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Carbon storage in old hedgerows: The importance of below-ground biomass

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Abstract

Ambitious climate change mitigation goals require novel carbon (C) sinks in agricultural systems. Thus, the establishment of new hedgerows is increasingly attracting attention as a C sequestration measure. Despite hedgerows being a traditional agroforestry system, few studies have been conducted on hedgerow C stocks. Data on below-ground biomass (BGB) in particular are limited. The aim of this study was therefore to quantify both above-ground biomass (AGB) and BGB C stocks, as well as litter and soil organic C stocks, of established hedgerow systems by destructive sampling at three sites in northern Germany. The total biomass C (TBC) stock of the sampled hedgerows was 105 ± 11 Mg ha^{-1} on average. An additional 11 ± 2 Mg ha^{-1} were found in hedgerow litter and dead roots. Coarse roots (34% of TBC), stumps (22%) and harvestable biomass (20%) were the largest biomass C pools of the hedgerows. The BGB:AGB ratio was 0.7 ± 0.1, showing the importance of BGB in old hedgerow systems. Compared with other woody systems, these old hedgerows seem to have a different biomass distribution, with more biomass allocated below-ground. About 15% of BGB C stock was stored in fine roots, whereas 85% was stored in coarse roots. The topsoil (0–30 cm) contained 85% of coarse root biomass C and 51% of fine root biomass C. Hedgerow C stock exceeded that of average German forests, and thus demonstrated their large potential for C sequestration when newly planted. This study provides detailed empirical data on C stocks in old hedgerow systems, and thus can be used to take hedgerow C sinks into account in C farming frameworks.

KEYWORDS

agroforestry, below-ground biomass, carbon accounting, climate-smart agriculture, root carbon, root sampling

1 | INTRODUCTION

Climate change is one of the most urgent and serious crises we have to face globally in the 21st century. To mitigate climate change, ambitious climate protection goals have been set in recent years at international and national levels. To achieve net zero targets, the land use, land-use change and forestry sector (LULUCF) is supposed to play

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an important role as it is the only sector under the United Nations Framework Convention on Climate Change where negative emissions from C sinks are possible. The European Commission wants to achieve climate neutrality in the EU by 2050, including ambitious targets for the LULUCF sector at 310 million Mg CO_2 equivalents in 2030 (European Council, 2022). At a national level, even stricter targets have been set, for example, in Germany net zero should be achieved by 2045 with the help of natural C sinks, which are expected to compensate for unavoidable emissions of 40 million Mg CO_2 equivalents in 2045 (KSG, 2019).

One potentially promising measure that could help increase terrestrial C sinks to meet these goals is to establish new hedgerows. Hedgerows are a traditional type of agroforestry and widely distributed in the temperate climate zone (Burel, 1996). Hedgerows can be defined as managed, linear structures composed of perennial shrubs or of shrubs and trees established adjacent to agricultural fields (Drexler et al., 2021). Besides climate change mitigation, hedgerows could help with adaptation to climate change by improving the microclimate, shading and enhancing water storage in adjacent agricultural fields (Böhm et al., 2014; Cleugh et al., 2002; Sánchez et al., 2010). In combination with livestock, hedgerows can provide shading and reduce heat stress (Mader et al., 1999). Moreover, hedgerows provide multiple other co-benefits, such as better erosion control and increased biodiversity (Montgomery et al., 2020). Hedgerows provide a habitat, shelter and resources for a wide range of species, including plant, birds, mammals and invertebrates, and support functionally important taxa such as pollinators and natural enemies of pests (Castle et al., 2019; Litza et al., 2019; Morandin et al., 2014). This multifunctionality makes the establishment of hedgerows a particularly promising measure to increase terrestrial C sinks in agriculture (Haddaway et al., 2018; Kay et al., 2019). In addition, hedgerows require little area (e.g. in Germany around 0.2% of agricultural land), allowing the majority of agricultural land to be used for food production, thus minimizing leakage effects.

Detailed information on the C stocks of hedgerows are needed in order to account for C stock changes due to the establishment and removal of hedgerows, for example, for national greenhouse gas reporting, and to estimate associated C sequestration potentials. Estimates of the C sequestration potential of hedgerows have recently been published in meta-analysis and modelling studies, and indicate a high C sequestration potential in both soil and biomass (Drexler et al., 2021; Mayer et al., 2022; Zellweger et al., 2022). Golicz et al. (2021) estimate that there are currently around 900,000 ha of small woody landscape features, such as hedgerows or woodlots, in Germany. Based on the meta-study by Drexler et al. (2021), these were estimated to store a total of 36.3 ± 22.2 Tg C in the biomass and 74.8 ± 30.3 Tg C in the soil, corresponding to about 34% of total agricultural biomass C stock and 6% of total agricultural soil organic carbon (SOC) stock in Germany. Golicz et al. (2021) state that the conversion of 1–10% of German cropland to hedgerows could sequester between 14 ± 52 and 143 ± 107 Tg C over 30 years. However, these calculations were based on limited empirical data on hedgerow C stocks. Recent empirical studies have focused on SOC storage and sequestration of hedgerows (e. g. Biffi et al., 2022; Chiartas et al., 2022; Van Den Berge, Vangansbeke, Baeten, Vanneste, et al., 2021; Viaud & Kunnemann, 2021), despite more than 80% of the additional C stocks of hedgerows, compared with cropland, being found in the biomass (Drexler et al., 2021). Empirical data on hedgerow biomass, particularly data on below-ground biomass (BGB), remain limited because sampling is labour-intensive and time-consuming.

To estimate BGB, fixed BGB:above-ground biomass (AGB) ratios are often applied. However, BGB:AGB ratios are land use and vegetation specific, and are thus not easily transferable (Mokany et al., 2006; Xing et al., 2019). Cardinael et al. (2018) defined Tier 1 emission factors for AGB and BGB C sequestration specifically for hedgerows adapted to different climate zones. These were subsequently included in the IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2019). For the temperate climate zone, the estimates on C sequestration in hedgerow biomass were based on just one study that sampled prairie shelterbelts for AGB in Saskatchewan and Manitoba, Canada (Kort & Turnock, 1999). Cardinael et al. (2018) estimated hedgerow BGB by applying a fixed BGB:AGB ratio of 0.26, which was based on an estimate for forests in the temperate climate zone by Cairns et al. (1997). Other widely used BGB:AGB ratios are between 0.2 and 0.5 for temperate forests according to Mokany et al. (2006). Levin et al. (2020) used an even lower BGB:AGB ratio of 0.19 in their study about biomass change in non-forest woody vegetation in Denmark according to the IPCC default for temperate forests (IPCC, 2019). The only empirical study about the BGB of hedgerows in the temperate climate zone found a mean BGB:AGB ratio of 0.94 ± 0.26 from the sampling of three old hedgerows in the United Kingdom, established up to 220 years ago (Axe et al., 2017). However, Axe et al. (2017) included stumps in the BGB pool. This ratio is very different from the above-mentioned BGB:AGB ratios, suggesting that BGB:AGB ratios derived from forest data are not applicable to hedgerows.

The aim of this study was therefore to quantify biomass C storage of established, temperate hedgerow systems using biomass harvesting, soil excavation and soil coring methods at typical hedgerow sites in northern Germany. We determined how much C is stored in the different hedgerow biomass components, both in AGB and BGB, and their contribution to total C storage. Based on the empirical data, we calculated BGB:AGB ratios and analysed the depth distribution of the different C pools.

2 | MATERIALS AND METHODS

2.1 | Study sites

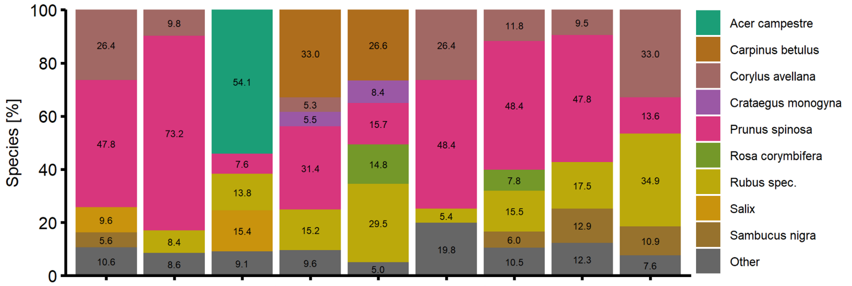
Three sampling sites with hedgerows typical of the region were selected: Rixdorf, Barkau and Droegendieck. All three sites are located in the Schleswig-Holstein uplands in northern Germany (Figure S1). The area is characterized by a dense network of hedgerows, known locally as 'Knicks', which were widely established in the 18th century to mark property boundaries (Baudry et al., 2000). The sampled hedgerows all date back to this period. They were created by first raising a bank of soil material, and then planting lines of shrubs and trees on top. Management includes regular trimming and periodic coppicing of the shrub layer about every 10–20 years, while some mature trees are left standing every 40–60 m. The climate in the study area is sub-oceanic, and is characterized by moderately warm summers and mild winters. Between 1991 and 2020, the mean annual temperature at the closest weather station in Dörnick, located on average 13 km away from the sampling sites, was 9.2°C and mean annual precipitation was 731 mm year^{-1} (DWD, 2022). A young moraine, hilly topography, formed during the last glacial period, shapes the landscape. Soil textures are sandy-loam to clay-loam, as identified by texture-by-feel analysis in soil pits at all three sites. At each of the three study sites, three hedgerow plots 100 m long and with different species composition were selected. The most dominant species across all hedgerow plots were blackthorn (*Prunus spinosa* L., 37.1% of total shoots), raspberries/blackberries (*Rubus spec.* L., 15.8% of total shoots) and hazel (*Corylus avellana*, 14.2% of total shoots; Figure 1). The average hedgerow width was 5.9 m, and was calculated as the midpoint between the maximum crown width and the minimum stem width measured in the field and verified via aerial pictures (Figure S2).

2.2 | Sampling and sample processing

To determine the C stored in the hedgerow biomass, we sampled the following biomass pools: AGB, subdivided into harvestable biomass, mature trees and stumps; litter, subdivided into leaf litter and dead wood litter; and BGB, subdivided into coarse roots (>2 mm) and fine roots (<2 mm). Coarse roots were further subdivided into coarse root biomass and coarse root necromass. Additionally, SOC stocks were measured down to a depth of 1 m. All C pools were sampled on respective subplots (Figure S3).

2.2.1 | Above-ground biomass

Harvestable AGB was sampled destructively by cutting all hedgerow biomass at the usual coppicing height in 10 subplots 10 m long per hedgerow plot ($n = 90$). Usual coppicing height was around 20 cm and ranged up to 50 cm, depending on the relief and the associated accessibility by harvesting machines. All biomass was weighed directly fresh in the field per subplot. Due to local conditions the segments had to be weighted on two different scales: by a telescopic handler with minimum load of 0.7 t and 50 kg resolution or on a mobile truck scales with a minimum load of 1.1 t and 10 kg resolution. Three aliquots (approximately 5 L each) per subplot were taken to the laboratory and dried in a drying oven at 105°C until constant mass was achieved to determine water content and subsequently dry matter for all subplot samples.



Site	Rixdorf			Droegendiek			Barkau		
Plot	1	2	3	1	2	3	1	2	3
Width [m]	6.4	5.8	4.9	4.3	9.1	7.4	4.2	4.7	6.7
Height [m]	5.4	4.8	6.1	7.0	9.8	6.9	3.9	3.6	4.3
Years since last coppice	13	16	16	17	28	21	16	14	20

FIGURE 1 Species composition and characteristics of the sampled hedgerow plots as a percentage of the total number of shoots. Only dominant species with a proportion ≥5% are shown. All species in the hedgerows can be found in Table S1.

After coppicing, stumps are left standing. This stump biomass was sampled at one hedgerow plot per site, each with five subplots covering an area of 1 m^2 ($n = 15$; Figure S4). The subplots were selected in a stratified random sampling approach with the strata representing the diversity of vegetation and different vegetation densities in the hedgerow plot covering the whole hedgerow width. Hedgerow width was defined as midpoint between the maximum crown width and the minimum stem width. After cutting the harvestable biomass at the usual coppicing height, the remaining above-ground stumps were cut at ground level to clearly differentiate between AGB and BGB. The stumps were cleared from soil as much as possible in the field and then transported to the laboratory. Large stumps were shredded in a wood chipper. Subsequently, the entire biomass was washed by hand with a high-pressure water hose over a 2 mm sieve, and dried in a drying oven at 60°C until constant mass was achieved to determine dry matter.

Mature trees could not be felled for AGB determination. Therefore, diameter at breast height was measured for all mature trees and species-specific allometric equations were used to determine their AGB covering the whole above-ground part (Zianis et al., 2005). The mature trees were each assessed within the 10 subplots per hedgerow plot for harvestable biomass of 10 m length.

2.2.2 | Litter biomass

Litter biomass was sampled on the same 1 m^2 ($n = 15$) subplots as the stump biomass. All leaf litter and deadwood were collected manually in the sampling subplot. Litter samples were transported to the laboratory, separated into leaf litter and dead wood, dried in a drying oven at 60°C, and weighed to determine dry matter.

2.2.3 | Below-ground biomass and soil organic carbon

Coarse root biomass and necromass were determined by excavating the soil to a depth of 1 m with a mini-digger, and divided into topsoil (0–30 m) and subsoil (30–100 cm) in the same 1 m^2 sampling subplots as for stump biomass and litter ($n = 15$). Coarse roots were cleared of soil as much as possible in the field and separated directly into biomass and necromass visually and by plasticity. After transporting the samples to the laboratory, large coarse roots were shredded in a wood chipper, the entire biomass was washed by hand with a high-pressure water hose over a 2 mm sieve, and then dried in a drying oven at 60°C until constant mass was achieved to determine dry matter.

In each of the hedgerow plots, 10 subplots were randomly selected to determine fine root biomass and SOC ($n = 90$). Using a paired-plot approach, in one hedgerow plot per site the adjacent cropland 30 m away from the hedgerow edge was also sampled to determine SOC in five randomly selected subplots. The sampled adjacent croplands were intensively managed and planted with rapeseed (Rixdorf), winter cereals (Droegendieck) or grass ley (Barkau) at the time of sampling. Soil cores with a diameter of 6 cm were taken to a depth of 1 m using a machine-driven soil auger in each subplot. The soil cores were divided into six depth increments: 0–5 cm, 5–10 cm, 10–30 cm, 30–50 cm, 50–70 cm and 70–100 cm. If compaction or stretching of the soil core occurred, the depth increments were corrected in situ by the difference between the core length and borehole depth (Walter et al., 2016). Soil samples for SOC determination were stored at 4°C until further analysis, subsequently dried at 60°C until constant mass was reached, and weighed. Visible living fine roots and stones were removed and the soil sieved to ≤2 mm. Stone and root weight were recorded to determine fine soil mass. An aliquot of fine soil was milled for subsequent C analysis. Soil samples for fine root determination were frozen at −17°C. To analyse fine root biomass, the roots were thawed and separated from soil using a hydropneumatic elutriation system (Gillison's Variety Fabrication, Inc.). The washing procedure was performed using a 630 μm sieve to avoid loss of fine root biomass. Any above-ground litter residues, coarse roots (>2 mm) or remaining soil particles were removed manually using tweezers. Fine roots were dried at 60°C until mass constancy, and weighed.

2.3 | Carbon analysis and carbon stock calculation

Total C and total nitrogen (N) content were determined by dry combustion on a milled subsample for each biomass C pool using an elemental analyser (LECO TruMac CN). For SOC, all soil samples were analysed. Soil samples with a C/N ratio >13 or inverse depth gradients in C/N ratio or C content 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 for these samples. For the other samples, total C content was assumed to equal total organic C content.

C stocks were calculated for each C pool depending on its C content (Table 1) and the area sampled. Fine root biomass C stock [Mg ha^{-1}] in each depth increment was

TABLE 1 Average carbon (C) and nitrogen (N) contents and C/N ratios (± SD (standard deviation)) of the different hedgerow biomass pools.

Carbon pool	Average carbon content [g kg^{-1}]	Average nitrogen content [g kg^{-1}]	Average C/N ratio	Reference/number of samples analysed
Harvestable biomass, mature trees	475	/	/	Average according to Schlesinger and Bernhardt (2013)
Stumps	488 ± 7	4 ± 2	131 ± 49	5
Leaf litter	386 ± 59	18 ± 2	21 ± 4	8
Dead wood litter	481 ± 5	9 ± 3	55 ± 18	7
Coarse root biomass	482 ± 6	7 ± 2	83 ± 32	10
Coarse root necromass	475 ± 15	9 ± 2	55 ± 11	10
Fine roots	392 ± 63	12 ± 4	37 ± 20	50

Note: Carbon contents were determined by dry combustion on subsamples for each carbon pool or were based on literature values.

calculated according to Equation (1) and summed up to 1 m depth to obtain overall fine root biomass C stocks:

$$\text{Fine root biomass } C \text{ stock}_i = \frac{DM_{\text{fine\_roots}_i} \times C_{\text{content}_{\text{fine\_roots}}}}{\text{Area}_{\text{core}} \times 10} \tag{1}$$

where $\text{DM}_{\text{fine\_roots}_i}$ is the dry mass of the fine roots [g] of the respective depth increment i, $C_{\text{content}_{\text{fine\_roots}}}$ is the average C content of the fine roots [g kg^{-1}], and $\text{Area}_{\text{core}}$ is the area of the soil core [cm^2].

SOC stock [Mg ha^{-1}] in each depth increment was calculated in accordance with Poeplau et al. (2017) Equation (2), and summed up to 1 m depth to obtain overall SOC stocks:

$$\text{SOC stock}_i = \frac{\text{Mass}_{\text{fine\_soil}_i} \times C_{\text{content}_{\text{fine\_soil}_i}}}{\text{Area}_{\text{core}} \times 10} \tag{2}$$

where $\text{Mass}_{\text{fine\_soil}_i}$ is the mass of the fine soil <2 mm [g], $C_{\text{content}_{\text{fine\_soil}_i}}$ is the C content of the fine soil [g kg^{-1}] of the respective depth increment i and $\text{Area}_{\text{core}}$ is the area of the soil core [cm^2].

C stocks for harvestable biomass, mature tree biomass, stumps biomass, coarse root biomass, coarse root necromass, leaf litter and dead wood litter [Mg ha^{-1}] were calculated for each individual subplot in accordance with Equation (3):

$$\text{Biomass } C \text{ stock} = \frac{\text{DM} \times C_{\text{content}}}{\text{Area}_{\text{subplot}} \times 10} \tag{3}$$

where *DM* is the dry mass of the harvestable biomass/mature trees/coarse roots/litter [g], C_{content} is the average C content of the respective C pool according to Table 1, and $\text{Area}_{\text{subplot}}$ is the area of the sampling subplot [cm^2]. For coarse roots, the two sampling depths (0–30 cm and 70–100 cm) were calculated individually and summed up to 1 m depth to obtain their respective overall biomass C stocks. For harvestable biomass and mature tree biomass, the subplot area was calculated based on average hedgerow width.

To analyse depth gradients, the fine root biomass density [mg cm^{-3}] in each depth increment was calculated according to Equation (4):

$$\text{Fine root biomass density}_i = \frac{\text{DM}_{\text{fine\_roots}_i}}{\text{Volume}_{\text{core}_i}} \tag{4}$$

where $\text{DM}_{\text{fine\_roots}_i}$ is the dry mass of the fine roots [mg], and $\text{Volume}_{\text{core}_i}$ is the volume of the soil core [cm^3] of the respective depth increment *i*. Moreover, by multiplying fine root biomass density by the average C content of the fine roots, fine root C density was calculated.

Coarse root biomass density [$\mathrm{mg\,cm^{-3}}$] in the topsoil and subsoil was calculated according to Equation (5):

$$\text{Coarse root biomass density}_i = \frac{\mathrm{DM}_{\text{coarse\_roots}_i}}{\text{Volume}_{\text{excavation subplot}_i}} \tag{5}$$

where $\mathrm{DM}_{\text{coarse\_roots}_i}$ is the dry mass of the coarse roots [mg] and $\text{Volume}_{\text{excavation subplot}_i}$ is the volume of the excavation subplot [$\mathrm{cm^3}$] of the respective depth increment i.

SOC density [$\mathrm{mg\,cm^{-3}}$] in the topsoil and subsoil was calculated in accordance with Equation (6):

$$\text{SOC density}_i = \frac{\text{Mass}_{\text{fine\_soil}_i} \times C_{\text{content}_{\text{fine\_soil}_i}}}{\text{Volume}_{\text{core}_i} \times 1000} \tag{6}$$

where $\text{Mass}_{\text{fine\_soil}_i}$ is the mass of the fine soil <2 mm [mg], $C_{\text{content}_{\text{fine\_soil}_i}}$ is the C content of the fine soil [$\mathrm{g\,kg^{-1}}$] and $\text{Volume}_{\text{core}_i}$ is the volume of the soil core [$\mathrm{cm^3}$] of the respective depth increment i.

To analyse C stock change, that is, C sequestration potential, with the establishment of hedgerows on cropland, the C stocks of the cropland have to be subtracted. Therefore, the SOC stocks of the reference croplands were averaged and subtracted from the average SOC stock of the hedgerows. It is also necessary to take into consideration changes in the C stock caused by the removal of C from agricultural biomass (IPCC, 2019). To calculate this change in biomass C stock, an average total biomass C (TBC) stock of 6.41 ± 0.75 $\mathrm{Mg\,ha^{-1}}$ for German cropland was assumed (Umweltbundesamt, 2022). The AGB of hedgerows fluctuates greatly due to regular coppicing (Drexler et al., 2021). We estimated long-term average C stocks for all C pools independent of the time within the rotation cycle. All nine sampled hedgerows were to be coppiced in the year of biomass sampling. The harvestable AGB sampled thus represents peak biomass before coppicing. To calculate the long-term average C stock in hedgerow biomass, we assumed linear growth in harvestable biomass and calculated a long-term average of harvestable biomass halfway through the rotation period. Although, hedgerow growth may be not completely linear, but slightly slower in the beginning and also when approaching maximum biomass (Biffi et al., 2023). BGB, mature trees and stumps are only marginally influenced by coppicing and were therefore assumed to be constant in its contribution to C storage.

2.4 | Data analysis

Data analysis and visualization were performed in R v4.0.3 (R Core Team, 2023) using Rstudio v1.2.1335 (RStudio Team, 2020). Data used for this study are publicly accessible at Drexler et al. (2023). To obtain robust estimates, for all C pools the C stocks of the subplots (sampling areas/soil cores) were averaged within the three sites, and the mean values across the three sites were reported. Mean C stocks between sites were compared using one-way ANOVAs for stump and coarse root biomass, which were sampled at one hedgerow plot per site. Two-way nested ANOVAs were conducted for AGB and fine root biomass C stocks (sampled at three hedgerow plots per site), with plots nested in site. To assess the correlation between hedgerow AGB and possible influencing factors, Pearson's correlation coefficient was determined at a significance level of $p < 0.05$. All mean values are given with standard deviations (SDs).

3 | RESULTS

3.1 | Above-ground biomass carbon stocks

Total long-term average AGB C stock was 62.9 ± 9.4 $\mathrm{Mg\,ha^{-1}}$ on average across the three sites, with harvestable biomass contributing 34%, stumps 37% and biomass of mature trees 28%. Long-term average harvestable biomass C stock was 21.4 ± 5.5 $\mathrm{Mg\,ha^{-1}}$ on average across the three sites, with significant differences between the sites ($p < 0.0001$). Mean long-term average harvestable biomass C stock (±SD between plots) at each site ranged from 15.1 ± 1.5 in Barkau, to 23.7 ± 3.5 $\mathrm{Mg\,ha^{-1}}$ in Droegendiek and 25.4 ± 7.7 $\mathrm{Mg\,ha^{-1}}$ in Rixdorf. The long-term average harvestable biomass C stock between hedgerow plots was significantly different ($p = 0.01$), with a minimum of 13.7 $\mathrm{Mg\,ha^{-1}}$ and maximum of 33.5 $\mathrm{Mg\,ha^{-1}}$. The coefficient of variation was 26% between the sites, 30% between the hedgerow plots and 49% between the subplots (Figure 2). Peak harvestable biomass C stock across the sites was 42.8 ± 11.0 $\mathrm{Mg\,ha^{-1}}$ on average. C sequestration potential in harvestable biomass depending on years since the last coppicing event ranged from 1.4 $\mathrm{Mg\,C\,ha^{-1}\,year^{-1}}$ for a hedgerow coppiced 28 years ago (Droegendiek 2) to 4.2 $\mathrm{Mg\,C\,ha^{-1}\,year^{-1}}$ for a hedgerow coppiced 16 years ago (Rixdorf 3). The average C sequestration rate in the harvestable biomass was 2.5 ± 0.7 $\mathrm{Mg\,C\,ha^{-1}\,year^{-1}}$. Biomass C stock of the mature trees was 17.9 ± 6.6 $\mathrm{Mg\,ha^{-1}}$ on average across the three sites. Mean biomass C stock of the mature trees (±SD between plots) at each site ranged from 13.2 ± 18.2 in Rixdorf, to 15.2 ± 19.6 $\mathrm{Mg\,ha^{-1}}$ in Droegendiek and 25.4 ± 19.1 $\mathrm{Mg\,ha^{-1}}$ in Barkau, thus opposite to the harvestable biomass C stock. On a subplot-level biomass C

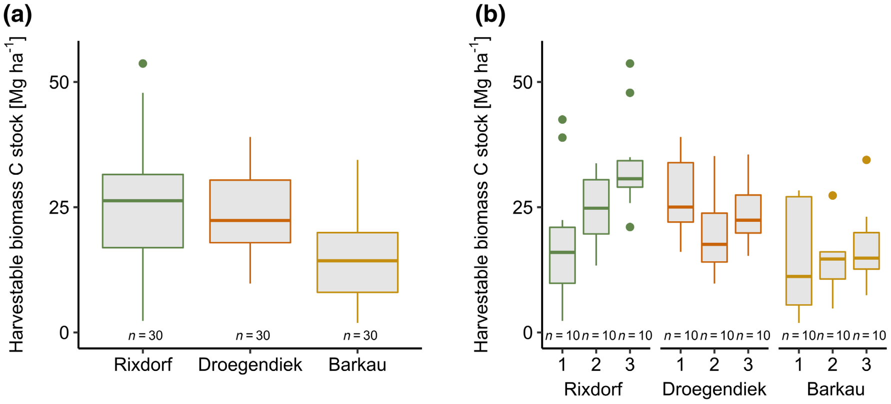


FIGURE 2 Long-term average harvestable biomass carbon (C) stocks for (a) the three sampling sites and (b) the nine hedgerow sampling plots.

stock of mature trees and harvestable biomass C stocks were negatively correlated (Pearson's correlation coefficient r(88) = −0.38, $p < 0.001$), thus indicating that there are minor differences between mature trees and shrubs regarding C storage per area. When combining harvestable biomass C stock and C stock of the mature trees, no significant differences between sites ($p = 0.5$) or plots ($p = 0.06$) were found. Looking at species-specific correlations, a significant positive correlation was found between the proportion of maple shoots (*Acer campestre*) and the long-term average harvestable biomass C stock, and a significant negative correlation between the proportion of elderberry shoots (*Sambucus nigra*) and the long-term average harvestable biomass C stock (Figure S5).

Stump C stock was 23.5 ± 9.3 Mg ha^{-1} on average across all sites. Mean stump C stock was not statistically significant between the sites ($p = 0.41$), but showed a high variability within the hedgerow plots. Average site stump C stock (±SD between subplots) ranged from 14.4 ± 16.9 Mg ha^{-1} in Rixdorf, to 23.2 ± 21.9 Mg ha^{-1} in Barkau and 33.0 ± 24.2 Mg ha^{-1} in Droegendiek. For stump biomass, which was sampled at five soil excavation subplots per site, species composition was also recorded at subplot level. Our sample size was too small to determine general correlations, but a clear relationship can be seen between high stump biomass C stock—and thus correlated with that also coarse root biomass C stock—and species with generally larger stem diameters (*Acer campestere* L., *Carpinus betulus* L., *Corylus avellana* L.), and a lower biomass where shrubs with generally smaller stem diameters dominate (*Crategus monogyna* Jacq., *Prunus spinosa* L., *Rubus* L., *Sambucus nigra* L.; Figure S6).

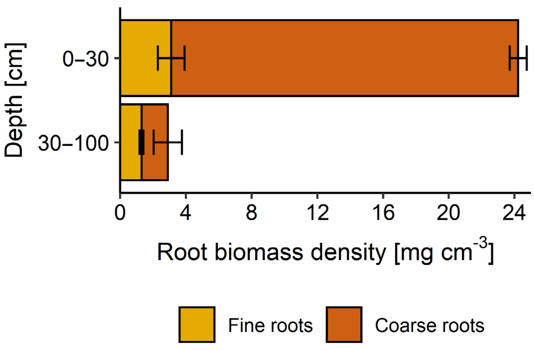


FIGURE 3 Root biomass density of fine roots (<2 mm) and coarse roots (>2 mm) in topsoil (0–30 cm) and subsoil (30–100 cm) as the mean across the three sites ($n = 3$). Error bars represent standard deviation of the mean.

3.2 | Below-ground biomass carbon stocks

Total BGB C stock was 42.4 ± 2.3 Mg ha^{-1} on average across the three sites, with about 15% of root C stored in fine roots and 85% stored in coarse roots. Coarse root biomass density was relatively high in the topsoil, while in the subsoil the distribution of fine and coarse root biomass was even (Figure 3). The topsoil (0–30 cm) contained 85% of the coarse root biomass C stock and 51% of the fine root biomass C stock.

Coarse root biomass C stock across the three sites was 36.0 ± 2.5 Mg ha^{-1} on average within 1 m soil depth. The mean coarse root C stock (± SD between subplots) was not statistically significant between the sites ($p = 0.94$), ranging from 34.2 ± 26.5 Mg ha^{-1} in Rixdorf, to 34.8 ± 21.8 Mg ha^{-1} in Barkau and 38.9 ± 17.5 Mg ha^{-1} in Droegendiek. Coarse root biomass was positively correlated with stump biomass at a subplot level, indicating a relationship with harvestable biomass as well (Figure 4).

Fine root biomass C stock was 6.4 ± 0.7 Mg ha^{-1} on average within 1 m soil depth. Mean fine root biomass C (± SD between subplots) did not differ significantly between sites ($p = 0.23$), ranging from 6.0 ± 3.8 Mg ha^{-1} in Barkau to 6.1 ± 3.1 Mg ha^{-1} in Droegendiek and 7.2 ± 3.0 Mg ha^{-1} in Rixdorf. Fine root biomass C stock between hedgerow plots was significantly different ($p = 0.01$), ranging from 3.5 ± 1.1 Mg ha^{-1} to 8.9 ± 3.0 Mg ha^{-1}. The coefficient of variation between the sites was 11%, between the hedgerow plots 25% and between the subplots 51% (Figure 5). Furthermore, the variability within the hedgerow plots was high, with a minimum fine root biomass C stock per soil core of 1.1 Mg ha^{-1} up to a maximum stock of 21.0 Mg ha^{-1} both within one hedgerow plot (Barkau 3; Figure 5). Fine roots were found up to a soil depth of 1 m, with average fine root biomass density decreasing sharply with increasing depth (Figure S7). The depth gradients of fine root biomass C and SOC were well aligned, whereas it has to be considered that SOC stocks were about 10 times higher than the fine root biomass C stocks (Figure 6).

3.3 | Litter and coarse root necromass carbon stocks

Leaf litter C stock across sites was 1.9 ± 1.2 Mg ha^{-1} on average. Dead wood litter C stock was 4.3 ± 1.0 Mg ha^{-1} on average. The median ratio of wood litter to leaf litter was 2.4, ranging from 1.2 to 26.4. Coarse root necromass stock was 4.4 ± 2.3 Mg ha^{-1} within 1 m depth on average across the sites. The proportion of coarse root necromass to total coarse roots ranged from 6% (Barkau) to 10% (Droegendiek) and 17% (Rixdorf) (Figure S8).

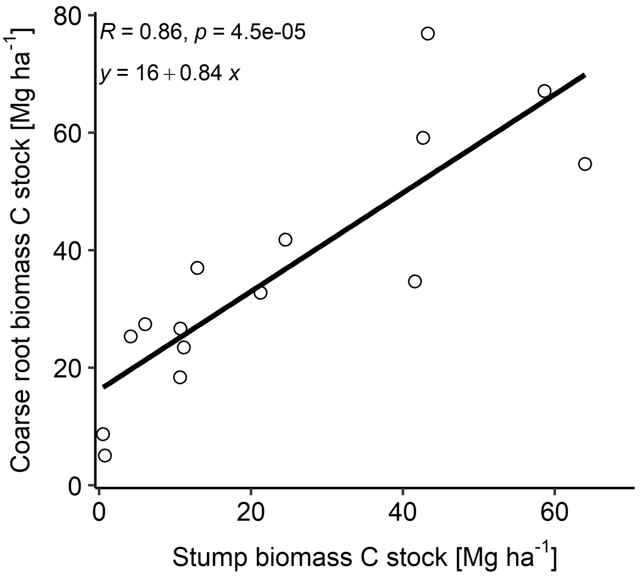


FIGURE 4 Relationship between stump and coarse root biomass C stocks for individual sampling subplots of 1 m^2 (n = 15).

3.4 | Total carbon stocks

Total C stock across the sites was 264 ± 13 Mg ha^{-1} on average, divided into a TBC stock of 105 ± 11 Mg ha^{-1}, a litter and necromass C stock of 11 ± 2 Mg ha^{-1}, and a SOC stock within 1 m soil depth of 148 ± 5 Mg ha^{-1}. TBC stock across sites varied between 95 Mg ha^{-1} in Rixdorf and 117 Mg ha^{-1} in Droegendiek. Coarse roots (average of 34% of TBC stock), stumps (average of 22% of TBC stock) and harvestable biomass (average of 20% of TBC stock) were the most important biomass C pools. The BGB:AGB ratio was 0.7 ± 0.1 on average across the sites, when stumps, harvestable biomass and biomass of mature trees were combined as AGB and fine and coarse roots were combined as BGB. Without considering mature trees the BGB:AGB ratio was 1.0 ± 0.1. When defining stumps as BGB and only harvestable biomass as AGB, the average ratio was 1.7 ± 0.3. The contribution of the different C pools to the total C stock was relatively consistent across all three sites (Figure 7). Total SOC stock made by far the largest relative contribution to total ecosystem C stock with a mean of 56% (Figure 7). However, when considering only C additionally stored with the establishment of new hedgerows on cropland, biomass C had a larger share than SOC. Averaged across the three sites, reference cropland SOC stock within 1 m soil depth was 85 ± 13 Mg ha^{-1}, thus leading to an average additional SOC stock of hedgerows of 63 Mg ha^{-1} (Figure 7). Compared with the average biomass C stock of cropland in Germany of 6.41 ± 0.75 Mg ha^{-1} (Umweltbundesamt, 2022), the long-term average additional TBC stock was 99 Mg ha^{-1}. Additionally, 11 ± 2 Mg C ha^{-1} would be stored within the litter layer and coarse root necromass with the

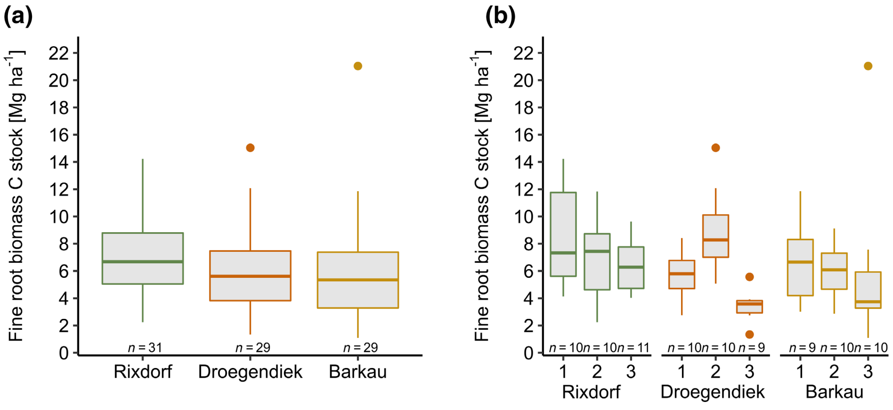


FIGURE 5 Fine root biomass carbon (C) stocks for (a) the three sampling sites and (b) the nine hedgerow sampling plots.

establishment of hedgerows on cropland. Thus, for the studied sites, C stock change with hedgerow establishment on cropland totalled 173 Mg ha^{-1}, with biomass contributing 57%, soil 37% and litter and necromass 6%. This number can be converted into a CO_2 sequestration potential of 63 kg CO_2 for each square metre of new hedgerow. This sequestration potential will be fully achieved when a new equilibrium of C stocks is reached, which will require several decades.

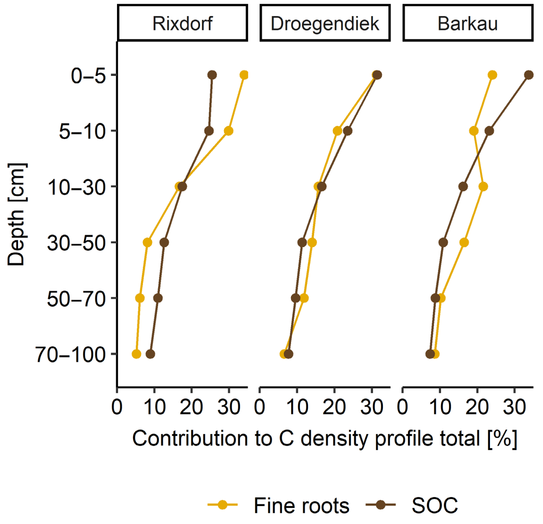


FIGURE 6 Relative contribution of each depth increment to overall carbon (C) density [mg C cm^{-3}] for fine roots and soil organic carbon (SOC), calculated for each depth increment as C density per depth increment divided by total C density.

4 | DISCUSSION

4.1 | Total biomass carbon stocks are comparable to previous estimates

Total biomass carbon stocks in our study were within the same range as previous estimates, indicating that despite differences in species composition, hedgerow type and hedgerow management, robust average values can be derived to estimate, for example, C sequestration potentials. In a meta-analysis on hedgerow C stocks, Drexler et al. (2021) compiled data from 64 sites and estimated a TBC stock of 92 ± 40 Mg ha^{-1} for hedgerows in the temperate climate zone. With 105 ± 11 Mg C ha^{-1} stored in the hedgerow biomass at the sampled sites, our estimate was

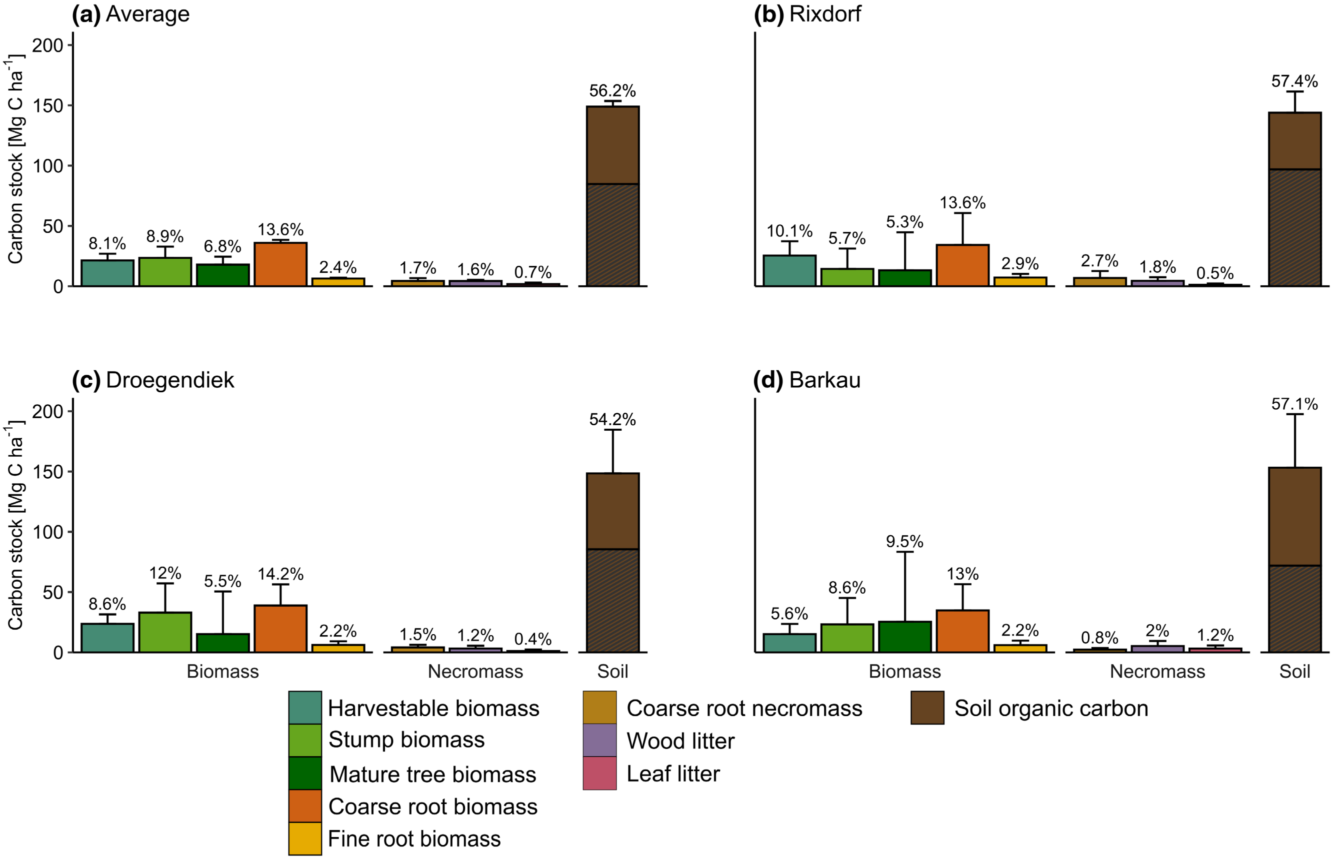


FIGURE 7 Carbon stock of the different hedgerow carbon pools and their percentage share of the total carbon stock as (a) the average across the three sites and (b), (c) and (d) for the individual sites averaged across the sampled subplots. For soil organic carbon (Soil), the hatched lower area indicates the soil organic carbon stock of the reference cropland plot, thus the non-hatched area indicates the additional soil organic carbon sequestered in the hedgerow soil. Error bars represent standard deviation of the mean.

similarly high. However, although within the same range, AGB and BGB in the old hedgerows sampled in our study were slightly different from previous estimates: the long-term average harvestable biomass C stock of hedgerows was estimated to be 47 ± 29 Mg ha^{-1} (Drexler et al., 2021). This estimate, however, included mature tree biomass. Combining harvestable biomass and mature tree biomass C stock our estimate would be 39 ± 2 Mg ha^{-1} which is thus lower than the estimate by Drexler et al. (2021). Axe et al. (2017) measured also a slightly higher estimate of harvestable biomass C stock in hedgerows in the United Kingdom and found between 32 ± 4 and 42 ± 5 Mg C ha^{-1} for hawthorn and blackthorn-dominated hedgerows at a medium growth stage. Much higher estimates were reported for hedgerows in Ireland by Black et al. (2023), with an AGB C stock of 58 Mg ha^{-1}, and for hedgerows in Denmark by Levin et al. (2020), with an AGB C stock of 62 Mg ha^{-1}, both from LIDAR estimates with hedgerows sampled for ground truthing. However, stumps may be included in these AGB C stock estimates, as no differentiation was made between harvestable biomass and stump biomass. This is also the case for the recent study on ABG C stocks of hedgerows in the United Kingdom by Biffi et al. (2023). In their study, AGB biomass C stocks between 8.3 Mg ha^{-1} for recently established hedgerows up to 40.4 Mg ha^{-1} for old hedgerows were found. These estimates, however, probably also included tree stumps, as plants were cut at ground level. Thus, these estimates are lower compared to our total AGB C stock estimate of 62.9 ± 9.4 Mg ha^{-1}, which includes mature tree, harvestable and stump biomass. The BGB biomass of the old hedgerows sampled in the present study was higher than previous estimates. Drexler et al. (2021) estimated BGB C stock including stumps to be 44 ± 28 Mg ha^{-1} based on Axe et al. (2017). BGB and stump biomass C stock combined (66 ± 11 Mg ha^{-1}) were on average 50% higher in our study than that reported in the meta-analysis by Drexler et al. (2021), indicating the underestimated importance of BGB built up over decades in hedgerow systems.

4.2 | BGB:AGB ratios need to be adapted to hedgerow ecosystems

The high hedgerow BGB C stock measured in our study resulted in high BGB:AGB ratios, which were even higher than those estimated by Axe et al. (2017). Axe et al. (2017) sampled stumps as BGB and found a BGB:AGB ratio of 0.9 ± 0.3 compared with an average ratio of 1.7 ± 0.3 in our study (when also considering stumps as BGB). While BGB is rarely sampled directly in the field, AGB can be measured more easily both destructively and non-destructively, for example, using UAV and LIDAR scanning analysis (Green et al., 2019; Lingner et al., 2018). When estimating BGB from AGB data via a fixed ratio, it is therefore important to consider which biomass components are measured as AGB. With destructive biomass sampling, AGB is often cut at the usual coppicing height rather than at ground level, thus potentially neglecting stumps. However, in our study, the stumps of hedgerow shrubs stored on average 22% of TBC stock and thus significantly influenced the BGB:AGB ratio. We defined stumps as AGB, and thus also estimated a BGB:AGB ratio for this allocation of 0.7 ± 0.1. Independently of the definition, the empirically measured BGB:AGB ratios of hedgerows were higher than the estimates of BGB:AGB ratios for temperate forests, for example, established by Mokany et al. (2006) in their global meta-analysis. Applying the BGB:AGB ratio of 0.26 used by Cardinael et al. (2018) according to Cairns et al. (1997) would have underestimated TBC stock by 25%, with an estimated BGB C stock of 16 Mg ha^{-1} rather than the 42 Mg ha^{-1} measured in the present study. If only harvestable biomass and mature trees and not stump biomass was included in the AGB, TBC would be underestimated by as much as 53%. The high BGB C stock of the sampled hedgerows can be explained by regular above-ground disturbance by hedgerow management (trimming and coppicing), which is known to lead to increased root growth (Mokany et al., 2006). Hedgerow management results in several little stems sprouting from a single stool, as shown by Axe et al. (2017). Stumps and coarse roots in the topsoil were large C pools in our study, and together accounted for more than half of TBC stock. Van Den Berge, Vangansbeke, Baeten, Vanhellemont, et al. (2021) showed that while total AGB was the same between trees grown in hedgerows and forests, tree architecture in hedgerows differs from those in forests due to reduced shading, increased physical growing space and potential benefits from fertilization residues from adjacent agricultural land. Compared with trees growing in forests, trees in hedgerows comprise more branch wood relative to stem wood, and develop more symmetrical, large crowns (Van Den Berge, Vangansbeke, Baeten, Vanhellemont, et al., 2021), which could influence BGB allocation. Relative BGB rises with increasing light intensity for most tree species, as shown by Annighöfer et al. (2022) for young forest trees grown in a meta-analysis with over 3000 observations, mostly from Germany.

Besides these growth characteristics of hedgerows, hedgerow management influences BGB:AGB ratios due to fluctuations in biomass. AGB fluctuates greatly due to regular coppicing in hedgerows, while BGB fluctuations are smaller as root systems are likely to stay largely intact after coppicing (Proe et al., 2002). This leads to a fluctuation in calculated BGB:AGB ratios, and might require adapted ratios to account for the time of AGB sampling within a rotation, for example, ratios could be developed depending on the number of years since the last coppicing event. Adjustment of BGB:AGB ratios might also be necessary depending on hedgerow age. The hedgerows sampled in our study were almost 300 years old. BGB:AGB ratios were shown to correlate negatively with stand age (Mokany et al., 2006), whereas intensive root systems, such as those of the hedgerows sampled in this study, may need some time and repeated coppicing to develop. The BGB:AGB ratios presented here refer to long-term average biomass and thus represent an average C storage in hedgerows, irrespective of hedgerow management. BGB:AGB ratios were also found to vary with hedgerow management (Black et al., 2023). In their study, Black et al. (2023) sampled eight hedgerows in Ireland, differing in hedgerow management between regular shaped hedgerows with frequent management and irregular wide hedgerows with less frequent management. The BGB:AGB ratios they measured ranged from 0.16 to 0.74, with higher ratios in more intensely managed hedgerows. Black et al. (2023) thus suggest developing adapted BGB:AGB ratios depending on hedgerow type and management to account for this variability. In addition to the management frequency, management techniques can differ between hedgerows. Besides coppicing, where all AGB is removed, another hedgerow management technique commonly used in the temperate climate zone (nowadays mostly practiced in United Kingdom) is hedge laying. Hedge laying involves removing only part of the AGB and laying selected main shrub stems (pleachers) horizontally on the ground (Staley et al., 2015). This may affect root growth differently and thus also lead to differing BGB:AGB ratios. However, mean C stocks between sites were not significantly different for all C pools in our study. This suggests that for similar hedgerow sites, either the calculated ratios can be applied to obtain robust long-term average BGB estimates depending on the long-term average AGB, or alternatively fixed average AGB and BGB C stocks can be used.

4.3 | Stumps and coarse roots are important biomass C pools of hedgerows

Besides harvestable biomass, coarse roots and stumps were the most important biomass C pools in the sampled hedgerows. The contribution of fine roots to overall C stocks is marginal compared with coarse roots in woody permanent vegetation (Fortier et al., 2013; Martani et al., 2021), although fine roots play an important role in SOC build-up (Rasse et al., 2005). In our study, only 6% of TBC was found in fine roots. This stresses the importance of sampling stumps and coarse roots in hedgerows when estimating their TBC stock, where regular coppicing leads to larger stumps, especially in old hedgerows. It also shows that regular coppicing of hedgerows removes only a small fraction of total biomass based on our data (22% on average). Moreover, the coarse root sampling method is important when evaluating C stocks of tree-based ecosystems: We found that coarse root biomass in hedgerow systems was underestimated systematically when sampled by soil coring. This is in contrast to Addo-Danso et al. (2016) who found no significant differences between coarse root biomass sampled via soil coring and sampled via soil excavation using soil pits in a method comparisons on 11 forest sites. Coarse root C stock derived from soil coring in our study was just 9.4 ± 0.7 Mg ha^{-1} across the three sites (data not shown), compared with 36.0 ± 2.5 Mg ha^{-1} via the soil excavation method, thus underestimating coarse root biomass C stock by 81%.

Their high allocation of biomass below-ground and the high stump biomass due to regular coppicing seem to distinguish hedgerows from other woody vegetation. Surprisingly, with a total average C stock of 264 ± 13 Mg ha^{-1} across the sampled hedgerow sites, the C stored is even higher than the average C stock of forests in Germany of 224 Mg C ha^{-1} (Wellbrock et al., 2017). Thus, planting 1 ha hedgerow can be equally efficient in sequestering C as planting 1 ha forest. For the region of Schleswig-Holstein hedgerows currently comprise around 20% of the terrestrial biomass pool of this region, with forests in Schleswig-Holstein storing around 12 Tg C (Wördehoff et al., 2012). When comparing hedgerows and forests, the contribution of C pools to TBC appears to differ, with more biomass allocated below-ground in hedgerows: Wellbrock et al. (2017) found 53% of the total C stock in the soil including organic layers, 40% in AGB, 6% in BGB and 1% in dead wood averaged across all German forests, compared with a hedgerow C pool distribution of 56% in the soil, 24% in AGB, 16% in BGB and 4% in litter at the three old hedgerow sites sampled in our study (Figure 8).

In our study, all hedgerow C stock estimates are reported in Mg C per hectare of hedgerow to aid comparisons with C stock estimates of other hedgerows and land-use types, for example, forest or cropland. However, in reality, hedgerows are linear features, and thus estimates need to be upscaled based on the area sampled for each C pool. Since it is hard to define the exact hedgerow width, this might result in errors. Hedgerow width can be defined either as the crown width or as the width of the stems at the hedgerow base. In our study, the crown width was about double the width of the stems at the hedgerow base. Thus, C stock of mature tree and harvestable biomass combined would be 66.4 Mg ha^{-1} using

FIGURE 8 Distribution of carbon stocks in above-ground biomass, below-ground biomass and soil (1 m depth) of hedgerows compared with forests and cropland in Mg C ha^{-1}. Hedgerow carbon stock given as a long-term average across the three sampled sites in this study, forest carbon stock as the average of all German forests according to Wellbrock et al. (2017), cropland biomass carbon stock as the average of all German croplands according to Umweltbundesamt (2022), and cropland soil organic carbon stock as the average of the three reference croplands sampled in this study.

minimum stem width for calculations and 29.8 Mg ha^{-1} with maximum crown width, instead of 39.3 Mg ha^{-1} with our medium width definition. This large deviation will not be the case for all hedgerows. For hedgerows which are often trimmed and consist of shrubs only, not including mature trees, crown width and the width of the stems at the hedgerow base will be closer together. However, particularly for hedgerows including mature trees the large difference between crown width and stem width stresses the importance of considering the area to which the C stock refers, for example, when combining area change derived by remote sensing techniques with C stock estimates to calculate C stock change with hedgerow establishment or removal. Our estimates were based on an average hedgerow width, which was defined as the midpoint between the maximum crown width and the minimum stem width. The idea behind the concept of an average hedgerow width is that areas within the hedgerow, which are grown wider (mostly mature trees), balance out with narrower grown areas (Figure S2). Harvestable biomass and biomass of mature trees was calculated directly based on this average width. For all other C pools, the subplot area sampled (e.g. 1 m^2) was upscaled, as the subplots were chosen representatively within the whole hedgerow area with differing vegetation densities. The estimates should thus only be applied to hedgerow area data with the same area definition. Other area definition could, for example, include the whole grassy hedgerow edge or be based on maximum crown width, both leading to lower TBC stocks as compared to our definition.

4.4 | Coarse roots mostly dominant in the topsoil contribute to high C stocks

Both fine and coarse roots were found to a soil depth of 1 m in our study, demonstrating that systems with permanent woody vegetation reach deep soil layers with their roots. However, most of the root biomass C was stored in the topsoil. For coarse roots, 85% of total coarse root C stock and for fine roots 51% of total fine root C stock were found in the topsoil (0–30 cm). This is comparable with other findings for regularly coppiced, permanent woody vegetation: Martani et al. (2021) found that 79% of BGB C stock (including stumps, coarse roots and rhizomes) of black locust, poplar and willow in a short-rotation coppice 11 years after establishment was stored in the topsoil (0–30 cm), whereas only 21% was stored in the subsoil (30–100 cm). These woody plants had particularly high proportions of C stocks in the topsoil compared with herbaceous perennial energy crops of giant reed, miscanthus and switchgrass. For poplar riparian buffers sampled in Canada, 61–73% of coarse root biomass was found in the topsoil (0–20 cm; Fortier et al., 2013). Rooting depths of at least 1 m in the sampled hedgerows demonstrate the need to account for roots at these depths when estimating BGB C stocks. Deep roots play an important role in water and nutrient uptake and SOC storage in deep soil layers (Germon et al., 2020). It is likely that both coarse and especially fine roots exceeded the sampling depth of 1 m. However, since most root C was found in the topsoil, this indicates that the total C pool of hedgerows is marginally underestimated by our sampling depth of 1 m. Fine root biomass C pool at 70–100 cm depth accounted for only 16% of the total fine root biomass C pool and 1% of the TBC pool of the sampled hedgerows. We found a strong alignment between the depth gradient of roots and SOC density (Figure 6), underlining the importance of roots in SOC formation. However, no direct correlation could be found between SOC and fine root biomass C for any sampling depth except the 70–100 cm sampling depth (data not shown). This is probably due to a mismatch in the time when SOC under the hedges had accumulated (centennial) compared with root growth periods (decades).

4.5 | SOC stock change was higher than expected

We found a higher total C sequestration potential, including both soil and biomass C, of hedgerows than previous estimates. In a meta-analysis for temperate climate regions, Drexler et al. (2021) calculated that hedgerows store 104 ± 42 Mg ha^{-1} more C than cropland. The C stock difference in our study was estimated to be 173 Mg ha^{-1} with hedgerow establishment on cropland, although it takes decades to build up this long-term average C stock (Figure 8). The greater C stock difference can be attributed to a larger change in SOC stock. The hedgerows sampled in this study were established almost 300 years ago. Data on hedgerow age were only reported in 55% of the studies included in the study of Drexler et al. (2021), but these hedgerows were much younger, with an average age of 39 years. The high SOC stock change could thus support the hypothesis that hedgerow SOC stock does not reach a new steady state within a few decades, but instead keeps building up SOC over much longer periods. For hedgerows sampled in England aged between 2 and 37 years, SOC storage was found to increase with hedgerow age (Biffi et al., 2022). Although SOC sequestration declined after 37 years, older hedgerows continued to sequester SOC. Moreover, it has to be noted that the sampled sites are so-called ‘Knicks’, where a bank was raised before the hedgerow was planted. To build this hedgebank, usually topsoil and subsoil material from directly adjacent agricultural fields was piled up in combination with the construction of a ditch (Kurz et al., 2011), which could partly contribute to the high SOC accrual. The mean SOC stock of the reference cropland (85 ± 13 Mg ha^{-1}) is in good agreement with data from the German Agricultural Soil Inventory for sites with similar soil properties (Drexler et al., 2022; Poeplau et al., 2020). Besides the higher SOC accrual, the consideration of litter and necromass C stock (totalling 11 ± 2 Mg ha^{-1}/4% of total C stock) also resulted in more C, as this C stock was not accounted for in previous estimates (e.g. Drexler et al., 2021; Golicz et al., 2021). Gross et al. (2022) also highlight the importance of deadwood for C stocks in hedgerows. Their study sampled litter and deadwood separately in five hedgerows in Alberta, Canada, and found that besides litter (2% of total C stock in their study), deadwood also contributed considerably to the total ecosystem C stock with a mean of 7%. In our study, deadwood outside the litter layer was not sampled separately. Deadwood components may thus be included in stump and harvestable biomass.

An additional C stock increase could be achieved in the vicinity of the hedges through root systems exceeding the hedgerows. To obtain a first estimate of this C sequestration potential, coarse roots, the most important additional below-ground C pool, were sampled from six subplots at the hedgerow edge (mostly grassy vegetation in the transition area from the hedgerow to the cropland) and three subplots on cropland directly adjacent to the hedgerow edge. Coarse root biomass C stock declined sharply from within the hedgerow to the hedgerow edge and the adjacent cropland, with a mean C stock across sites of 36.0 ± 2.5 Mg ha^{-1} in the hedgerow, 6.0 ± 4.0 Mg ha^{-1} at the hedgerow edge and 2.2 ± 1.2 Mg ha^{-1} in the cropland directly adjacent to the hedgerow edge (Figure S9). These additional root C stocks that have advanced from the hedgerow can be accounted for as additional C stock with hedgerow establishment. Summed up, an additional coarse root biomass C stock of 0.8 Mg ha^{-1} would be achieved with an average hedgerow width of 5.9 m, assuming an additional edge with a width of 0.5 m and a 1 m cropland strip being influenced by the hedgerow. This additional C stock change is minor compared with the total C stock change of 173 Mg ha^{-1}. However, further studies are needed to better quantify these additional biomass C stocks adjacent to the hedgerows and also further into the adjacent croplands. Besides BGB C stocks, SOC stocks can also be influenced outside but adjacent to the hedgerow area by hedgerow roots and litterfall. Lesaint et al. (2023) found significantly higher topsoil SOC stocks adjacent to hedgerows up to 2 m away from the hedgerow. Pardon et al. (2017) even found SOC contents differ in an agroforestry system compared with a treeless reference up to 30 m from the row of trees.

5 | CONCLUSIONS

Hedgerows are a climate change mitigation measure that offers multiple co-benefits. We quantified all C pools of old hedgerow systems in northern Germany and showed that the biomass C stock of hedgerows is high, indicating a large C sequestration potential with the establishment of hedgerows in agricultural landscapes. Hedgerow TBC stock of the almost 300-year-old hedgerows sampled exceeded the average forest TBC stock potentially due to high light availability, fertilization from adjacent fields and favourable soil conditions. BGB C stocks were particularly important in the sampled hedgerows, indicating that hedgerow plants allocate a greater proportion of biomass below-ground. This potentially increases the resilience of hedgerow ecosystems to disturbances such as drought stress, which is particularly important for adaptation to climate change. On average 63% of the hedgerow biomass was found below-ground and in the stumps. Coarse roots in particular contribute substantially to C storage in hedgerow systems. This demonstrates the need to take these C pools into account and to adapt frequently used BGB:AGB ratios for hedgerow ecosystems. Applying commonly used forest BGB:AGB ratios would have resulted in a strong underestimation of the C stock of the old hedgerows sampled in our study. Our study provides robust estimates of C storage by all hedgerow components. C stocks between sites were not significantly different for all C pools. The estimates can thus be applied to assess C stocks of hedgerows with similar characteristics, including species composition and hedgerow age, and help refine emission factors for both national greenhouse gas reporting and for CO_2 certificates in C farming frameworks. Combined with the identification of changes in the hedgerow area, for example, by remote sensing techniques, these estimates can be used to account for emissions related to the establishment and removal of hedgerows.

AUTHOR CONTRIBUTIONS

Sophie Drexler: Conceptualization; data curation; formal analysis; investigation; methodology; validation; visualization; writing – original draft; writing – review and editing. **Eiko Thiessen:** Conceptualization; data curation; investigation; methodology; validation; writing – review and editing. **Axel Don:** Conceptualization; funding acquisition; investigation; methodology; supervision; validation; writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in zenodo at https://doi.org/10.5281/zenodo.10060735.

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REFERENCES

Addo-Danso, S. D., Prescott, C. E., & Smith, A. R. (2016). Methods for estimating root biomass and production in forest and woodland ecosystem carbon studies: A review. *Forest Ecology and Management*, *359*, 332–351. https://doi.org/10.1016/j.foreco.2015.08.015

Annighöfer, P., Mund, M., Seidel, D., Ammer, C., Ameztegui, A., Balandier, P., Bebre, I., Coll, L., Collet, C. , Hamm, T., Huth, F., Schneider, H., Kuehne, C., Löf, M., Petritan, A. M., Petritan, I. C., Schall, P., & Jürgen, B. (2022). Examination of aboveground attributes to predict belowground biomass of young trees. *Forest Ecology and Management*, *505*, 119942. https://doi.org/10.1016/j.foreco.2021.119942

Axe, M. S., Grange, I. D., & Conway, J. S. (2017). Carbon storage in hedge biomass—A case study of actively managed hedges in England. *Agriculture, Ecosystems & Environment*, *250*, 81–88. https://doi.org/10.1016/j.agee.2017.08.008

Baudry, J., Bunce, R. G. H., & Burel, F. (2000). Hedgerows: An international perspective on their origin, function and management. *Journal of Environmental Management*, *60*(1), 7–22. https://doi.org/10.1006/jema.2000.0358

Biffi, S., Chapman, P. J., Grayson, R. P., & Ziv, G. (2022). Soil carbon sequestration potential of planting hedgerows in agricultural landscapes. *Journal of Environmental Management*, *307*, 114484. https://doi.org/10.1016/j.jenvman.2022.114484

Biffi, S., Chapman, P. J., Grayson, R. P., & Ziv, G. (2023). Planting hedgerows: Biomass carbon sequestration and contribution towards net-zero targets. *Science of the Total Environment*, *892*, 164482. https://doi.org/10.1016/j.scitotenv.2023.164482

Black, K., Lanigan, G., Ward, M., Kavanagh, I., Ó.hUallacháian, D. O., & Sullivan, L. (2023). Biomass carbon stocks and stock changes in managed hedgerows. *Science of the Total Environment*, *871*, 162073. https://doi.org/10.1016/j.scitotenv.2023.162073

Böhm, C., Kanzler, M., & Freese, D. (2014). Wind speed reductions as influenced by woody hedgerows grown for biomass in short rotation alley cropping systems in Germany. *Agroforestry Systems*, *88*, 579–591. https://doi.org/10.1007/s10457-014-9700-y

Burel, F. (1996). Hedgerows and their role in agricultural landscapes. *Critical Reviews in Plant Sciences*, *15*(2), 169–190. https://doi.org/10.1080/07352689.1996.10393185

Cairns, M. A., Brown, S., Helmer, E. H., & Baumgardner, G. A. (1997). Root biomass allocation in the world's upland forests. *Oecologia*, *111*, 1–11. https://doi.org/10.1007/s004420050201

Cardinael, R., Umulisa, V., Toudert, A., Olivier, A., Bockel, L., & Bernoux, M. (2018). Revisiting IPCC tier 1 coefficients for soil organic and biomass carbon storage in agroforestry systems.

Environmental Research Letters, *13*(12), 124020. https://doi.org/10.1088/1748-9326/aaeb5f

Castle, D., Grass, I., & Westphal, C. (2019). Fruit quantity and quality of strawberries benefit from enhanced pollinator abundance at hedgerows in agricultural landscapes. *Agriculture, Ecosystems & Environment*, *275*, 14–22. https://doi.org/10.1016/j.agee.2019.01.003

Chiartas, J. L., Jackson, L. E., Long, R. F., Margenot, A. J., & O'Geen, A. T. (2022). Hedgerows on crop field edges increase soil carbon to a depth of 1 meter. *Sustainability*, *14*(19), 12901. https://doi.org/10.3390/su141912901

Cleugh, H., Prinsley, R., Bird, R. P., Brooks, S. J., Carberry, P. S., Crawford, M. C., Jackson, T. T., Meinke, H., Mylius, S. J., Nuberg, I., Sudmeyer, R. A., & Wright, A. J. (2002). The Australian National Windbreaks Program: Overview and summary of results. *Australian Journal of Experimental Agriculture*, *42*, 649–664. https://doi.org/10.1071/EA02003

Drexler, S., Broll, G., Flessa, H., & Don, A. (2022). Benchmarking soil organic carbon to support agricultural carbon management: A German case study. *Journal of Plant Nutrition and Soil Science*, *185*(3), 427–440. https://doi.org/10.1002/jpln.202200007

Drexler, S., Gensior, A., & Don, A. (2021). Carbon sequestration in hedgerow biomass and soil in the temperate climate zone. *Regional Environmental Change*, *21*(3). https://doi.org/10.1007/s10113-021-01798-8

Drexler, S., Thiessen, E., & Don, A. (2023). Dataset to: Carbon storage in old hedgerows: The importance of below-ground biomass [data set]. *Zenodo*. https://doi.org/10.5281/zenodo.10060735

DWD. (2022). *(Deutscher Wetterdienst), Vieljährige Mittelwerte 1991–2020*. https://www.dwd.de/DE/leistungen/klimadatendeutschland/vielj_mittelwerte.html

European Council. (2022). *'Fit for 55': provisional agreement sets ambitious carbon removal targets in the land use, land use change and forestry sector [Press release]*. https://www.consilium.europa.eu/en/press/press-releases/2022/11/11/fit-for-55-provisional-agreement-sets-ambitious-carbon-removal-targets-in-the-land-use-land-use-change-and-forestry-sector/

Fortier, J., Truax, B., Gagnon, D., & Lambert, F. (2013). Root biomass and soil carbon distribution in hybrid poplar riparian buffers, herbaceous riparian buffers and natural riparian woodlots on farmland. *Springerplus*, *2*(539). https://doi.org/10.1186/2193-1801-2-539

Germon, A., Laclau, J.-P., Robin, A., & Jourdan, C. (2020). Tamm review: Deep fine roots in forest ecosystems: Why dig deeper? *Forest Ecology and Management*, *466*, 118135. https://doi.org/10.1016/j.foreco.2020.118135

Golicz, K., Ghazaryan, G., Niether, W., Wartenberg, A. C., Breuer, L., Gattinger, A., Jacobs, S. R., Kleinebecker, T., Weckenbrock, P., & Große-Stoltenberg, A. (2021). The role of small Woody landscape features and agroforestry Systems for National Carbon Budgeting in Germany. *Land*, *10*(10), 1028. https://doi.org/10.3390/land10101028

Green, S., Martin, S., Gharechelou, S., Cawkwell, F., & Black, K. (2019). *BRIAR: Biomass Retrieval in Ireland Using Active Remote Sensing*. Environmental Protection Agency, Report No. 305, Ireland.

Gross, C. D., Bork, E. W., Carlyle, C. N., & Chang, S. X. (2022). Agroforestry perennials reduce nitrous oxide emissions and their live and dead trees increase ecosystem carbon storage. *Global Change Biology*, *28*(20), 5956–5972. https://doi.org/10.1111/gcb.16322

Haddaway, N. R., Brown, C., Eales, J., Eggers, S., Josefsson, J., Kronvang, B., Randall, N. P., & Uusi-Kämppä, J. (2018). The multifunctional roles of vegetated strips around and within agricultural fields. *Environmental Evidence*, *7*(14). https://doi.org/10.1186/s13750-018-0126-2

IPCC. (2019). In E. Calvo Buendia, K. Tanabe, A. Kranjc, J. Baasansuren, M. Fukuda, S. Ngarize, A. Osako, Y. Pyrozhenko, P. Shermanau, & S. Federici (Eds.), *2019 refinement to the 2006 IPCC guidelines for National Greenhouse gas Inventories*. Published: IPCC.

Kay, S., Rega, C., Moreno, G., den Herder, M., Palma, J. H. N., Borek, R., Crous-Duran, J., Freese, D., Giannitsopoulos, M., Graves, A., & Jäger, M. (2019). Agroforestry creates carbon sinks whilst enhancing the environment in agricultural landscapes in Europe. *Land Use Policy*, *83*, 581–593. https://doi.org/10.1016/j.landusepol.2019.02.025

Kort, J., & Turnock, R. (1999). Carbon reservoir and biomass in Canadian prairie shelterbelts. *Agroforestry Systems*, *44*, 175–186. https://doi.org/10.1023/A:1006226006785

KSG. (2019). Bundes-Klimaschutzgesetz vom 12. Dezember 2019 (BGBl. I S. 2513), das durch Artikel 1 des Gesetzes vom 18. August 2021 (BGBl. I S. 3905) geändert worden ist, (2019).

Kurz, P., Machatschek, M., & Iglhauser, B. (2011). *Hecken. Geschichte und Ökologie. Anlage, Erhaltung und Nutzung*. Leopold Stocker Verlag.

Lesaint, L., Viaud, V., & Menasseri-Aubry, S. (2023). Influence of soil properties and land use on organic carbon storage in agricultural soils near hedges. *Soil Use and Management*, *39*, 1140–1154. https://doi.org/10.1111/sum.12928

Levin, G., Angelidis, I., & Gyldenkærne, S. (2020). Assessment of change in biomass from 2006 to 2014/2015 of non-forest woody vegetation in Denmark. *Technical Documentation. Aarhus University, DCE – Danish Centre for Environment and Energy*, *30*, 34 *Technical Report No. 178*.

Lingner, S., Thiessen, E., Müller, K., & Hartung, E. (2018). Dry biomass estimation of hedge banks: Allometric equation vs. structure from motion via unmanned aerial vehicle. *Journal of Forest Science*, *64*(4), 149–156. https://doi.org/10.17221/152/2017-jfs

Litza, K., Diekmann, M., & Cousins, S. (2019). Hedgerow age affects the species richness of herbaceous forest plants. *Journal of Vegetation Science*, *30*(3), 553–563. https://doi.org/10.1111/jvs.12744

Mader, T. L., Dahlquist, J. M., Hahn, G. L., & Gaughan, J. B. (1999). Shade and wind barrier effects on summertime feedlot cattle performance. *American Society of Animal Science*, *77*, 2065–2072. https://doi.org/10.2527/1999.7782065x

Martani, E., Ferrarini, A., Serra, P., Pilla, M., Marcone, A., & Amaducci, S. (2021). Belowground biomass C outweighs soil organic C of perennial energy crops: Insights from a long-term multispecies trial. *GCB Bioenergy*, *13*(3), 459–472. https://doi.org/10.1111/gcbb.12785

Mayer, S., Wiesmeier, M., Sakamoto, E., Hübner, R., Cardinael, R., Kühnel, A., & Kögel-Knabner, I. (2022). Soil organic carbon sequestration in temperate agroforestry systems—A meta-analysis. *Agriculture, Ecosystems & Environment*, *323*, 107689. https://doi.org/10.1016/j.agee.2021.107689

Mokany, K., Raison, R. J., & Prokushkin, A. S. (2006). Critical analysis of root: Shoot ratios in terrestrial biomes. *Global Change Biology*, *12*(1), 84–96. https://doi.org/10.1111/j.1365-2486.2005.001043.x

Montgomery, I., Caruso, T., & Reid, N. (2020). Hedgerows as ecosystems: Service delivery, management, and restoration. *Annual Review of Ecology, Evolution, and Systematics*, *51*(1), 81–102. https://doi.org/10.1146/annurev-ecolsys-012120-100346

Morandin, L. A., Long, R. F., & Kremen, C. (2014). Hedgerows enhance beneficial insects on adjacent tomato fields in an intensive agricultural landscape. *Agriculture, Ecosystems & Environment*, *189*, 164–170. https://doi.org/10.1016/j.agee.2014.03.030

Pardon, P., Reubens, B., Reheul, D., Mertens, J., De Frenne, P., Coussement, T., Janssens, P., & Verheyen, K. (2017). Trees increase soil organic carbon and nutrient availability in temperate agroforestry systems. *Agriculture, Ecosystems & Environment*, *247*, 98–111. https://doi.org/10.1016/j.agee.2017.06.018

Poeplau, C., Jacobs, A., Don, A., Vos, C., Schneider, F., Wittnebel, M., Tiemeyer, B., Heidkamp, A., Prietz, R., & Flessa, H. (2020). Stocks of organic carbon in German agricultural soils—Key results of the first comprehensive inventory. *Journal of Plant Nutrition and Soil Science*, *1–7*, 665–681. https://doi.org/10.1002/jpln.202000113

Poeplau, C., Vos, C., & Don, A. (2017). Soil organic carbon stocks are systematically overestimated by misuse of the parameters bulk density and rock fragment content. *Soil*, *3*(1), 61–66. https://doi.org/10.5194/soil-3-61-2017

Proe, M. F., Griffiths, J. H., & Craig, J. (2002). Effects of spacing, species and coppicing on leaf area, light interception and photosynthesis in short rotation forestry. *Biomass & Bioenergy*, *23*, 315–326. https://doi.org/10.1016/S0961-9534(02)00060-0

R Core Team. (2023). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/

Rasse, D. P., Rumpel, C., & Dignac, M.-F. (2005). Is soil carbon mostly root carbon? Mechanisms for a specific stabilisation. *Plant and Soil*, *269*(1–2), 341–356. https://doi.org/10.1007/s11104-004-0907-y

RStudio Team. (2020). *RStudio: Integrated development for R*. RStudio, PBC, Boston, MA http://www.rstudio.com/

Sánchez, I. A., Lassaletta, L., McCollin, D., & Bunce, R. G. H. (2010). The effect of hedgerow loss on microclimate in the Mediterranean region: An investigation in Central Spain. *Agroforestry Systems*, *78*(1), 13–25. https://doi.org/10.1007/s10457-009-9224-z

Schlesinger, W. H., & Bernhardt, E. S. (2013). *Biogeochemistry, an analysis of global change* (3rd ed.). Elsevier.

Staley, J. T., Amy, S. R., Adams, N. P., Chapman, R. E., Peyton, J. M., & Pywell, R. F. (2015). Re-structuring hedges: Rejuvenation management can improve the long term quality of hedgerow habitats for wildlife in the UK. *Biological Conservation*, *186*, 187–196. https://doi.org/10.1016/j.biocon.2015.03.002

Umweltbundesamt. (2022). Submission under the United Nations Framework Convention on Climate Change and the Kyoto Protocol 2022. National Inventory Report for the German Greenhouse Gas Inventory 1990–2020. *Climate Change | 25/2022*, 1044.

Van Den Berge, S., Vangansbeke, P., Baeten, L., Vanhellemont, M., Vanneste, T., De Mil, T., Van den Bulcke, J., & Verheyen, K. (2021). Biomass increment and carbon sequestration in hedgerow-grown trees. *Dendrochronologia*, *70*, 125894. https://doi.org/10.1016/j.dendro.2021.125894

Van Den Berge, S., Vangansbeke, P., Baeten, L., Vanneste, T., Vos, F., & Verheyen, K. (2021). Soil carbon of hedgerows and 'ghost' hedgerows. *Agroforestry Systems*, *95*, 1087–1103. https://doi.org/10.1007/s10457-021-00634-6

Viaud, V., & Kunnemann, T. (2021). Additional soil organic carbon stocks in hedgerows in crop-livestock areas of western France. *Agriculture, Ecosystems & Environment*, *305*, 107174. https://doi.org/10.1016/j.agee.2020.107174

Walter, K., Don, A., Tiemeyer, B., & Freibauer, A. (2016). Determining soil bulk density for carbon stock calculations: A systematic method comparison. *Soil Science Society of America Journal*, *80*(3), 579–591. https://doi.org/10.2136/sssaj2015.11.0407

Wellbrock, N., Grüneberg, E., Riedel, T., & Polley, H. (2017). Carbon stocks in tree biomass and soils of German forests. *Central European Forestry Journal*, *63*, 105–112. https://doi.org/10.1515/forj-2017-13

Wördehoff, R., Spellmann, H., Evers, J., Aydın, C. T., & Nagel, J. (2012). *Kohlenstoffstudie Forst und Holz Schleswig-Holstein*. Nordwestdeutsche Forstliche Versuchsanstalt.

Xing, D., Bergeron, J. A. C., Solarik, K. A., Tomm, B., Macdonald, S. E., Spence, J. R., & He, F. (2019). Challenges in estimating forest biomass: Use of allometric equations for three boreal tree species. *Canadian Journal of Forest Research*, *49*(12), 1613–1622. https://doi.org/10.1139/cjfr-2019-0258

Zellweger, F., Flack-Prain, S., Footring, J., Wilebore, B., & Willis, K. J. (2022). Carbon storage and sequestration rates of trees inside and outside forests in Great Britain. *Environmental Research Letters*, *17*(7). https://doi.org/10.1088/1748-9326/ac74d5

Zianis, D., Muukkonen, P., Mäkipää, R., & Mencuccini, M. (2005). Biomass and stem volume equations for tree species in Europe. *Silva Fennica Monographs*, *4*, 1–63. https://doi.org/10.14214/sf.sfm4

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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