3.697	<0.01 **
	Hedgerow_plot *Width	−0.038	0.009	−4.340	<0.001 ***
	Hedgerow_plot *Vegetation_density	0.008	0.003	2.832	<0.01 **
$R^2_{marginal} = 0.410$, $R^2_{conditional} = 0.826$					

[1] Calculated according to Nakagawa et al. (2017).

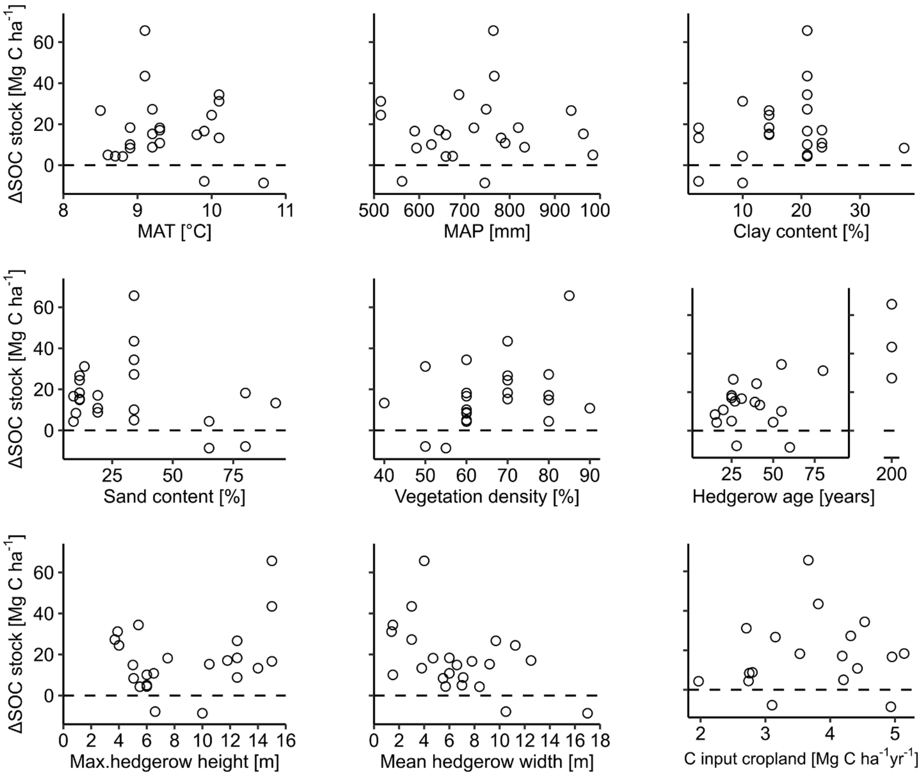

Fig. 5. Difference in soil organic carbon stock (Δ SOC) between hedgerow and reference cropland plots in 0–30 cm soil depth for the individual sites as a function of possible explanatory variables.

the temperate climate zone that sampled SOC stocks to 1 m soil depth at 21 sites in California and found a relative SOC stock increase of 36 % in 0–100 cm (Chiartas et al., 2022). The hedgerows sampled in our study, however, were older, with an average age of 60 years (median 35 years) compared with an average hedgerow age of 17 years in the study by Chiartas et al. (2022). Moreover, crops grown in the reference cropland and hedgerow species varied greatly between the two studies. Although both studies were located within the temperate climate zone, the climate in the sampling region in Chiartas et al. (2022) also differed from the climate in this study (higher MAT and MAP). Previous meta-analyses have found an average SOC stock difference with hedgerow establishment on cropland of 21 % (Cardinael et al., 2018) and 32 % (Drexler et al., 2021), but these were restricted to an average sampling depth of around 30 cm. These estimates were within the same range found in the 0–30 cm depth increment of our study (30 ± 43 %). The same applies to the empirical study by Wenzel et al. (2023), where a relative SOC stock difference was found of 15 % for hedgerows 1–30 years old and 38 % when considering hedgerows of 31–70 years of age in 0–40 cm soil depth for hedgerows sampled in Austria. We calculated an average C sequestration rate based on ΔSOC stock and hedgerow age of 0.42 ± 0.32 Mg ha^{-1} yr^{-1} in 0–30 cm soil depth. This is in good agreement with the estimated C sequestration rate in topsoil of 0.45 Mg ha^{-1} yr^{-1} after hedgerow establishment on cropland by Cardinael et al. (2018) in a literature review for the temperate climate zone. In a meta-analysis, Mayer et al. (2022) estimated C sequestration rates of 0.32 Mg C ha^{-1} yr^{-1} in 0–20 cm soil depth and 0.28 Mg C ha^{-1} yr^{-1} in 20–40 cm. That topsoil estimate is thus lower than the C sequestration rate in topsoil in our study. However, the differing sampling depths make comparisons between studies difficult. We calculated a C sequestration rate of 0.65 ± 0.55 Mg ha^{-1} yr^{-1} in 0–100 cm soil depth. Despite different sampling depths, climates, and cropping systems, the estimates of SOC stock change and the C sequestration rates all fall within the same range, suggesting that these are quite robust average estimates of SOC stock change that can be applied to hedgerows in the temperate climate zone.

However, the variability between sites was high. The sampled sites differed greatly regarding site properties, e.g. soil texture and rock content, which is reflected in the absolute SOC stocks. The average SOC stock of the reference cropland of 86 ± 30 Mg C ha^{-1} in 0–100 cm soil depth was slightly lower, but still within the same range as the German average for cropland mineral soils of 96 ± 48 Mg ha^{-1} (Poeplau et al., 2020). Mean total organic C input of the cropland was 3.7 ± 0.9 Mg ha^{-1} yr^{-1} on average across the sites. This is equal to the average mean organic C input in Germany (Jacobs et al., 2020), which indicates a good applicability of the estimates to German cropland sites, irrespective of cropland management.

Although, we measured SOC stock change for hedgerows varying in age (15 to >200 years), we found a significant interactive effect of hedgerow and age class only if the old hedgerows (>200 years) were included in the analysis. These had high SOC stock differences between the hedgerow and reference cropland. Overall, SOC stock change without these old hedgerows would have been 20 ± 28 Mg ha^{-1} (22 ± 22 %) in 0–100 cm soil depth, compared with the average of 29 ± 32 Mg ha^{-1} (36 ± 49 %) for all sites. Besides their greater age, high subsoil SOC stocks found in these hedgerows may also have contributed to the large SOC stock differences. For the other sites, no differences in ΔSOC between younger (15–30 years) and older (>30 years) hedgerows were found. This is in contrast to the expected temporal dynamics of SOC stocks after a land-use change, with increasing differences as SOC accumulates over time, which has been found for afforestation of cropland (Poeplau et al., 2011). Higher SOC stock differences with older hedgerows have also already been found for hedgerows up to 70 years old (Biffi et al., 2022; Wenzel et al., 2023). Differences in ΔSOC depending on hedgerow age might not be apparent in our study due to an overlap with other influencing factors, as we sampled across a large region at sites that have a wide range of soil properties such as texture.

Hedgerow width explained the variability in ΔSOC stocks both in the topsoil (0–30 cm) and when looking at the whole profile depth (0–100 cm). For the topsoil, besides width, hedgerow height and vegetation density also affected SOC stock change: a smaller ΔSOC stock between the hedgerow and reference cropland was found for hedgerows that are wider, taller and have a lower vegetation density. A low vegetation density may lead to low C input and thus to low SOC stocks in the hedgerow. Regarding hedgerow width and height, the effect identified was contrary to expectations. Tall hedgerows may be associated with a higher C input due to more above-ground vegetation. For narrow hedgerows the opposite could be hypothesised, as more wind erosion is found in narrow hedgerows (Torita and Satou, 2007), which may lead to less litter accumulation and thus less C input into the soil. Our results were primarily driven by the two sites with lower SOC stocks in the hedgerow compared with the reference cropland (KR, SH), and by the three sites with old hedgerows and a high SOC stock difference (BA, RI and DR). Compared with the other sites, the hedgerows at sites KR and SH were relatively tall, wide and with a low vegetation density, whereas those at sites BA, DR, RI were on average narrower and taller and had a higher vegetation density. In particular, the low vegetation density and great height (caused by a high proportion of trees) were probably caused by infrequent management. Regular coppicing is necessary to maintain a hedgerow with dense and shrubby vegetation (Black et al., 2023). Thus, frequent hedgerow management, including coppicing, may also be favourable for C sequestration in hedgerow soil due to increased C input with denser vegetation. Moreover, C input via roots and rhizodeposition may be favoured via coppicing, as regular above-ground disturbance is known to lead to increased root growth (Mokany et al., 2006). The two sites (KR and SH) with a negative hedgerow effect on SOC stocks also had a high sand content, which was also included in the final models for both soil depths (Table 2). Thus, besides hedgerow management, it may be that site properties, in particular texture, influence the negative hedgerow effect on SOC stocks.

4.2. Hedgerow effect with soil depth

Differences in SOC content between hedgerow and reference cropland soils generally decreased with increasing depth (Fig. 4). Only the 30–50 cm depth increment had higher SOC differences than the 10–30 cm depth increment. This could be due to the influence of tillage and the subsequent more uniform SOC contents in the topsoil, as well as a sharp decline in SOC contents in the subsoil of croplands. In comparison, SOC contents in hedgerow soils decrease more gradually. Additionally, hedgerow roots bring C to greater depths compared with the roots of annual crops, which may also foster SOC accrual below 30 cm soil depth (Drexler et al., 2023). Although the greatest absolute SOC stock change occurs in topsoil and the major proportion of SOC is stored in topsoil, SOC in the subsoil (30–100 cm) contributed considerably to the total SOC stock, both in the hedgerow and in the cropland soil. The subsoil accounted for 41 % (12 ± 17 Mg C ha^{-1}) of the absolute SOC stock increase with hedgerow establishment. Not considering subsoil SOC would have underestimated total mean hedgerow SOC stock by 38 % (44 Mg C ha^{-1}), highlighting the importance of accounting for subsoil SOC stocks in hedgerow systems. It is reported that sampling to 0–50 cm is sufficient to detect SOC changes due to management practices (Skadell et al., 2023). However, in the case of hedgerow systems, this would miss 21 % (6 Mg C ha^{-1}) of total SOC stock in 50–100 cm depth. This is in line with the hypothesis that deep soil C input from deep-rooting, permanent woody species in particular contributes to increased hedgerow SOC stocks (Cardinael et al., 2015; Mulia and Dupraz, 2006; Upson and Burgess, 2013). However, this finding is in contrast to the results of the recent empirical study on SOC stock changes with hedgerow establishment on cropland conducted by Wenzel et al. (2023) on a regional scale in North-East Austria with only fine-textured soils and the soil groups Chernozems and Phaeozems. Wenzel et al. (2023) found no significant differences in SOC stocks between hedgerow and adjacent cultivated soils already in the 20–40 cm depth increment, and found indications of subsoil SOC losses under older hedgerows. However, this may be due to missing tillage down to 30 cm depth under hedgerows that reduces the translocation of C into the 20–30 cm soil layer and thus results in lower SOC stock differences when looking at this depth increment (Fig. 4). In our study, we separated the topsoil and subsoil along the maximum tillage depth and did not detect SOC losses in the subsoil. SOC stocks were significantly increased between the reference cropland and hedgerow soils for all soil depths. However, the variability between sites was high. Particularly large differences in subsoil SOC stock between the hedgerow and the reference cropland were found for sites BA, DR and RI. These three sites were all located in the Schleswig-Holstein uplands in northern Germany with a hedgerow type known locally as “Knick”. These hedgerows were widely established in this area in the 18th century and were created by first raising a bank of soil material and then planting lines of shrubs and trees on top. As this hedgebank was usually constructed from soil material from directly adjacent agricultural fields (Kurz et al., 2011), this translocation could partly contribute to the high subsoil SOC accrual. However, these were also the sites with the oldest hedgerows, all in the age class >200 years, which could also explain the large difference in SOC stocks. Findings by Biffi et al. (2022) and Wenzel et al. (2023) for hedgerows in the temperate climate zone have shown that no equilibrium is reached even after decades, and that hedgerows continue to sequester C in soils in the long term, albeit with declining SOC sequestration rates over time. Subsoil SOC stocks may be increased in old hedgerows due to favourable conditions for SOC stabilisation in subsoils (Cardinael et al., 2017). Hedgerows planted on a hedgebank are widespread in northwest Germany, make up a substantial proportion of all hedgerows in Germany, and continue to be established today. Further studies are therefore needed to disentangle the processes of C sequestration in this type of hedgerow and estimate their overall climate change mitigation potential while also considering soil translocation and burial.

4.3. Effect beyond the actual hedgerow area

Hedgerow edge SOC stocks were significantly higher than those of adjacent and reference croplands, leading to an additional C sequestration effect with hedgerow establishment. Hedgerow edges are the transition area from the hedgerow to the cropland, and often comprise grassy or ruderal vegetation that is partly managed with infrequent mowing. Hedgerow SOC stocks and SOC stocks from the mostly grassy hedgerow edge were not significantly different in our study, which supports previous findings that there is no difference in SOC stocks between hedgerows and grassland (Cardinali et al., 2014; Drexler et al., 2021). For the adjacent cropland, it was hypothesised that SOC stocks are still influenced by the hedgerow through litterfall and root growth expanding from beneath the hedgerow (Drexler et al., 2023; Lesaint et al., 2023). Adjacent cropland and reference cropland SOC stocks were not significantly different in our study. However, for the majority of the sites, SOC stocks were higher in the adjacent cropland than in the reference cropland, indicating that the hedgerow influence on the adjacent cropland is not negligible. The difference in SOC stock between adjacent and reference croplands was 9 ± 19 Mg C ha^{-1} on average, but reached a level of up to >20 Mg C ha^{-1}. It is unlikely that this increase is solely due to additional litter input from the hedgerow, but indicates that roots from the hedgerow and hedgerow edge have a high lateral expansion beyond the hedgerow and increase C input (Rasse et al., 2005). The SOC difference was also higher below the ploughing depth (Fig. 4), where expanding hedgerow roots might have favourable growing conditions. ΔSOC stocks for both the hedgerow edge and the adjacent cropland were higher on average if they were east and north of the hedgerow compared with west (Figs. S.7 and S.8). Although these effects were not significant, this indicates that in the lee side of the hedgerow (main wind direction west) the effect beyond the actual hedgerow area on SOC stocks is stronger.

We found no differences in topsoil C/N ratio along the transect from the hedgerow edge to the cropland, despite the differences in average SOC stock (Fig. S.2). Only the C/N ratio of the hedgerow soil was significantly higher. This indicates that the hedgerow not only changed the total SOC stock, but also caused a shift in soil organic matter quality due to C input not only differing in mass, but also in quality. Whereas the hedgerow system seems to have lower litter quality and thus lower rates of decomposition, the change in SOC stocks in the adjacent cropland and edge seems to be driven not by a change in C input quality, but more by a change in C input mass. For the adjacent cropland, this effect could be driven, for example, by a difference in yield due to changed microclimatic conditions or differing plant protection measures close to the hedgerow.

4.4. Upscaling: Implications for the C sequestration potential of hedgerow establishment on cropland in Germany

Our estimates of C stocks and C stock change with hedgerow establishment were all given per full hectare of hedgerow, which is crucial for comparisons with other land uses and climate change mitigation measures. However, hedgerows are linear features, and thus a comparison of cropland fields with and without hedgerows requires a weighting of the proportion of hedgerow area within the total agricultural land. We therefore calculated a scenario in which total SOC stock in 0–100 cm soil depth of a cropland with a hedgerow is 87.0 Mg C ha^{-1} compared with 85.9 Mg C ha^{-1} for a cropland without a hedgerow, when assuming a German average square field size of 5 ha, the establishment of a hedgerow 7 m in width along one field border (25 % of field borders), and including the additional effect within the edge (1 m width) and the adjacent cropland (2 m width). Upscaling this to the total cropland area of Germany of around 12 Mio. ha, the establishment of hedgerows on 25 % of cropland field borders would equal the establishment of a hedgerow length of around 537,000 km or 376,000 ha of hedgerow. These additional hedgerows would result in a total SOC stock increase of around 13 Tg C, which equals 48 Tg CO_2. Additionally, 33 Tg C could be sequestered in hedgerow biomass based on the estimates by Drexler et al. (2021). This increase in hedgerow area would equal the establishment of hedgerows on around 3 % of total cropland area in Germany. For biodiversity goals, small woody features, including hedgerows but also other trees outside forests such as tree rows and roadside vegetation, on 6 % of cropland area has been found to be optimal (Vallé et al., 2023). The EU Biodiversity Strategy aims to dedicate as much as 10 % of agricultural area to so-called high-diversity landscape features, including fallow land, field margins and ditches for example (European Commission, 2020). However, the planting of 537,000 km of hedgerows (around 3 % of total cropland area) is already ambitious compared with the current total hedgerow length on agricultural land (cropland and grassland) of around 90,000 km in Germany, according to the digital landscape model (BKG, 2023). Considerable efforts regarding new funding programmes and education would be needed to establish these hedgerows and overcome challenges such as high maintenance and initial investment costs (Poschlod and Braun-Reichert, 2017). Current emissions from agriculture including land use in Germany are around 100 Tg CO_2-equivalents per year (Umweltbundesamt, 2023). The establishment of 376,000 ha hedgerow could thus offset about 0.9 % of these annual emissions (potential sequestration of 244,000 Mg C yr^{-1}) through C sequestration in soils, assuming a potential sequestration rate of 0.65 Mg ha^{-1} yr^{-1}. This annual C sequestration is possible until a new equilibrium is reached, which may take several decades (Biffi et al., 2022). More hedgerows can thus only offset a small fraction of current CO_2 emissions from agriculture. However, their importance will increase with decreasing total GHG emissions and the need to offset unavoidable GHG emissions, which will largely be generated by agriculture, in order to achieve net-zero goals.

5. Conclusions

Our study provides country-specific estimates of SOC stock changes with the establishment of hedgerows on cropland. The SOC stock change was 29 ± 22 Mg ha^{-1} (36 ± 49 %) on average across the sites in 0–100 cm soil depth. Comparisons with other studies indicate that these estimates can be generalised for a wide range of hedgerows in the temperate climate zone. Estimates of SOC stock change can help account for CO_2 emissions and C sequestration in soils resulting from hedgerow loss or the establishment of new hedgerows on cropland, e.g. in national greenhouse gas inventories. Differences in SOC stocks between hedgerows and the reference croplands were significant for both topsoil and subsoil. We found an absolute SOC stock increase of 41 % with hedgerow establishment in the subsoil (30–100 cm), stressing the need to account for SOC stocks within the whole soil profile. Additionally, increased SOC stocks were found along the transect from the hedgerow to the cropland, which should also be included when accounting for SOC stock changes with hedgerow establishment. SOC stock changes varied greatly between sites. We found indications that hedgerow width, hedgerow height and vegetation density may be responsible for between-site variability in topsoil SOC stock changes, which may be linked to hedgerow management such as regular coppicing. Particularly high SOC stock differences were found for old hedgerows (>200 years), indicating that soils beneath hedgerows can be a long-term C sink. Our study showed that hedgerow establishment on cropland not only increases biomass C stocks, but also significantly increases SOC stocks. The intensification of agriculture has led to drastic reductions in hedgerow length in the past throughout the temperate climate zone. Re-establishing these lost hedgerows can contribute to increasing C sinks on agricultural land and thus contribute to climate change mitigation and the achievement of net-zero targets. Besides climate change mitigation, the establishment of hedgerows can help target other sustainability goals, such as counteracting biodiversity loss, and supporting adaptation to climate change. Hedgerows are thus a promising nature-based solution that should increasingly be implemented.

CRediT authorship contribution statement

Sophie Drexler: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Axel Don:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

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

Data availability

The data that support the findings of this study are openly available in zenodo at https://doi.org/10.5281/zenodo.11046895.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geoderma.2024.116878.

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