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Carbon Sequestration in the Aboveground Living Biomass of Windbreaks—Climate Change Mitigation by Means of Agroforestry in Hungary

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Abstract: The land use sector is a crucial pillar in achieving the EU climate goals set for 2050. A significant part of the climate change mitigation potential of the land use sector is inherent to agroforestry. Windbreaks are important agroforestry elements of Hungarian agricultural landscapes. The new and improved agroforestry subsidy system may positively affect the extension of windbreaks in Hungary, making it relevant to assess their carbon sequestration potential. In our study, we examined the carbon sequestration of windbreaks at the country level and in two sample areas of 24,000 hectares based on National Forestry Database volume stock data, as well as information collected from the Hungarian Forest Cover Map using orthophoto interpretation. We estimated the total annual carbon sequestration realized in the aboveground biomass pool of Hungarian windbreaks to be −33.1 ktCO_2/year, which is 0.67% of the total annual carbon sequestration of the aboveground biomass pool of all Hungarian forests, as reported by the Hungarian Greenhouse Gas Inventory. On the other hand, according to our estimate, the weighted mean annual carbon sequestration in the aboveground biomass of windbreaks was −2.4 tCO_2/ha/year in the 2010–2020 period. This value is very close to the average mean annual carbon sequestration per hectare value of all forests, as reported by the Hungarian Greenhouse Gas Inventory. This means that planting a given area of windbreaks in between agricultural fields can have similar climate change mitigation effects as planting forests in the same given area.

Keywords: climate change mitigation; carbon removal; aboveground woody biomass; greenhouse gas inventory

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1. Introduction

Achieving the climate change mitigation goals set out by the Paris Agreement and the European Green Deal will probably not be feasible without the inclusion of the land use and forestry sector (LULUCF sector) in climate mitigation pathways [1]. As the IPCC [2] states, the LULUCF sector offers significant near-term mitigation potential at a relatively low cost; however, it cannot compensate for delayed emission reductions in other sectors. A significant part of the climate change mitigation potential of the LULUCF sector is inherent in agroforestry systems [2]. Political and societal interest in the climate change mitigation potential of tree-based solutions for more sustainable and climate-friendly land use pathways has recently increased [3]. This has led to increased interest in the quantification of tree-cover extent [4] and the area occupied by trees outside forests [3]. Agroforestry has come into focus due to its potential for carbon sequestration and a broad range of other ecosystem services [5,6].

As defined by the IPCC [2], agroforestry is a set of diverse land management systems that integrate trees and shrubs with crops and/or livestock in space and/or time. Agroforestry accumulates carbon in woody vegetation and in the soil [7] and offers multiple co-benefits such as increased land productivity, diversified livelihoods, reduced soil erosion, improved water quality, and more favorable regional climates [8–11]. In addition to the aforementioned co-benefits, agroforestry can improve the soil health, infiltration, and structural stability [12]; it can reduce ambient temperatures and crop heat stress [13,14]; and it can also increase groundwater recharge in drylands when managed at moderate intensity [15,16]. Agroforestry systems can also positively influence human health [17] and improve dietary diversity [18].

The specific effects of temperate agroforestry systems on long-term carbon sequestration are often system dependent [3,19]. According to the global analysis of Chapman et al. [20], the maximum technical climate mitigation potential of agroforestry systems worldwide is 9.4 $GtCO_2eq$/year, which is a conservative estimate as the authors take only aboveground biomass into account. Griscom et al. [21] considered both above- and belowground carbon; however, they only examined some types of agroforestry systems, i.e., windbreaks, alley cropping systems, and silvopastoral systems. According to their estimate, the economically feasible climate mitigation potential of the mentioned agroforestry systems is only about 0.8 $GtCO_2eq$/year globally. In Europe, the most common agroforestry systems are agrosilvopastoral systems, windbreaks, hedgerows, and shelterbelts [22,23]. Kay et al. [24] estimated the carbon sequestration potential of a wide range of agroforestry practices in Europe. They found that the carbon sequestration potentials ranged between 0.09 and 7.29 tC/ha/year [24]. They estimated that implementing agroforestry in areas with significant environmental pressure could lead to a carbon sequestration of 2.1 to 63.9 million tC/year depending on the type of agroforestry; this amount corresponds to 1.4%–43.4% of European agricultural greenhouse gas (GHG) emissions.

At the field scale, agroforestry systems accumulate between −0.59 and −6.24 tCO_2/ha/year of aboveground carbon [2]. Belowground carbon often constitutes 25% or more of the carbon gains in agroforestry systems [25,26]. According to the IPCC [27] guidelines for Greenhouse Gas Inventory (GHGI) preparation, agroforestry systems can comprise the following: fallows, hedgerows, alley cropping, multistrata systems, parklands, shaded perennial-crop systems, silvoarable systems, and silvopastoral systems. As the IPCC methodology focuses only on the carbon stocks and carbon sequestration capacity of agroforestry systems, it combines all linear plantations around fields (i.e., shelterbelts, windbreaks, boundary plantings, and live fences) into one category called hedgerows and gives default biomass coefficients for this combined category [27]. This classification is different from that of Nair [28], who defines hedgerows as agrosilvopastoral systems with woody hedges for browsing, mulch, green manure, and soil conservation. Nair [28] defines windbreaks as narrow strips of trees, shrubs, and/or grasses planted to protect fields, homes, canals, and other areas from the wind and blowing sand. As wind erosion is a serious problem, the use of windbreaks to protect agricultural fields and homesteads is a common agroforestry practice in many parts of the temperate zone. The greatest benefits from the use of windbreaks occur in areas with winter snow and hot, dry, and windy summers, such as in lowlands and great plains [28]. Windbreaks modify the microclimate of the protected zone by decreasing the wind velocity. At the same time, the vertical transport of heat is reduced, and humidity is increased behind a windbreak, which generally reduces evapotranspiration as well [28].

In Hungarian agricultural landscapes, windbreaks (i.e., field protection tree rows and field protection forest strips) are common elements that protect fields from wind and soil erosion. According to the knowledge of the authors, in Hungary, no countrywide estimate on the carbon sequestration of agroforestry systems has been made available yet. Honfy et al. [29] carried out a case study of alley cropping systems of black locust (*Robinia pseudoacacia* L.) intercropped with triticale (× *Triticosecale* W.) and evaluated the land equivalent ratios (LER). They found that most of the tested treatments had favorable LER ratios when the trees were five years old [29]. As LER ratios higher than one signify increased biomass production when compared to sole cropping, we can assume that the carbon sequestration of agroforestry systems is also higher than that of land used only for agricultural crop production. Current data availability about temperate agroforestry systems is limited by a low number of studies and a heavy focus on alley-cropping and hedgerow systems, despite the existence of many other types of agroforestry practices [30]. Obtaining accurate measurements of carbon sequestration in field studies is further constrained by the lack of standardized field and laboratory methodology [30]. In addition to the above, only few region-specific allometric equations are available for the tree species typical of agroforestry [31], limiting the precision of volume stock and biomass carbon estimates.

In the Eighth National Communication and Fifth Biennial Report of Hungary [32] agroforestry systems are listed as opportunities to mitigate the agricultural damage caused by climate change. However, no numerical estimate is given on the magnitude of the carbon sequestered in existing agroforestry systems in the country, neither is the climate change mitigation potential of planting additional agroforestry systems numerically estimated. In the Hungarian GHGI, the area and carbon sequestration of orchards are estimated [33]; other types of agroforestry systems are not mentioned in the report. This means that the estimation of the carbon storage and sequestration of the Hungarian agroforestry systems is a significant research gap. Thus, the contribution of agroforestry towards Hungary's Intended Nationally Determined Contribution and towards LULUCF targets set for 2030 in the LULUCF Regulation [34] has not been estimated.

Nevertheless, in the context of Carbon Farming [35], the carbon sequestration and storage using agroforestry has become even more relevant. In response to these new challenges, new incentives have been introduced in the Hungarian agricultural subsidy system. An important innovation starting in 2023 is that the agricultural land occupied by agroforestry systems remains eligible for direct area-based subsidies [36]. In addition, agroforestry systems can be counted as agroecology program elements and as landscape elements as well. Windbreaks (i.e., field protection tree rows and field protection forest strips) and trees planted on grasslands are subsidized in Hungary. Considering the favorable changes in the subsidy system, it is crucial to assess the carbon sequestration potential of these landscape elements, as they become important means of land-based climate change mitigation.

The objective of our study was to give a countrywide estimate on the carbon sequestration occurring in the aboveground biomass pool of windbreaks in Hungary. We also intended to estimate the magnitude of the area of windbreaks that are not under forest management planning. For this purpose, we assessed two sample areas in the Hanság and Hajdúhát-Bihar forest planning districts. The assumptions behind the study objectives are the following: (i) a significant amount of carbon is sequestered in the biomass of windbreaks annually; (ii) the area of windbreaks that are not under forest management planning is not negligible in Hungary.

2. Materials and Methods

2.1. Data Sources and Sampling

In our study we used the National Forestry Database (NFD) as the data source, which is the official database of the Hungarian Forest Authority. NFD stores detailed data on each forest stand (sub-compartment) subject to forest management planning [37,38]. Forest management planning (FMP) is based on field surveys during which the main stand attributes (such as the height, diameter, basal area, age, and canopy closure) are surveyed. From the sampled data, the annual increment is modeled for each year in between two surveys based on the yield tables [38]. The harvest is officially registered for each forest stand each year. In the NFD digital maps, more than 300 raw and derived data are available for each forest sub-compartment [37]. Data on the standing volume are stored in tree species rows, which are the basic units of the database [37,38]. The NFD stores data on the primary function (i.e., timber production, windbreak, nature protection, etc.) assigned to each forest sub-compartment.

Our other data source was the Hungarian Forest Cover Map [39], which is prepared and made freely available online by the Forest Authority. This map shows the polygon and the identifiers of each forest sub-compartment under FMP as well as the Google Satellite imagery of the total area of Hungary.

In Hungary, not all windbreaks are under FMP, and the windbreaks under FMP may not have windbreak as primary function assigned to them in the NFD. Table 1 shows the different types of windbreaks existing in Hungary and the data sources used by this study for their area and carbon sequestration estimation.

Table 1. The different types of windbreaks in Hungary and the data sources used for their area and carbon sequestration estimation (FMP: forest management planning, NE: not estimated).

	Hanság Sample Area	Hajdúhát-Bihar Sample Area	Total for Hungary
Windbreaks under FMP with windbreak as the primary function	NFD data on the area and wood stock change between 2010 and 2020 (queried from the NFD based on primary function identifier code); carbon sequestration calculated based on IPCC methodology.	NFD data on the area and wood stock change between 2010 and 2020 (queried from the NFD based on primary function identifier code); carbon sequestration calculated based on IPCC methodology.	NFD data on the area and wood stock change between 2010 and 2020 (queried from the NFD based on primary function identifier code); carbon sequestration calculated based on IPCC methodology.
Windbreaks under FMP without windbreak as the primary function	Identified using orthophoto interpretation; NFD data on the area and wood stock change between 2010 and 2020 (queried from the NFD based on sub-compartment identifier code).	Identified using orthophoto interpretation; NFD data on the area and wood stock change between 2010 and 2020 (queried from the NFD based on sub-compartment identifier code).	Unidentified, NE
Windbreaks not under FMP	Area data obtained using orthophoto interpretation	Area data obtained using orthophoto interpretation	Estimated area and carbon sequestration

We queried all stands with windbreak as the primary function from the 2010 and 2020 state of the NFD at the country level. We matched the two states of the forest sub-compartments based on the sub-compartment identifier code. This way we obtained the whole country's windbreak under FMP group for further carbon sequestration analysis.

We also selected sampling areas in the Hajdúhát-Bihar and Northern Hanság and Southern Hanság (both together hereinafter also referred to as Hanság) forest planning districts. We selected 10-10 EOTR (EPSG:23700-HD72/EOV) sections in the Hanság and in the Hajdúhát-Bihar districts. EOTR stands for the Hungarian Unified National Map System [40], and each EOTR section has an area of 2400 ha. This way we obtained a sampling area of 24,000 ha in the Hajdúhát-Bihar district and another sampling area of 24,000 ha in the Hanság (Figures 1 and A1–A3). We selected these sampling areas in order to represent the two largest and most important lowland areas of Hungary, where windbreaks are most common.

In these sampling areas, we identified all windbreaks under FMP using the Hungarian Forest Cover Map. Some of these windbreaks were defined in the NFD with windbreak as the primary function, and others had a different primary function. We queried the descriptive statistics and the dendrometrical parameters of these sub-compartments from the 2010 and the 2020 state of the NFD. We matched the two states of the forest sub-compartments based on the sub-compartment identifier code. These two states were the basis for the calculation of the carbon sequestration of these sub-compartments. We also identified the primary function of each sub-compartment.

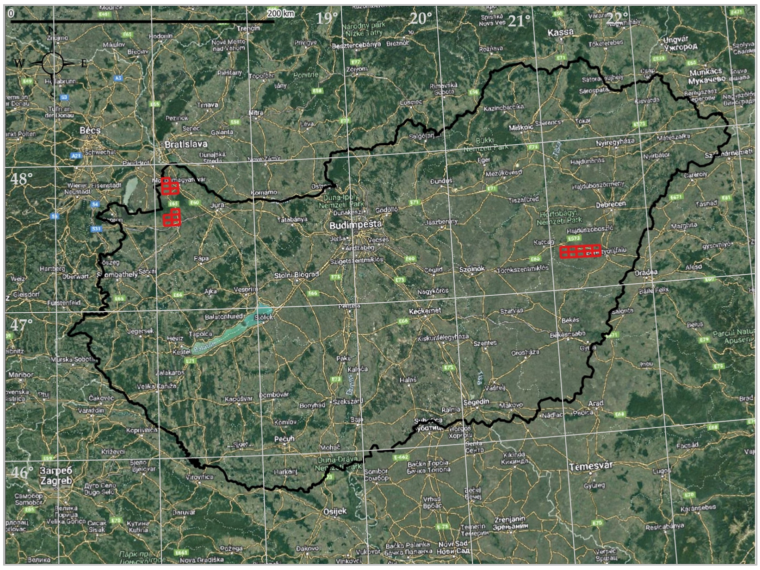

Figure 1. The overview map of the sample areas examined in this study.

In the following step, we identified all windbreaks not under FMP based on visual orthophoto interpretation. We measured the area of these windbreaks. The orthophoto interpretation and the area measurements were carried out online on the website of the Hungarian Forest Cover Map [39].

2.2. Methods of the Analysis

In this study, the carbon sequestration of three different type of windbreaks was estimated. The examined types of windbreaks were the following: windbreaks under FMP with windbreak as the primary function, windbreaks under FMP with a different primary function, and windbreaks not under FMP. For the tree types of windbreaks, different data sources and estimation methods were used (Figure 2).

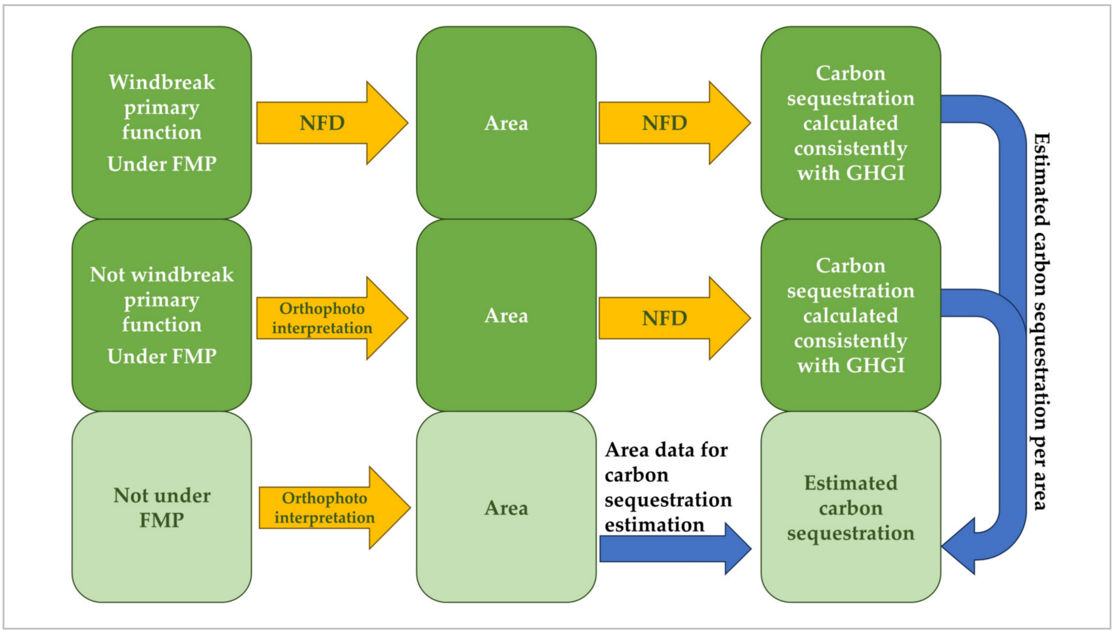

Figure 2. The flowchart of the carbon stock estimation process used in this study. (FMP: forest management planning, GHGI: greenhouse gas inventory, NFD: National Forestry Database).

In the case of the windbreaks under FMP, we calculated the aboveground biomass carbon stock changes for each sub-compartment between the 2010 and 2020 states. The calculation was based on the NFD data, and we used the IPCC [27,41] methodology, consistent with the Hungarian GHGI. For each sub-compartment, we calculated the carbon stock change for each tree species row separately as follows [33,41,42].

$$\Delta C_{tsr} = C_{t2} - C_{t1} \quad (1)$$

$$C_{tn} = \sum_{i=1}^{9} \left(SV_{tn} \times CF \times D \times \frac{44}{12} \right) \quad (2)$$

where:

ΔC_{tsr}: carbon stock change of a given tree species row (t CO_2);

C_{t2}: carbon stock of the tree species row in year $t2$ (t CO_2);

C_{t1}: carbon stock of the tree species row in year $t1$ (t CO_2);

C_{tn}: carbon stock of all tree species rows per sampling point in year tn (t CO_2);

SV_{tn}: standing volume of the tree species row in year tn (m^3);

CF: tree species specific carbon fraction value (tC/t dm);

D: tree species specific density value (t dm/m^3 standing volume);

44/12: the ratio of the molar mass of carbon dioxide to carbon.

After calculating the carbon stock changes for each tree species row separately, we summed them up, and thus we obtained the total carbon stock change for each sub-compartment. Thereafter, we summed the carbon stock changes for each group. We calculated the mean carbon stock change per hectare and the cumulative carbon stock change for each group. In order to compare the carbon sequestration across groups we performed the Kruskal–Wallis test, as the primary assumptions for ANOVA analysis were not met. We used Statistica software (Version 14.0.1.25, Tulsa, OK, USA) for the analysis.

In order to estimate the carbon sequestration of windbreaks not under FMP, we used the mean carbon sequestration value of the windbreaks under FMP in the same forest management planning district.

$$\Delta C_{not\ under\ FMP,districtX} = AVG\Delta C_{under\ FMP,districtX} \times Area_{not\ under\ FMP,\ districtX} \quad (3)$$

where:

$\Delta C_{not\ under\ FMP,districtX}$: total carbon sequestration of windbreaks not under FMP in the forest management planning district X;

$AVG\Delta C_{under\ FMP,districtX}$: mean carbon sequestration of windbreaks under FMP in the forest management planning district X;

$Area_{not\ under\ FMP,districtX}$: total area of windbreaks not under FMP in the forest management planning district X.

In order to obtain a countrywide estimate of windbreaks not under FMP we used the following equation.

$$\Delta C_{not\ under\ FMP} = Area_{windbreaks} \times AVG\left(\frac{Area_{not\ under\ FMP,districtX}}{Area_{under\ FMP,districtX}}\right) \times \mathrm{AVG}\Delta\mathrm{C}_{windbreaks} \quad (4)$$

where:

$\Delta C_{not\ under\ FMP}$: total carbon sequestration of windbreaks not under FMP in the whole country;

$Area_{windbreaks}$: area of all forest sub-compartments with windbreak primary function in the country;

$Area_{not\ under\ FMP,districtX}$: area of windbreaks not under FMP in the two sampling areas (Hanság and Hajdúhát-Bihar);

$Area_{under\ FMP,districtX}$: area of windbreaks under FMP in the two sampling areas (Hanság and Hajdúhát-Bihar);

$AVG\Delta C_{windbreak}$: country total mean carbon sequestration of windbreaks under FMP with windbreak as the primary function.

We also examined the yield class distribution of the forest sub-compartments with windbreak as the primary function and the yield class distribution of the forest sub-compartments with timber production as the primary function. For this investigation, we queried the yield class distribution of all sub-compartments with these specific functions from the NFD.

2.3. Characteristics of the Hanság and the Hajdúhát-Bihar Forest Planning Districts

The Northern Hanság and the Southern Hanság forest planning districts are located in the northwest of Hungary. A large part of the Hanság region is a low flood plain covered with bog clay, silt, and peat; most of the area is drained [43]. In the rainy months, approximately one quarter of the area is periodically submerged. In the study area, meadow and bog soils are found with a thin fertile layer. The average annual temperature in the Hanság region is around 10 °C, reaching 16.5–16.7 °C in the summer. The sum of the annual sunshine hours is 1880–1930. Around 730–750 h of sunlight can be expected in the summer and around 180 h in the winter. The average daily temperature exceeds 10 °C in 186 days (between 14 April and 19 October). The frost-free period usually lasts 192–194 days. The average temperature of the hottest days is around 34.0 °C. The temperature of the coldest days is between −15.0 and −15.5 °C. The precipitation is between 550 and 590 mm. During the vegetation period, approximately 320–360 mm rain is expected [43]. The aridity index is between 1.18 and 1.27 [43].

The Hajdúhát-Bihar forest planning district is located in the eastern part of Hungary. It has a moderately warm and dry climate. The annual number of sunshine hours is between 1960 and 2000 h. We can expect 790–800 h of sunshine in the summer and 180–185 h in the winter [43]. The average annual temperature is generally around 9.9–10.3 °C. The average temperature of the growing season is between 17.0 and 17.4 °C. The average daily temperature exceeds 10 °C in 198–200 days. The frost-free period lasts 190–197 days. The average temperature of the hottest summer days is around 34.0–34.6 °C. The annual amount of precipitation is 520–540 mm. During the vegetation period approximately 310–320 mm rain is expected [43]. The aridity index of the region is 1.30–1.35. In the study area, meadow soils are found with a thin fertile layer and prone to salinization.

3. Results

According to our results, the area of windbreaks under FMP with windbreak as the primary function is 10,089 ha, which is 0.52% of the forest area under FMP in Hungary. According to our estimate, the mean carbon sequestration in the aboveground biomass of the forest sub-compartments with windbreak as the primary function was −2.0 t CO_2/ha/year at the country level (Table 2, Figure 3). The Kruskal–Wallis test indicated that the mean carbon sequestration of the windbreaks under FMP located in the Hanság study area was not significantly different from the country's total value at a 0.95 confidence level. As regards the Hajdúhát-Bihar study area, a mean carbon sequestration value of −5.8 tCO_2/ha/year was observed. According to the Kruskal–Wallis test, this value was significantly higher than the country's total value at a 0.95 confidence level. The mean carbon sequestration values weighted by the area of the stands were higher when compared to the unweighted means (Table 2).

In the country's total windbreak group, black locust (*Robinia pseudoacacia*) produced most of the carbon sequestration (−9469 tCO_2/ha/year) followed by other hard broadleaved and oak (*Quercus*) species (Figure 4). However, in the Hanság study area, black locust and other soft broadleaved species produced CO_2 emissions, while pines (*Pinus*) and hybrid poplars produced more carbon sequestration than the country's average. As regards the Hajdúhát-Bihar study area, the carbon sequestration of oaks, black locust, and hybrid poplars was predominant. This was related to the area distribution of the species.

Table 2. The area, the final harvest ratio, and the mean annual carbon sequestration values of the study areas and the country's total estimates (NE: not estimated, FMP: forest management planning).

	Hanság—Windbreaks under FMP	Hanság—Windbreaks Not under FMP	Hajdúhát-Bihar—Windbreaks under FMP	Hajdúhát-Bihar—Windbreaks Not under FMP	Total Hungary—Windbreaks under FMP	Total Hungary—Windbreaks Not under FMP	Total Hungary—All Windbreaks
Total area (ha)	472	389	258	184	10,089	4237 (est.)	14,300 (est.)
Area not subject to final harvest in the study period (ha)	438	NE	254	NE	8883	NE	NE
Final harvest %	7%	NE	1%	NE	12%	NE	NE
Total carbon sequestration (t CO_2)	−811	−554	−1652	−1058	−24,135	−8944	−33,079
Mean carbon sequestration in the aboveground biomass (t CO_2/ha/year)	−1.4	−1.4 (est.)	−5.8	−5.8 (est.)	−2.0	−2.0 (est.)	−2.0 (est.)
Mean carbon sequestration in the aboveground biomass weighted with the area (t CO_2/ha/year)	−1.7	NE	−6.4	NE	−2.4	NE	NE
Mean carbon sequestration in the aboveground biomass of the areas not subject to final harvest in the study period (t CO_2/ha/year)	−2.5	NE	−6.3	NE	−3.5	NE	NE
Mean carbon sequestration in the aboveground biomass of the areas not subject to final harvest in the study period weighted with the area (t CO_2/ha/year)	−2.6	NE	−6.8	NE	−3.9	NE	NE

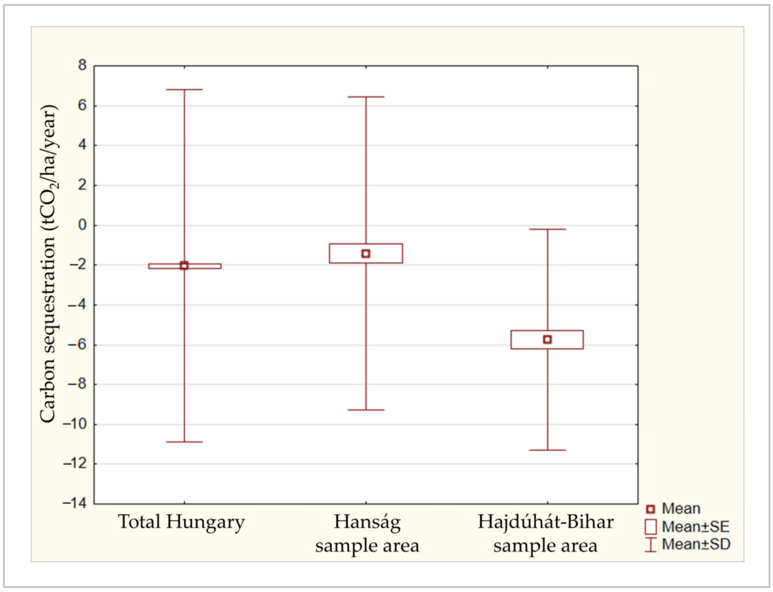

Figure 3. Mean, standard error, and standard deviation of the annual carbon sequestration per hectare values of the windbreaks under FMP in the two sample areas and that of the country's total windbreak group. (Negative values mean carbon sequestration expressed in tCO_2, whereas positive values mean emissions.).

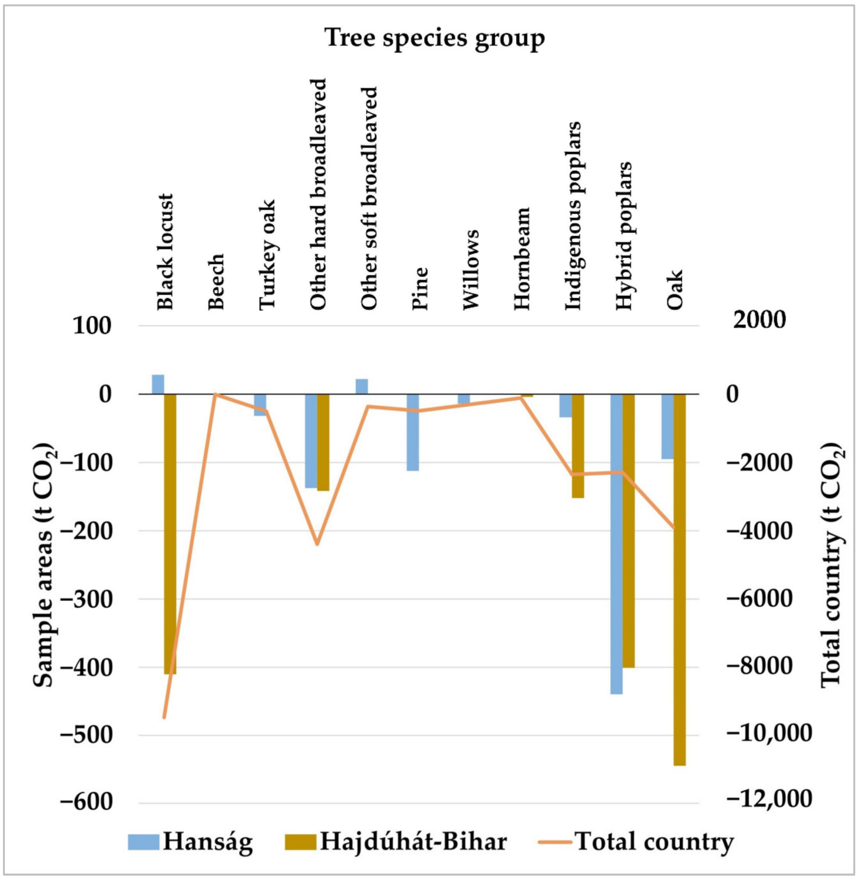

Figure 4. The total annual carbon sequestration of windbreaks under FMP in the two sample areas and that of the country's total windbreak under FMP group sorted by tree species group. (Negative values mean carbon sequestration expressed in tCO_2, whereas positive values mean emissions. Black locust: *Robinia pseudoacacia*, Beech: *Fagus sylvatica*, Turkey oak: *Quercus cerris*, Pine: *Pinus* sp., Willows: *Salix* sp., Hornbeam: *Carpinus betulus*, Indigenous poplars: *Populus* sp., Hybrid poplars: *Populus* × *euramericana*, Oak: *Quercus* sp.)

We examined the yield class distribution of the windbreaks under FMP with windbreak as the primary function and compared it to the yield class distribution of the forest stands with timber production as the primary function (Figure 5). According to our results, the less productive yield classes were overrepresented among windbreaks. In the Hanság study area, 60% of the windbreaks under FMP had the primary function defined as windbreak, while in the Hajdúhát-Bihar study area, this ratio was only 31%. We also identified the primary function of each windbreak under FMP in the Hanság and Hajdúhát-Bihar sample areas. The most common primary functions were windbreak, timber production, riverside protection, and nature conservation (Figure 6).

According to the results of the visual orthophoto interpretation, 42% of the area of windbreaks in the Hajdúhát-Bihar study area was not under FMP, while in the Hanság study region, this ratio was 45% (Table 1). In the Hajdúhát-Bihar study area, the total estimated annual carbon sequestration of windbreaks was −2710 tCO_2/year, while in the Hanság region, it was −1365 tCO_2/year (Table 2, Figure 7). We estimated the total annual aboveground biomass carbon sequestration of windbreaks to be around −33.1 $ktCO_2$/year in Hungary (Table 2, Figure 7).

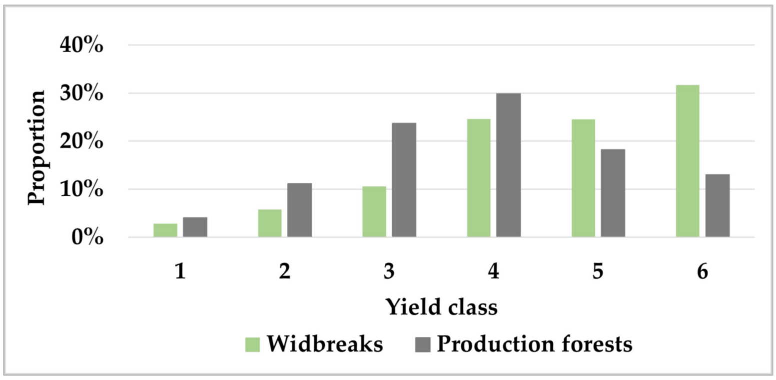

Figure 5. The yield class distribution of windbreaks under FMP with windbreak as the primary function and that of production forests as of the 2021 state of the NFD. (1 indicates the most productive yield class, while 6 indicates the less productive yield class.).

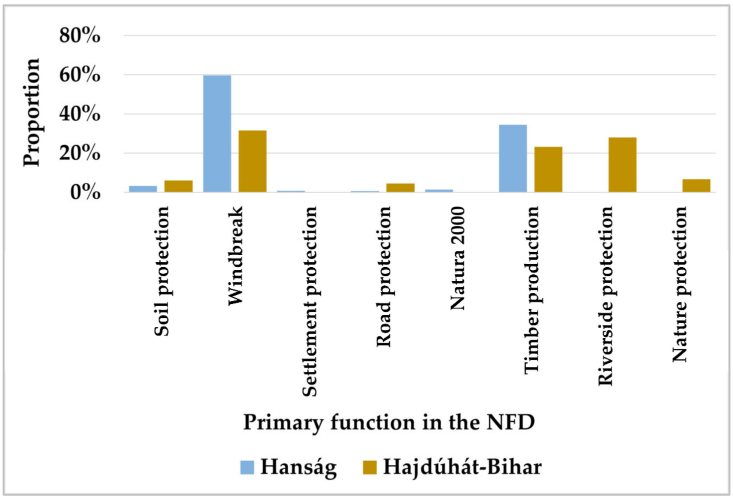

Figure 6. The distribution of windbreaks under FMP between different primary functions in the two sample areas (Hajdúhát-Bihar and Hanság).

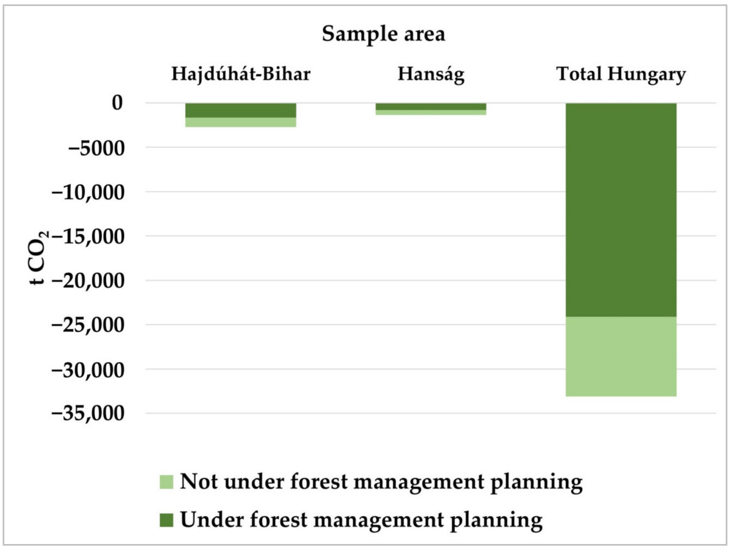

Figure 7. The estimated total annual carbon sequestration of windbreaks in the Hajdúhát-Bihar and the Hanság sample areas and the estimated country total value. (Negative values mean carbon sequestration expressed in tCO_2, whereas positive values mean emissions).

4. Discussion

According to the Hungarian GHGI, the mean carbon sequestration in the aboveground living biomass pool in Hungarian forests was −2.3 tCO_2/ha in 2021 [33,44]. The mean carbon sequestration in forest land remaining forest land was reported to be −2.1 tCO_2/ha in 2021. On the other hand, in the land converted to forest land category, a −3.8 tCO_2/ha mean aboveground biomass carbon sequestration was reported [33,44]. According to our results, the weighted mean annual carbon sequestration of the forest sub-compartments with windbreak primary function was −2.4 tCO_2/ha, which is very close to the average mean annual carbon sequestration per hectare value of all forests as reported by the GHGI. This result indicates that planting a given area of windbreaks in between agricultural fields can have similar climate change mitigation effects as planting forests in the same given area. We estimated the total annual carbon sequestration in the aboveground biomass pool of windbreaks to be −33.1 $ktCO_2$/year at the country level. This is 0.67% of the total carbon sequestration of the aboveground biomass pool of all forests in Hungary as reported by the GHGI [33,44]. It is important, however, to note that the estimated area of windbreaks in Hungary is only 0.5% of the total area of forest land under FMP.

The IPCC guidelines for GHGI preparation [27,41] gives default carbon sequestration factors for agroforestry systems. According to Table 5.1 of the IPCC [41], the aboveground biomass accumulation rate of temperate agroforestry systems is −7.7 tCO_2/ha/year; however, this value does not include the carbon loss occurring at final harvest. According to Table 5.2 of the IPCC [27], the aboveground biomass accumulation rate of temperate silvoarable systems is −0.91 tCO_2/ha/year, while the default aboveground carbon sequestration of temperate hedgerows is −0.87 tCO_2/ha/year, although these values do not include the carbon loss occurring at final harvest either. According to our estimate, the weighted mean annual carbon sequestration in the aboveground biomass of windbreaks under FMP where final harvest did not take place in the study period was −3.9 tCO_2/ha/year. Our estimate was 2.99 tCO_2/ha/year higher than the default value as defined by the IPCC [27] for silvoarable systems. According to the Sixth Assessment Report of the IPCC [2], at the field scale, agroforestry systems accumulate between −0.59 and −6.24 tCO_2/ha/year in the aboveground biomass. Our estimate for windbreaks in Hungary is within this range. According to Table 5.2 of the IPCC [27], the belowground biomass carbon accumulation rate in temperate silvoarable systems is −0.23 tCO_2/ha/year. Taking this into account, we could estimate a total belowground biomass carbon accumulation of −3.3 $ktCO_2$/year in windbreaks in Hungary. This amount would be 10% of the carbon sequestration of the aboveground biomass pool.

Amichev et al. [45] estimated the annual carbon stock additions in white spruce (*Picea glauca*) shelterbelts using two models. Shelterbelt tree growth was modeled with the Physiological Principles in Predicting Growth (3PG) model, and carbon flux and stocks in shelterbelts were modeled with the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3). They examined all carbon pools including above- and belowground biomass, litter, and soil. According to their estimate, the annual carbon stock increase in shelterbelts was between −8 and −15 tCO_2/ha/year. This value is much higher than our estimate. The reason for this is most probably attributable to the inclusion of the soil carbon storage pool. Several studies emphasize that carbon sequestration in the soil gives the most significant part of the total carbon sequestration of agroforestry systems [46–49]. Furthermore, Dhillon and Van Rees [47] reported that the amount of soil organic carbon stored in shelterbelt forested areas was on average about 20% higher than carbon stored in the adjacent agricultural fields. Ma et al. [49] reported that the forested area of shelterbelt systems stored an additional 53.8 tC/ha when compared to the adjacent cropland areas. Thus, it would also be important to study the soil carbon sequestration dynamics of Hungarian agroforestry systems.

According to our results, in Hungarian windbreak systems, black locust, oaks, other hard broadleaved species, and indigenous and hybrid poplars produced the largest carbon sequestration. In the Hanság and in the Hajdúhát-Bihar study area, many windbreaks under FMP had a primary function defined as timber production or nature conservation. This means that it is likely that many such forests are not defined as windbreak in the NFD at the country level. For this reason, our countrywide estimate for the carbon sequestration of windbreaks is most likely underestimated. Our results also show that many windbreaks in Hungary are not under forest management planning, i.e., 42% and 45% in the Hajdúhát-Bihar and Hanság study areas, respectively. This underlines the importance of surveying trees outside forests and agroforestry systems in the whole country. A comprehensive countrywide survey on Hungarian agroforestry systems could contribute to the accuracy of the Hungarian GHGI and could be included in the climate change mitigation measure planning process, as well as in the Nationally Determined Contributions of the country.

In the context of Carbon Farming, it is also of high importance to be able to quantify the carbon sequestration realized in trees outside forests that are present in agricultural landscapes (be it groups of trees, tree lines, or other types of agroforestry systems). In order to enhance climate change mitigation, it is essential to reward additional carbon sequestration at the farm level. This can be implemented only if a transparent and comprehensive methodology is given to quantify and account for the carbon sequestration of agroforestry systems. For Hungary, such a methodology is still not elaborated; thus, this will be an important step of future research.

5. Conclusions

Although windbreaks are important elements of Hungarian agricultural landscapes, our results indicate that in Hungary the area of windbreaks is only 0.5% of the area of forest land. By increasing the area of windbreaks, significant additional carbon could be sequestered, as according to this study their mean annual carbon sequestration in the aboveground biomass is not lower than the average carbon sequestration of Hungarian forests. This result is significant in the context of Carbon Farming and the new agroforestry subsidy system introduced in the country. This indicates that the proper accounting of the carbon sequestered in agroforestry systems could enhance their upscaling.

According to our results, the mean annual carbon sequestration of windbreaks at the country level was -2.4 tCO_2/ha/year, while in the two sample areas, the mean carbon sequestration was -1.7 and -6.4 tCO_2/ha/year. This means that the carbon sequestration capacity of windbreaks can vary significantly due to site conditions, tree species, and harvesting intensity. That is why a more detailed country level field survey and/or remote sensing-based assessment of these systems would be necessary to obtain a more accurate estimate on their carbon storage, carbon sequestration, and climate change mitigation potential. As soil is an important part of these systems, and agroforestry practices have numerous beneficial impacts on soils, it would be also crucial to assess the soil organic carbon stocks under Hungarian windbreaks.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

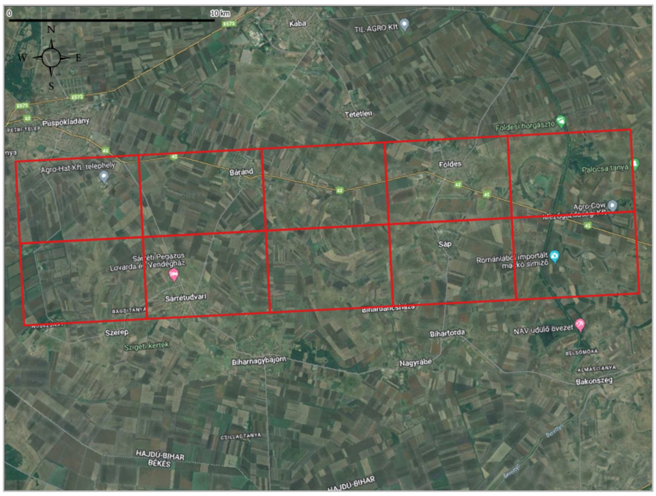

Figure A1. The sample area located in the Hajdúhát-Bihar forest planning district.

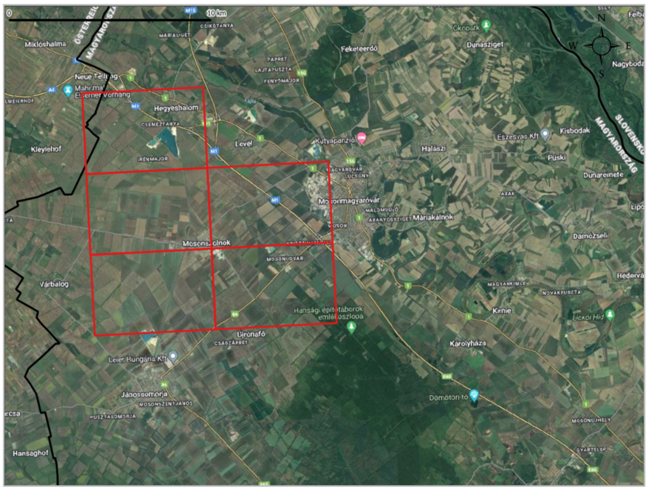

Figure A2. The sample area located in the Northern Hanság forest planning district.

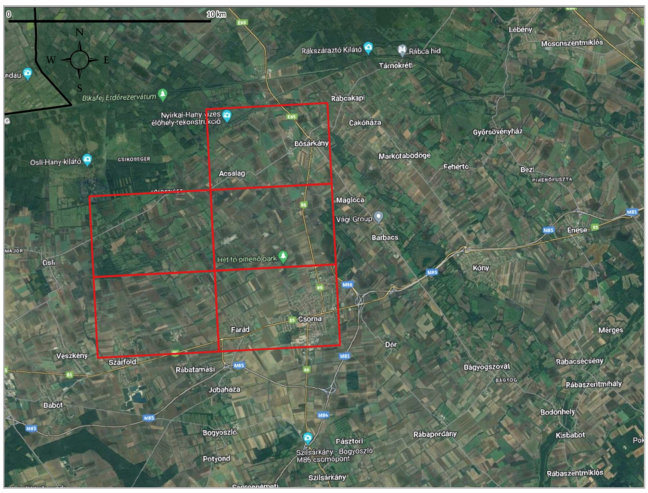

Figure A3. The sample area located in the Southern Hanság forest planning district.

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