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The Role of Small Woody Landscape Features and Agroforestry Systems for National Carbon Budgeting in Germany

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Abstract: The intensification of food production systems has resulted in landscape simplification, with trees and hedges disappearing from agricultural land, principally in industrialized countries. However, more recently, the potential of agroforestry systems and small woody landscape features (SWFs), e.g., hedgerows, woodlots, and scattered groups of trees, to sequester carbon was highlighted as one of the strategies to combat global climate change. Our study was aimed to assess the extent of SWFs embedded within agricultural landscapes in Germany, estimate their carbon stocks, and investigate the potential for increasing agroforestry cover to offset agricultural greenhouse gas (GHG) emissions. We analyzed open-source geospatial datasets and identified over 900,000 hectares of SWFs on agricultural land, equivalent to 4.6% of the total farmland. The carbon storage of SWFs was estimated at 111 ± 52 SD teragrams of carbon (Tg C), which was previously unaccounted for in GHG inventories and could play a role in mitigating the emissions. Furthermore, we found cropland to have the lowest SWF density and thus the highest potential to benefit from the implementation of agroforestry, which could sequester between 0.2 and 2 Tg of carbon per year. Our study highlights that country-specific data are urgently needed to refine C stock estimates, improve GHG inventories and inform the large-scale implementation of agroforestry in Germany.

Keywords: CORINE; Copernicus land monitoring service; carbon sequestration; biomass carbon stock; agroforestry

1. Introduction

Globally, the contribution of the land sector (i.e., Agriculture, Forestry, and Other Land Uses, or AFOLU) is estimated to account for 25% (10–12 Pg) of the net anthropogenic greenhouse gas (GHG) emissions, with approximately 50% arising directly from agriculture [1]. Unless these are substantially reduced, the world will fail to meet the Paris Agreement's target of limiting the increase in average global temperatures to less than 2 °C, relative to pre-industrial levels [2].

The Federal Republic of Germany was one of the first countries to develop a long-term action plan for a low carbon economy and is considered a pioneer in this transition [3]. In their updated Climate Change Act from 2021 [4], the German government stated the ambitious goals of reducing 65% of GHG emissions by 2030, reducing 80% of GHG emissions by 2040, and achieving GHG neutrality by 2045. In 2019, farming contributed 61.8 Tg of carbon dioxide equivalents [5], or 8% of the total GHG emissions in Germany [6]. To address this challenge, new plans for AFOLU sectors include the support for carbon sinks in soils and forestry-related ecosystem services [7]. Germany completed its first agricultural topsoil inventory in 2018 and estimated the mean SOC stocks for croplands (61 ± 25 Mg ha^{-1}), grasslands (88 ± 32 Mg ha^{-1}), and plantation crops, i.e., orchards and vineyards (62 ± 25 Mg ha^{-1}) [8]. Other than these main land use types, we have limited information on the carbon storage potential of emerging land use systems such as agroforestry and interspersed landscape components such as hedges and small woody patches. Increasing recognition by the international community of their potential to contribute to climate change mitigation has led to increased efforts by researchers to quantify their C sequestration potential. However, this remains difficult due to multiple methodological challenges associated with the large-scale assessment of biomass-associated C stocks across heterogeneous landscapes (e.g., [9]).

Farmland including tree biomass (broadly defined as agroforestry) was quantified for the first time by Zomer et al. (2009) [10] and resulted in a major revision to estimates of the C storage potential of agricultural landscapes. This initial approach was subsequently refined in [11], resulting in the global farmland carbon pool estimates of 45.3 and 47.4 Pg C for the years 2000 and 2010, respectively, which were significantly higher than the baseline (11.1 Pg C) stipulated by the Intergovernmental Panel on Climate Change (IPCC). The estimates of Zomer et al. (2016) [11] were based on broad assumptions (e.g., a linear increase in C stock with increasing percentage of tree cover), but they successfully highlighted the importance of accounting for farmland trees and agroforestry systems.

In Europe, the intensification of food production has resulted in trees disappearing from agricultural landscapes [12,13]. Traditional agroforestry systems such as 'knicks' (shelterbelts of Northern Germany), 'pré-vergers' (French orchard intercropping), and 'dehesas' (Spanish oak-dominated grazed woodlands) were modified to a large extent to accommodate forms of agricultural management that draw on mechanization and low landscape complexity to remain profitable [12]. Several recent meta-analyses have found significantly higher levels of soil carbon under agroforestry compared to agricultural systems without trees [14–17]. This highlights the potential for additional carbon sequestration through agroforestry, particularly when land area is considered. Agricultural land accounts for 39% of the total European Union's land area, whereas less than 10% is under forestry [18,19]. The remaining small woody landscape features (SWFs), or agroforests as defined by Plieninger (2011) [20]—i.e., hedgerows, isolated trees, riparian woodlands, scattered fruit trees, tree rows, and woodlots—were identified as providing numerous ecosystem functions and services, including C sequestration. Both SWFs and actively managed agroforestry systems play roles in GHG budgeting [21,22]. However, fundamental information regarding their extent and C dynamics is lacking [20].

Factors such as local climate and soil conditions [23], land use history [24], tree density and species, and farm management practices (e.g., frequency of harvesting and pruning) [25] influence the rate and extent to which trees on farms contribute to the sequestration and storage of above-ground and below-ground C. In order to better account for some of these factors, Cardinael at al. (2018) [26] carried out a rigorous literature review to develop coefficients for land use conversion and biomass increments across different climatic regions and agroforestry classes. These coefficients served to refine Tier 1 IPCC Good Practice Guidance [27] on inventorying and reporting GHG emissions but have yet to be widely adopted in practice.

Since no previous assessment of the total contribution of SWF to the carbon storage of German agricultural landscapes was carried out, we propose a novel methodology based on publicly accessible datasets. The methodology can be easily reproduced and replicated, thus constituting a valuable tool to improve current assessments at the pan-European scale and to monitor the development of carbon storage in SWFs over time. This paper was aimed to (1) carry out a national level assessment of the extent and C stock of small woody landscape features (trees and shrubs present on agricultural land) across Germany and (2) apply the updated IPCC coefficients [26] to estimate the carbon sequestration potential of the increased adoption of agroforestry across the country.

We used datasets produced by Copernicus Land Monitoring Service [28] such as the novel Copernicus Small Woody Features 2015 dataset [29], as well as the CORINE Land Cover produced by the Federal Agency for Cartography and Geodesy (BKG), to (i) estimate the extent of small woody landscape features embedded in the agricultural landscape mosaic, (ii) improve estimates of carbon storage of agricultural landscapes by accounting for and quantifying C stocks of small woody landscape features, and (iii) create scenarios to estimate the potential of agroforestry systems to sequester C using the updated IPCC guidelines [26].

2. Materials and Methods

2.1. Conceptual Approach

In this work, we adopted the IPCC Tier 1 approach with default carbon storage values for given land cover types where country-specific biomass data and emission/removal factors were not available [27] to estimate carbon stocks in German SWFs and quantify the carbon sequestration potential of the widespread implementation of agroforestry, i.e., hedgerows (shelterbelts), silvoarable systems, and silvopastoral systems. The steps comprised (1) defining the extent of SWFs across Germany; (2) deriving national-level biomass C estimates through a literature review; (3) estimating the C stocks in above-ground biomass, below-ground biomass, and SOC in accordance with the IPCC methodology; and (4) estimating the potential contribution of agroforestry implementation to agricultural C budget in countrywide land use scenarios.

2.2. Data Collection and Geoprocessing

Two publicly available datasets were integrated to map tree and shrub extent over large scales in agricultural areas in Germany. First tree and shrub cover were extracted from the satellite-based Copernicus Small Woody Features 2015 dataset [29], which delineates SWF structures based on the following specifications: a maximum width of 30 m and a minimum length of 50 m for linear features and a minimum and maximum area of 200 and 5000 m^2, respectively, for patches and additional features. Second, agricultural areas were extracted from the CORINE Land Cover 5 ha CLC5 (2015) product by the German Federal Agency for Cartography and Geodesy [30]. We only accounted for SWFs on agricultural land, excluding urban areas or other open vegetation.

Our estimates were based on detailed vector layers, which distinguish small woody features into three distinct land cover classes based on geometric characteristics (linear, patchy, and additional; Figure 1) whereas the publicly available raster-based product only separates between two classes (linear and patchy). After visual inspection of the dataset and comparison with a high-resolution base map, the additional woody feature class was also included in the framework. This class includes woody elements that were identified by the pre-classification but did not satisfy all geometric requirements. The additional woody feature class is still connected to a valid SWF or have an area higher than 1500 m^2 [20]. As the class represents meaningful features that are neither linear nor patchy, it was included to avoid the underestimation of the carbon stocks. Our vector layers were rasterized and overlaid with relevant CORINE land cover classes, i.e., non-irrigated arable land (in 'Cropland', CORINE Code 211); pastures, meadows, and other permanent grasslands under agricultural use ('Grassland', Code 231); vineyards (Code 221); and fruit tree and berry plantations ('Orchard', Code 222) [30].

Figure 1. Three classes of small woody landscape features, i.e., linear, patchy, and additional, embedded within agricultural landscapes.

Prior to the analysis, all datasets were reprojected to EPSG 25832 and resampled to a 5 m resolution. Total land cover area and/or hedgerow length were estimated for 16 distinct land use classes, which were based on the combination of the four CORINE land cover classes and the four woody landscape feature classes (three SWF classes and the 'no SWF' class) that were identified within each of the CORINE class. We used the raster calculator in QGIS 3.6 [31], and the data were tabulated using the rasterDT package (Ver. 0.3.1) [32] using R Statistical Software (Ver. 4.1) [33]. To assess the spatial patterns of SWFs, the CORINE 2015 dataset was compared against the CORINE 2015 dataset with the SWF dataset using command 'lsp_compare' of the R package 'motif' (Ver. 0.4.3) [34]. The window size was 500 m, and the distance function was 'Jensen–Shannon' with dissimilarity ranging between 0 (low change) and 1 (high change). We analyzed the datasets at the scale of pedoclimatic regions (BKR: Boden–Klima–Räume [35]) of Germany to understand the spatial patterns and abundance of existing SWFs.

2.3. Calculations of Biomass Carbon Stocks

To estimate carbon stored in SWF biomass, we referred to the Framework for Data-Deficient Areas formulated by Willcock et al. (2012) [36], and we used regionally appropriate carbon estimates derived from the literature (Table 1). The literature search was limited to central Europe, with focus on Germany. The hedgerow biomass was adapted from Drexler et al. (2021) [37] as a proxy for all linear SWFs, values for orchards were adapted from Strohbach and Haase, (2012) [38] and values for vineyards were adapted from the IPCC report (2019) [27]. The steps taken to estimate total biomass carbon (TBC) in non-linear (patchy and additional) SWF structures in cropland and grassland landscape matrices were as follows:

- Identify the above-ground (ABG) C stock in German temperate forests based on information from the National Forest Inventory (C stock equal to 103 Mg C ha^{-1} [39]).
- Adopt the IPCC (2006) assumption used to develop the GLC2000 Class 17: Forest/Cropland Mosaic [40] and assume an ABG C stock loss equal to 50% of the total ABG C stock of German temperate forests [41].
- Assume further losses due to disturbance and/or harvest equal to 50% of the maximum ABG C in accordance with the IPCC Tier 1 assumption for agroforestry systems [27].

- Calculate carbon in below-ground (BLG) biomass as a fraction (0.23 ± 75%) of the mean ABG carbon [37].
- Sum up ABG C stock and BLG C stock to obtain TBC stock [37].

Table 1. Biomass carbon stock estimates (mean ± SD) established for SWFs and agricultural systems including cropland, grassland, and permanent crops (vineyards and orchards). ABG—above-ground, BLG—below-ground, TBC—total biomass carbon.

SWF Structure/ Agricultural System	Maximum ABG C Stock	Mean ABG C Stock	Mean BLG C Stock	Mean TBC Stock	Literature
			Mg C ha^{-1}		
Linear [1]	-	24.0 ± 15.0	22.0 ± 14.0	46.0 ± 29.0	[37]
Patchy and additional	52.0 ± 37.0	26.0 ± 19.0	6.0 ± 4.0	32.0 ± 23.0	Own estimation
Cropland	-	-	-	5.0	[42]
Grassland	-	-	-	7.0	[42]
Vineyard	5.5 ± 0.99	2.8 ± 0.5	0.6 ± 0.5	3.4 ± 0.7	[27]
Orchard	16.0 ± 3.6	8.0 ± 1.8	1.8 ± 1.5	9.8 ± 2.3	[38]

[1] For linear features, the mean ABG and BLG were available from literature, with an expected 50% loss of biomass applied in accordance with the IPCC Tier 1 assumption for the agroforestry systems [27].

2.4. Calculations of the Soil Carbon Stocks

The SOC (soil depth of 0–30 cm) for linear SWFs was adopted from Drexler et al. (2021) [37], based on findings by Axe et al. (2017) [43]. The SOC (0–30 cm) for patchy and additional SWFs on cropland was estimated by applying the same TBC-to-SOC (21:4) ratio established by Drexler et al. (2021) [37]. The empirically derived SOC data (0–30 cm) for cropland, grassland, orchard, and vineyard systems were adapted from the Thünen Report 64 [8]. The SWF SOC stocks were assumed to be 17 ± 12 Mg C ha^{-1} (linear SWFs) [24] and 10 ± 8 Mg C ha^{-1} (patchy and additional SWFs) higher relative to the SOC stocks established for cropland, orchard, and vineyard systems. No change in SOC for SWFs on grassland was assumed based on findings by Drexler et al. (2021) [37] and Cardinael et al. (2018) [26]. For a detailed breakdown of values, see Appendix A (Table A1).

2.5. Agroforestry Scenarios

In addition to the assessment of the current extent of SWF cover present on farmland and the estimation of their biomass carbon stock, we estimated the potential increase in carbon sequestered by the widespread uptake of agroforestry practices due to the inclusion of trees and shrubs in agricultural land. The potential C sequestration (in ABG, BLG, and SOC) was estimated for three scenarios under which (i) 1%, (ii) 5%, and (iii) 10% of the total amount of croplands, grasslands, vineyards, and orchards in Germany were converted into agroforestry. To develop the land use scenarios, we followed the updated IPCC report (2019) which differentiates between 5 temperate agroforestry systems:

- Hedgerows: linear plantation around fields, including shelterbelts, windbreaks, boundary plantings, and live fences (tree density = 816 stems km^{-1}).
- Silvoarable systems: woody species planted in parallel tree rows to allow for mechanization and intercropped with an annual crop; usually used for timber; low tree density per hectare (tree density = 202 stems ha^{-1}).
- Silvopastoral systems: woody species planted on permanent grasslands, often grazed (tree density = 854 stems ha^{-1}).
- Orchard systems: land planted with woody vegetation, often fruit trees. Understory vegetation is usually mowed or grazed (tree density = N/A).
- Vineyard systems: a plantation of vines, typically producing grapes used for winemaking, but also kiwifruit or passionfruit (tree density = N/A).

The IPCC (2019) agroforestry system definitions and coefficients, alongside their confidence intervals for silvoarable and silvopastoral systems, were used to estimate the potential for C sequestration in ABG biomass, BLG biomass, and SOC (Table A2). The C sequestration rate (ABG biomass, BLG biomass, and SOC) for hedgerows was adapted from the work of Drexler et al. (2021) [37] to reflect country-specific and land-use-specific conditions.

3. Results

3.1. Estimation of the Extent of SWFs

Small woody landscape features in Germany were found to cover 906,243 ha (2.5% of the total land area) across four agricultural systems (Table 2). Grassland systems contributed the greatest acreage of SWFs (517,619 ha or 57% of the total SWF area). Cropland systems had the lowest SWF cover relative to their size (366,678 ha or 2.8% of the total arable area), and orchard systems had the highest (17,528 ha or 9.0% of the total orchard system area). The vineyard systems contributed an SWF cover of 4423 ha (3.5% of the total vineyard area).

Table 2. Total area (ha), agricultural area without SWF (small woody landscape feature) cover (ha), SWF area (ha), and proportion of SWF cover (%) of four agricultural systems across Germany (including CORINE codes).

Agricultural System	Total Area (ha)	Area (No SWFs) (ha)	SWF Area (ha)	SWF Cover (%)
Cropland (211)	12,880,136	12,513,463	366,672	2.8
Grassland (231)	6,433,403	5,915,784	517,619	8.0
Vineyard (221)	127,033	122,610	4423	3.5
Orchard (222)	195,770	178,241	17,528	9.0
Total	**19,636,342**	**18,730,098**	**906,243**	**4.6**

The distribution of SWFs and the distribution of the four agricultural systems, i.e., cropland, grassland, and permanent crops (vineyards and orchards) were found to differ between 50 pedo-climatic regions in Germany (Figure 2). Linear SWFs were the most abundant (520,204 ha), followed by additional (356,164 ha) and patchy SWFs (29,875 ha). The spatial configuration of linear > additional > patchy SWFs was identified for every agricultural system.

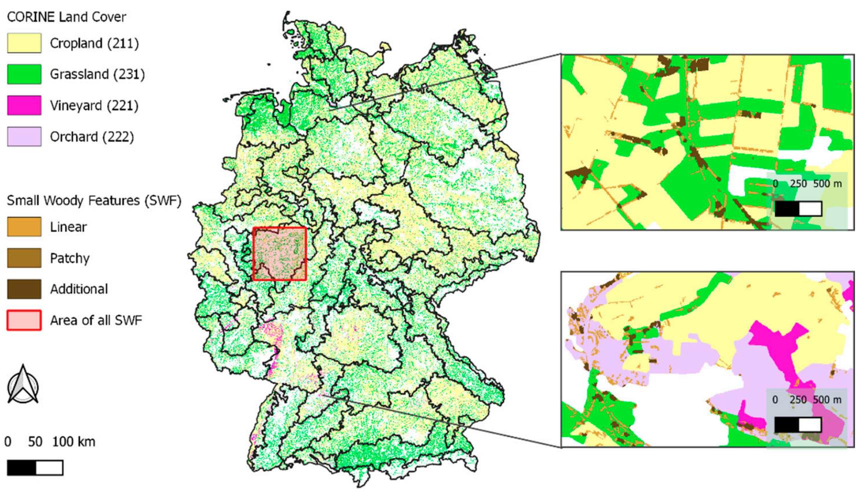

Figure 2. Distribution of SWFs (small woody features) across four agricultural systems. Linear SWFs covered the largest area, and patchy SWFs covered the least. The virtually superimposed red square denotes the total area covered by SWFs relative to the size of Germany. BKR = Boden–Klima–Räume (pedo-climatic regions). Data sources: GeoBasis-DE/BKG (Bundesamt für Kartographie und Geodäsie) CORINE Land Cover 5 ha CLC5 (2015), 2021; Copernicus Land Monitoring Service—High Resolution Layer Small Woody Features—2015 reference year, 2021.

The pedoclimatic regions in the south and north-east had the lowest SWF cover (0–3%) (Figure 3A). These regions were dominated by cropland (Figure 2). The pedoclimatic regions in the northwest dominated by grasslands had the highest SWF cover (7–8%) (Figure 3A). Landscape structural change, i.e., increasing structural complexity arising from variable SWF cover, was primarily observed in the south, south-west, and central-east, i.e., the areas south of Berlin and north of Leipzig and Dresden, of the country (Figure 3B).

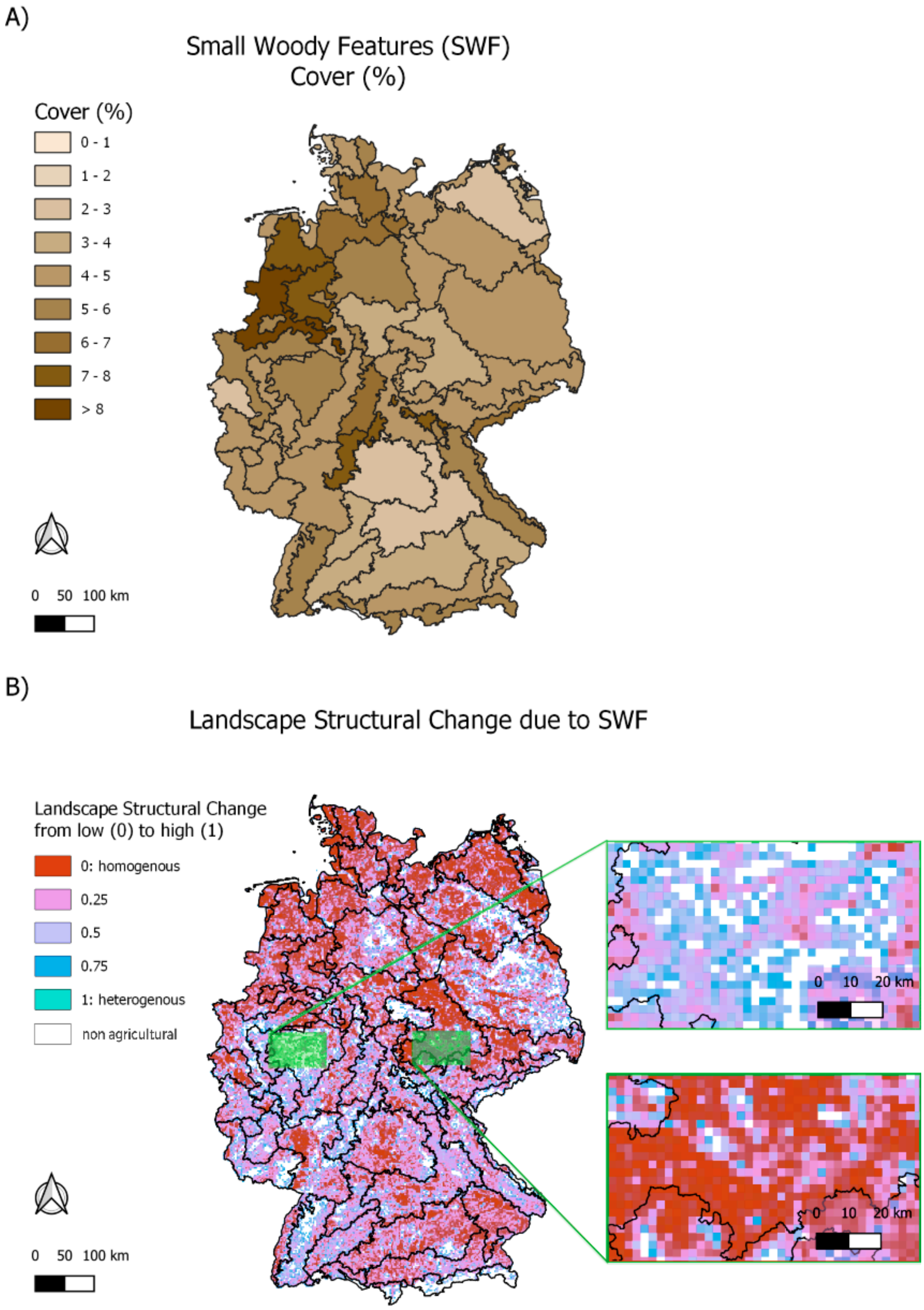

Figure 3. Density of SWFs (small woody landscape features) across 50 growing regions (BKR = Boden–Klima–Räume) (**A**). Landscape structural change arising from inclusion of small woody features (linear, patchy, and additional) into agricultural land use maps (CORINE) (**B**). Data sources: GeoBasis-DE/BKG (Bundesamt für Kartographie und Geodäsie). CORINE Land Cover 5 ha CLC5 (2015), 2021; Copernicus Land Monitoring Service—High Resolution Layer Small Woody Features—2015 reference year, 2021.

3.2. Quantification of C Stocks of Small Woody Landscape Features

The total C stock of SWFs across Germany was estimated at 111.1 ± 52.5 Tg, with a TBC of 36.3 ± 22.2 Tg and an SOC of 74.8 ± 30.3 Tg. The total SWF C stock constituted 7.9% of the total C stock of agricultural landscapes (Table 3). The SWF TBC was equal to 24% of the estimated annual biomass carbon in cropland systems and half of the herbaceous TBC of grassland systems. The absolute SWFs' TBC was the highest for grassland systems at 20.6 ± 11.9 Tg and second highest (after orchard systems) when considered as a share of all carbon pools combined (SWF TBC = 3% and SWF SOC = 7%) (Figure 4). In cropland and vineyard systems, the SWFs TBC stock constituted 2% of their overall carbon pool and SOC constituted 3% and 4%, respectively.

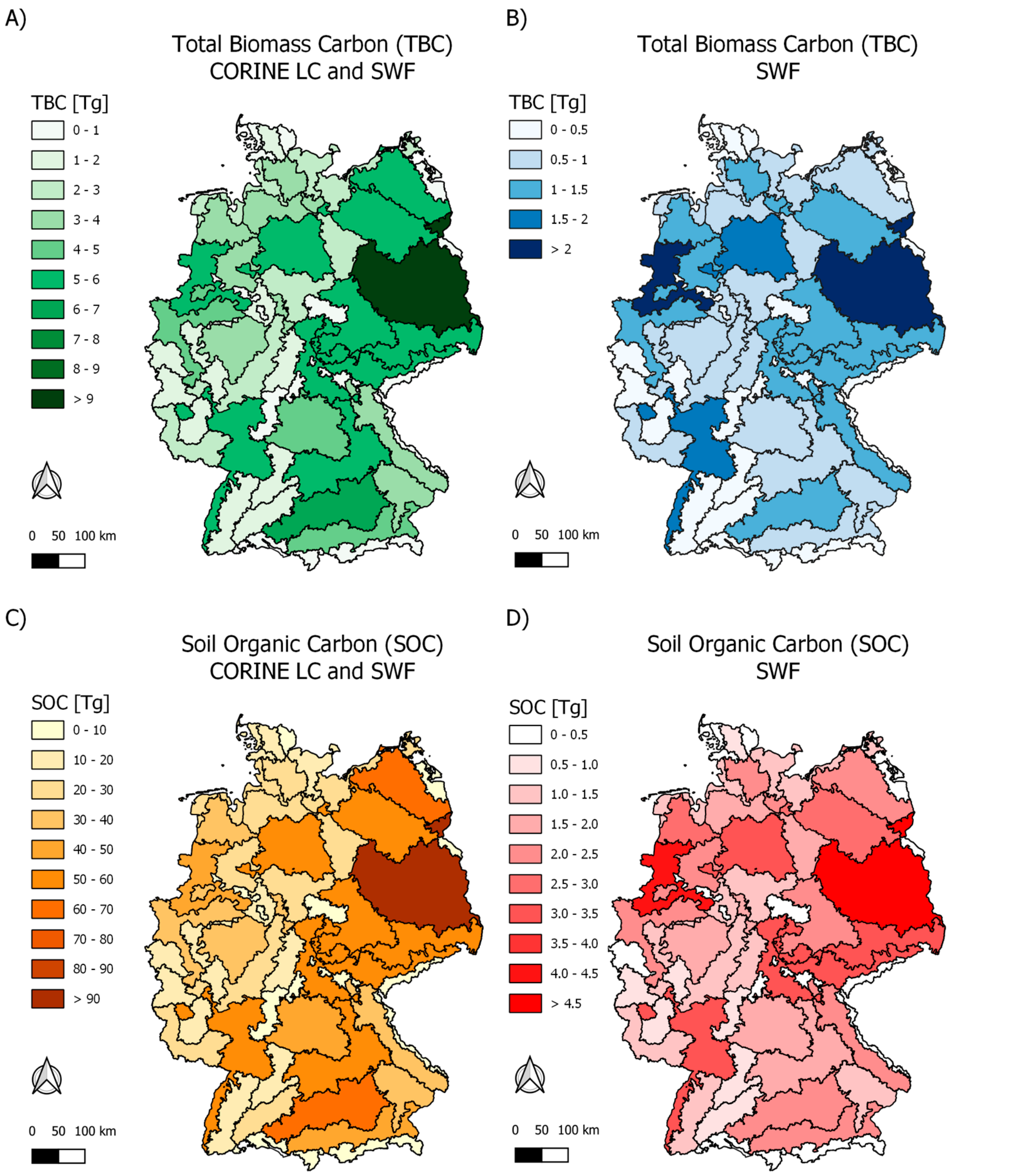

Figure 4. The estimated TBC stock for agricultural land use with SWFs (**A**) and SWF only (**B**); the estimated SOC stock for agricultural land use with SWFs (**C**) and SWF only (**D**). Data sources: Copernicus Land Monitoring Service—High Resolution Layer Small Woody Features—2015 reference year, 2021.

Table 3. Revised carbon stocks (±SD; in Tg C) in Germany after the inclusion of the total biomass carbon stock (TBC, in Tg C) of herbaceous vegetation (including crops), perennial crops, and SWFs. SOC—soil organic carbon, SWF—small woody landscape feature. Numbers refer to CORINE codes.

Agricultural System	SOC	Other TBC [1]	SWF TBC	SWF SOC	Revised C Stocks
			Tg C		
Cropland (211)	763.3 ± 312.8	62.6 ± 46.9	14.8 ± 9.7	27.6 ± 13.0	868.3 ± 382.5
Grassland (231)	520.6 ± 189.3	41.4 ± 31.1	20.6 ± 11.9	45.6 ± 16.6	628.1 ± 248.8
Vineyard (221)	7.6 ± 3.1	0.4 ± 0.1	0.2 ± 0.1	0.3 ± 0.2	8.5 ± 3.4
Orchard (222)	11.1 ± 4.5	1.7 ± 0.4	0.7 ± 0.4	1.3 ± 0.6	14.8 ± 5.9
Total (Tg C)	**1302.6 ± 510**	**106.1 ± 78.5**	**36.3 ± 22.2**	**74.8 ± 30.3**	**1519.8 ± 640.6**

[1] Herbaceous biomass C stocks: 5 Mg C ha^{-1} and 7 Mg C ha^{-1} for cropland and grassland systems, respectively; perennial crop C stocks: 3.4 Mg C ha^{-1} and 9.8 Mg C ha^{-1} for vineyards and orchards, respectively.

The regions with the highest total agricultural area had the highest crop and herbaceous TBC and SOC (Figure 4A–C). The TBC of small woody landscape features constituted a substantial input into the living biomass carbon stocks of agricultural landscapes (Figure 4B), whereas the SWF SOC pools were negligible relative to SOC pools of cropland and grassland systems (Figure 4D).

Overall, the inclusion of SWF C stock (TBC and SOC) in agricultural systems (Figure 5) increased the estimated carbon storage of cropland systems by 4.9% (42 Tg C), grassland systems by 10.5% (66 Tg C), orchard systems by 13.7% (2 Tg C), and vineyard systems by 6.0% (1 Tg C). The contribution of Other TBC sources (herbaceous biomass (i.e., crop and grass) and woody biomass (i.e., perennial crops in vineyard and orchard systems)) ranged from 5 to 12%.

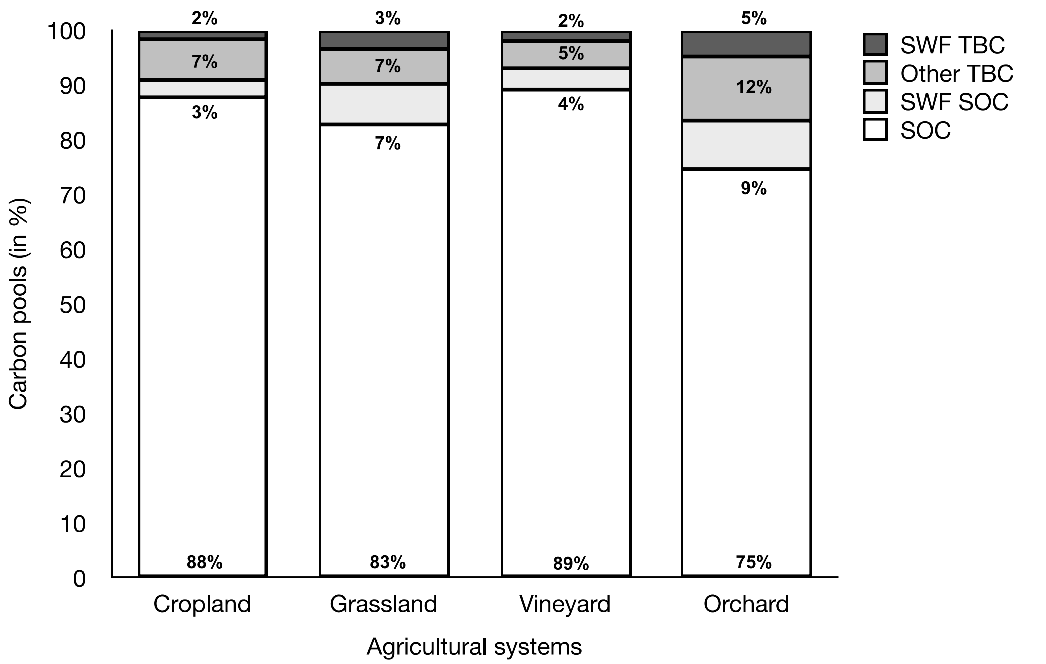

Figure 5. Relative contribution of the components to total carbon pools in four agricultural systems. 'Other TBC' refers to annual crop TBC in arable systems, herbaceous TBC in grassland systems, and woody (not SWF) TBC in vineyard and orchard systems.

3.3. The Carbon Benefit of Implementing Agroforestry Practices across Germany

A modest increase (1%) in Germany's cropland converted to either hedgerow or silvoarable systems with an average tree density of 8070–13,931 stems ha^{-1} [24]; based on [28] or 202 (±269) stems ha^{-1} [26], respectively, could result in a maximum C sequestration (in TBC and SOC) ranging from 0.1 to 14.0 Tg C across their expected maturity cycle (30 years) (Table 4). In the 1% land conversion scenario, the installation of hedgerows, i.e., the hypothetical conversion of a full ha of land into hedgerow, were found to be equivalent to the installation of 7,820,915 km of hedgerows with an average width of 4 m. The installation of hedgerows resulted in the highest C gains (14 ± 11 Tg C), followed by the conversion of cropland to silvoarable systems (6.0 ± 3.3 Tg C). The planting of hedgerows on grasslands yielded similar C gains (6.0 ± 5.0 Tg C) to the conversion to silvopastoral systems (5.5 ± 3.1 Tg C). The existing perennial systems, i.e., orchards and vineyards, were found to derive only a minor additional C benefit (0.1 ± 0.1 and 0.2 ± 0.2 Tg C ha^{-1}, respectively) from the installation of hedgerows. In the remaining scenarios, the carbon sequestration potential was found to increase by factors of 5 and 10.

Table 4. Carbon sequestration potential (in total biomass carbon and soil organic carbon) in Germany for three land conversion scenarios (mean ± 95% CIs; from [26]). Numbers refer to CORINE codes.

		Land Converted		
Agricultural System	**Target Agroforestry System**	**1%**	**5%**	**10%**
		C Sequestration Potential (Tg C) over 30 Years		
Cropland (211)	Hedgerow	14 ± 11	73 ± 55	143 ± 107
	Silvoarable	6.0 ± 3.3	30.2 ± 16.4	60.4 ± 32.9
Grassland (231)	Hedgerow	6 ± 5	34 ± 25	62 ± 47
	Silvopastoral	5.5 ± 3.1	27.5 ± 15.7	55.0 ± 31.3
Vineyard (221)	Hedgerow	0.1 ± 0.1	0.7 ± 0.5	1.4 ± 1
Orchard (222)	Hedgerow	0.2 ± 0.2	1.1 ± 0.8	2.0 ± 1.5

Each land conversion scenario resulted in a positive impact on the carbon sequestration potential of agricultural landscapes across Germany relative to annual carbon emissions estimated at 61.8 Tg C in 2019 (Figure 6). In the 1% land conversion scenario, the amount of additional land to be converted in each farming system was found to be lower than the amount of land currently covered by SWFs. The potential for C sequestration ranged between 0.005 Tg C (vineyard systems with hedgerows) and 0.5 Tg C yr^{-1} (cropland systems with hedgerows). The implementation of hedgerows could sequester between 0.5 and 4.8 Tg C yr^{-1} across three scenarios for cropland systems and between 0.2 and 2 Tg C yr^{-1} for grassland systems. The conversion of cropland to silvoarable systems could sequester between 0.2 and 2 Tg C yr^{-1}, and the conversion of grassland to silvopastoral systems could sequester between 0.2 and 1.8 Tg C yr^{-1}. Orchard and vineyard systems occupy limited land area, and any increase in C sequestered by hedgerows would be negligible on a national level.

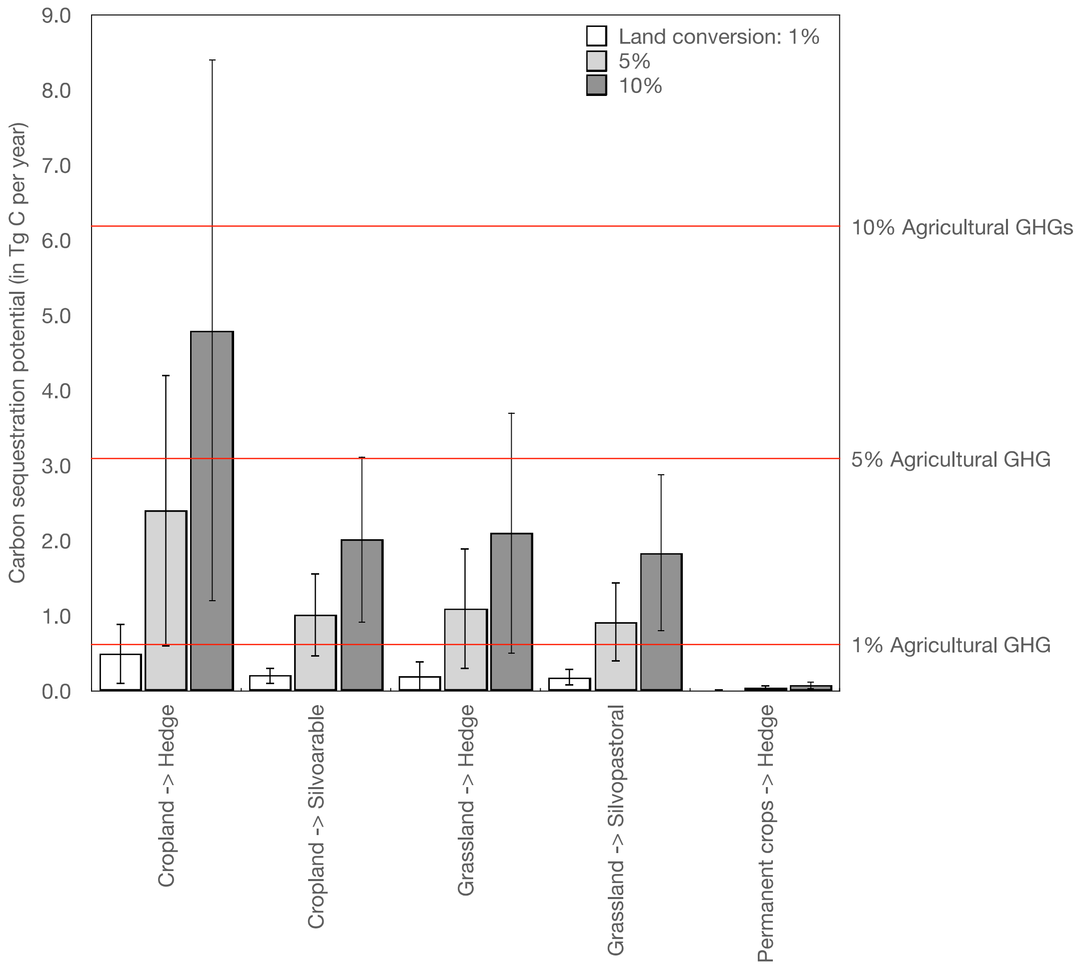

Figure 6. The potential of agroforestry systems to sequester carbon (in Tg yr^{-1}) according to three land conversion scenarios. Red lines denote the percentages of the 2019 agricultural GHG emissions baseline in Germany (61.8 Tg C yr^{-1}) for comparison purposes [5].

4. Discussion

4.1. The Extent of SWFs in Germany

The nationwide assessment of SWFs resulted in the identification of 906,243 ha of wooded land across German cropland, grassland, vineyards, and orchards. The SWF area was found to be equivalent to 4.6% of the total farmland area, a value three times lower than the European mean tree cover estimates (14.5%) put forward by Zomer et al. (2009) [10]. This difference could be attributed to the used dataset resolution, i.e., the 1 km^2 used by Zomer et al. (2009), whose calculations were based on 500 m tree cover map by [44] compared to 5 m^2 in the present study, which was based on the high-resolution SWF Copernicus product [29]. We note the difference in methodological approaches, i.e., tree cover per pixel vs. total SWFs cover derived from accurately delineated objects. While the work of Zomer et al. (2009) was a benchmark study to show the importance of agroforestry at a global scale, we showed that high-resolution data are required for accurate national monitoring and reporting.

Our findings identified grassland and orchard systems as having the highest SWF cover, which is consistent with previous studies that found European agroforestry to be dominated by grazed woodlands and grasslands with sparse trees [45] and consistent with cropland management practices that favor landscape homogenization [46].

Linear SWFs were the most frequently encountered spatial SWF arrangement, covering over 520,000 ha across the country. In a former assessment, den Herder et al. (2017) [45] estimated their extent across Germany at 73,000 ha. Their estimates were derived from the

Land Use and Land Cover (LUCAS) data, and which has been shown to underestimate the hedgerow extent. In the UK, for example, 456,000 ha of hedges was recorded during the Countryside Survey (2007) in England and Wales alone [47], as opposed to the 240,000 ha reported by den Herder et al. (2017) for the entire country [45].

In addition to the linear SWFs, the additional and patchy SWFs, which comprise groups of trees, abandoned farmland encroached by trees and shrubs (including abandoned permanent crop fields), grazed woodlots, and forest fragments, were found to cover close to 390,000 hectares across the agricultural landscape in Germany. These structures are often studied for their contribution to biodiversity conservation [48–51], but no methodology for assessing of their extent across Europe has been developed. We highlight their abundance within German landscapes and note the lack of fundamental information including tree density, stand age, and the contribution of the understory to the carbon storage of SWF structures that warrant further investigation.

4.2. The Estimated Carbon Storage Potential of SWFs

We showed that the living biomass and soils of SWFs are important carbon stocks in German agricultural landscapes. Although SWFs cover only 4.6% of the agricultural area, they contribute 7.3% (111 $\pm$ 52 SD Tg) to the total agricultural TBC and SOC stocks. In contrast to cropland, the SWF soil carbon stock is not affected by tillage but shows positive sequestration rates in response to the agricultural management (cutting or pruning) of the above-ground biomass [37].

The maintenance of traditional agroforestry practices is supported within the Eco-Schemes of the Common Agricultural Policy (CAP; § 20 3 CAP Direct Payments Act) and at the federal state level [52]. This covers particularly old fruit trees established on meadows ('Streuobstwiese'). The installation of new agroforestry systems is not recognized as agricultural management at present (2021), but the process to change the legislation is ongoing. In January 2021, the German parliament agreed to subsidize agroforestry [53]. As part of the new national strategic plan of the German government, the planting of trees on cropland and grassland will be supported from 2023 onwards within the new CAP, pending approval in 2022 by the European Commission [54]. Agroforestry is expected to contribute to achieving the EU Green Deal targets, especially through climate change mitigation, water quality improvement, soil degradation limitations, the protection of biodiversity, and pesticide-use reductions [55].

Hedgerow-bordered fields benefit from lower evapotranspiration and thus drought stress, as well as serving as shade dispensers for livestock [56]. The carbon storage potential of hedgerows was recognized early on in Canada [57] and the United Kingdom [43], where hedgerows were found to store between 11 and 105 Mg C km^{-1} and between 10 and 14 Mg C km^{-1}, respectively. In Germany, the CarboHedge project commenced in 2019 with the goal of quantifying the above-ground and below-ground biomass and SOC sequestration rates typical of German hedgerows; it led to the obtainment of the country-specific information on TBC and SOC sequestration rates [37] that was used in this study. In contrast, the C storage in TBC and soil associated with the remaining SWF structures (patchy and additional) was estimated in accordance with the guidance set out by the IPCC for Tier 1 assessment (with elements of Tier 2 assessment where regional data were available) and the Framework for Data-Deficient Areas formulated by Willcock et al. (2012) [36]. Our estimates broadly corresponded to the values stipulated in the IPCC GL2000 dataset for Forest/Cropland Mosaic (range: 6.8–35.5 Mg ha^{-1} for the IPCC eco-floristic regions assigned to Germany) and were conservative relative to the C storage estimates of 'Small woodlands' (81 $\pm$ 18.0 Mg ha^{-1}), which included successional poplar-dominated and old oak-dominated forest stands investigated in the urban landscape of Leipzig, central Germany [38]. Empirical assessments of the carbon storage potential of non-linear SWFs, particularly, that of their below-ground biomass, are needed in future work to refine the current estimates.

Furthermore, trends in SWF presence and the level of landscape complexity were linked to pedoclimatic regions of Germany. Regions dominated by cropland had the lowest SWF cover, and regions dominated by grassland had the highest SWF cover (7–8%). Understanding the spatial distribution of SWFs could assist with targeting regions characterized by inherently low SWF cover for the implementation of carbon sequestration-oriented agronomic practices such as agroforestry at a national scale.

4.3. The Carbon Sequestration Potential of Agroforestry Systems

We calculated the carbon sequestration potential of agroforestry systems adopted at a conservative level of 1% and moderate levels of 5% and 10% of total agricultural land. This hypothetical land conversion showed a high potential for offsetting GHG emissions, ranging from 0.005 (CIs: 0.002–0.008) to 4.8 (CIs: 1.2–8.4) Tg C per year. Planting hedgerows on 125,135 ha of cropland could result in an annual CO_2 sequestration close to 1% of the GHG emissions from farmland in 2019 [5]. Assuming no future tillage takes place, approximately 20% of the carbon would be permanently stored in the soil [37].

Integrating tree lines in cropland and pastures provides lower carbon sequestration than the installation of hedgerows. This can be explained by the structure of hedges, which have a high stem density of 81,368 stems ha^{-1} per hedge [43] or 125–816 stems ha^{-1} in hedgerow agroforestry systems [26], and the regrowth capacity after regular trimming that results in high carbon input to SOC through the turnover of litter and dead root material [37]. In contrast, trees in silvoarable agroforestry systems such as alley cropping are planted with greater (15 m) inter-row spacing [12] and lower (99–111 stems ha^{-1}) stem density [26], resulting in lower carbon sequestration.

Whereas hedgerows are traditionally planted as windbreaks with no marketable products besides their biomass for energy production, tree species in agroforestry systems are intentionally selected for their production of fruits, or precious timber, and may therefore offer additional income [58] and increased productivity per area [59]. The concept of successional or dynamic agroforestry, where trees, shrubs, and bushes are planted in spatial proximity and temporal succession [60], adopted for temperate regions may combine the agroecological benefits of hedges with a high biomass production and carbon sequestration, as well as the fruit or timber production of selected tree species among other ecosystem services related to both structures. Finally, installing hedgerows in perennial systems (vineyard and orchard systems) has only a minor effect on the carbon sequestration at a national level, but it could increase other ecosystem services, e.g., biodiversity conservation, and thus lead to pollination success [61].

Farmers are aware of the environmental benefits of agroforestry systems, but the effects on the overall productivity of systems remain uncertain [62]. In addition, a lack of effective policy measures, e.g., at the EU and national levels, currently constitutes a major constraint of the wider adoption of tree-planting measures in agriculture (e.g., [13,63]). Therefore, the development of improved legal frameworks and incentive mechanisms, along with the reduction of administrative burdens, is likely to increase the farmer adoption of agroforestry measures, including in highly productive pedoclimatic regions [13,62]. The widespread adoption of agroforestry in Germany and other temperate regions should be considered for the future agricultural mitigation of climate change.

4.4. Study Limitations and Data Needs for Future Research

In our study, we applied regional estimates specific to temperate Europe, derived from scientific literature sources, to develop a national assessment of above- and below-ground carbon stocks and sequestration rates for small woody landscape features in Germany. We acknowledge that our approach did not account for high variability in carbon storage and sequestration rates across temperate agroforestry systems driven by species-site-, or management-specific heterogeneity inherent to these systems [14,25,64,65]. Moreover, though we applied a systematic methodology to estimate carbon storage potential at a national scale here, our approach may not have accounted for inconsistencies in individual study measurements used to derive our coefficients [37,64]. Although recent advances have been made to differentiate between climatic conditions and typologies of agroforestry systems [26], accurate assessments remain limited by data availability, particularly in temperate zones.

Given the increasing recognition of the potential of tree-based systems for climate regulation, we reiterate the need for consistent and precise empirical datasets documenting carbon storage and GHG emissions and removals in agroforestry systems at the national or sub-national levels [14,26]. This would be particularly relevant for the patchy features class identified in the Copernicus dataset used here. Such data could be obtained through a combination of standardized long-term field measurements [14,37] and remote-sensing sensing such as airborne LiDAR in combination with digital orthoimagery [66], and they should account for temporal-, spatial-, species-, and management-specific variation. Agroforestry practices have long been associated with a suite of broader agroecological benefits beyond carbon sequestration, including the rehabilitation of degraded land, improved nutrient recycling, soil erosion control, and the diversification of income sources for farmers ([67,68]). Therefore, a coordinated examination of the optimization of SWF and agroforestry benefits for climate in the context of broader socio-economic considerations is needed to guide policies and improve agroforestry implementation amongst farmers (e.g., [69]).

5. Conclusions

In this work, we successfully estimated the carbon stocks in German SWFs and quantified the carbon sequestration potential of the widespread implementation of agroforestry, i.e., hedgerows (shelterbelts), silvoarable systems, and silvopastoral systems. The results highlighted the need to account for SWF extent and carbon stocks for a more accurate assessment of the C storage capacity of agricultural landscapes in Germany. Empirical data for non-linear SWFs are urgently needed to validate the TBC and SOC estimates derived through a literature review and to decrease uncertainties associated with the estimates. Additionally, the current SWF dataset does not include, e.g., scattered trees, which might result in an underestimation of C stocks; in the future, regional datasets could be used for more precise assessments. Furthermore, the widespread implementation of agroforestry was shown to be a promising approach to offset parts of the agricultural GHG emissions. However, the analysis should be refined by, e.g., considering farmer adoption rates as opposed to the total land area to be converted and having regional TBC and SOC data for silvoarable and silvopastoral systems. While we acknowledge the shortcomings of our study, our methodology has the benefit of being reproducible and can be used to inform SWF assessments across Europe.

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Appendix A

Table A1. Soil organic carbon (SOC) in the upper (0–30 cm) soil layer in agricultural systems and SWFs.

Agricultural System	SOC	SWF (Linear) SOC	SWF (Patchy, Additional) SOC	Literature
	Mg C ha^{-1}			
Arable system	61 ± 25	78 ± 37	71 ± 33	[8,37]
Grassland system	88 ± 32	88 ± 32	88 ± 32	[8,37]
Orchard and vineyard systems	62 ± 25	79 ± 37	72 ± 37	[8,37]

Appendix B

Table A2. The IPCC Tier 1 carbon sequestration rates for above-ground (ABG) and below-ground (BLG) biomass and soil organic carbon (SOC) in the upper (0–30 cm) soil layer for different agroforestry systems. Confidence intervals for hedgerows derived by applying the IPCC guidance that assumes an error of 75% when information is not available. MC—length of maturity cycle.

Agricultural System	Target AF System	Land Converted	ABG	BLG	SOC	MC
		(%)	(Mg C ha^{-1} yr^{-1})			(yr)
Arable system	Hedgerow	1, 5, 10	3.8 (ABG + BLG + SOC) ± 75%			30
	Silvoarable	1, 5, 10	0.91 ± 0.49	0.23 ± 0.17	0.47 ± 1.34	30 ± 10
	Silvopastoral	1, 5, 10	2.33 ± 1.21	0.70 ± 0.53	1.93 ± 1.54	30 ± 10
Grassland system	Hedgerow	1, 5, 10	3.5 (ABG + BLG + 0 Mg C SOC)			
	Silvopastoral	1, 5, 10	2.33 ± 1.21	0.70 ± 0.53	1.93 ± 1.54	30 ± 10
Orchard system	Hedgerow	1, 5, 10	3.8 (ABG + BLG + SOC)			
Vineyard system	Hedgerow	1, 5, 10	3.8 (ABG + BLG + SOC)			

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