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# Climate Benefit Assessment of Doubling the Extent of Windbreak Plantations in Hungary

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**Abstract:** Agroforestry systems are recognized as sustainable land use practices that foster environmental health and promote adaptive responses to global change. By harnessing the synergies between trees and agricultural activities, agroforestry systems provide multiple benefits, including soil conservation, biodiversity enhancement, and carbon sequestration. Windbreaks form integral elements of Hungarian agricultural landscapes, and the enhanced agroforestry subsidy framework might have a favorable impact on their expansion, underscoring the importance of evaluating their potential for carbon sequestration. In the present study, we assess the implications of doubling the extent of windbreak plantations in Hungary by planting an additional 14,256 hectares of windbreaks. We evaluate the total carbon sequestration and the annual climate change mitigation potential of the new plantations up to 2050. For the modeling, we use the recently developed Windbreak module of the Forest Industry Carbon Model, which is a yield table-based model specific to Hungary and allows for the estimation of living biomass, dead organic matter, and soil carbon balance. We project that new windbreak plantations will sequester 913 kt C by 2050, representing an average annual climate change mitigation potential of 144 kt $CO_2$ eq. Our findings reveal that doubling the extent of windbreak plantations could achieve an extra 5% carbon sequestration in forested areas as compared to business-as-usual (BAU) conditions. We conclude that new windbreak plantations on agricultural field boundaries have substantial climate change mitigation potential, underscoring agroforestry's contribution to agricultural resilience and achieving Hungary's climate goals set for the land-use (LULUCF) sector.

**Keywords:** climate change mitigation; carbon sequestration; agroforestry; shelterbelts; windbreaks; modeling

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## 1. Introduction

The land-based sector plays a pivotal role in climate change mitigation efforts, particularly within the frameworks outlined by the Paris Agreement, EU climate law, and overarching net zero targets [1]. This sector encompasses a range of activities, including agriculture, forestry, and land-use management, which collectively contribute to both greenhouse gas emission reduction and carbon sequestration [2]. EU climate law sets ambitious emission reduction targets, with specific emphasis on the land-use and forestry sectors as integral components of achieving net zero emissions by 2050 [1,3]. Leveraging the potential of the land-based sector for climate change mitigation entails implementing sustainable agricultural practices, afforestation and reforestation initiatives, and enhancing soil carbon sequestration [2]. Agroforestry, the integration of trees and shrubs into agricultural landscapes, is regarded as a sustainable approach to climate change mitigation and resource management [4]. By incorporating trees or shrubs alongside crops or livestock, agroforestry systems create microclimates that promote beneficial interactions among plants, animals, and soil organisms [5]. This results in enhanced nutrient cycling, reduced wind erosion, improved soil health and water retention, and increased habitat diversity, contributing to overall ecosystem health and resilience [6]. In Europe, the most common forms of agroforestry include windbreaks, alley cropping, silvopasture, and forest farming [7,8]. Agroforestry also plays a crucial role in climate change mitigation by sequestering carbon dioxide ($CO_2$) from the atmosphere, which is then stored in biomass, soils, litter, and woody debris [2].

According to Lal [9], in temperate climate zones, replacing natural ecosystems with conventional agriculture can lead to carbon losses of up to 60%. Advances in cultivation technology, including mechanization and widespread monocultures, have contributed to declines in soil organic carbon (SOC) levels in recent decades [10,11]. Expanding agroforestry practices offers an opportunity to counteract this harmful trend by reducing soil $CO_2$ emissions and increasing carbon sequestration in both soil and woody biomass [12–14]. The potential for carbon sequestration varies depending on the agroforestry practice used. According to Kay et al. [15], 8.9% of arable land in the 27 member states of the European Union is suitable for agroforestry practices. Converting these areas to agroforestry systems could lead to carbon sequestration between −7.78 and −234.85 Mg $CO_2$ eq per year, representing 1.4% to 43.4% of the total greenhouse gas emissions in Europe. Therefore, expanding agroforestry on a larger scale offers significant opportunities for achieving zero-emission agriculture in the future. In support of these findings, Hart et al. [16] and Aertsens et al. [17] advocated agroforestry as the most promising tool for climate change mitigation and adaptation in agriculture.

Estimating the carbon sequestration capacity of agroforestry systems requires robust methodologies and models. Common methods include direct measurement of biomass and soil carbon stocks, as well as indirect approaches such as remote sensing and modeling approaches. Agroforestry system models offer the potential for advancing ecological understanding while providing improved directions for future experimentation [18]. Agroforestry model forecasts can also be utilized to aid decision-makers in the formulation of climate change mitigation strategies and interventions. Nonetheless, the complex interactions within agroforestry systems across spatial and temporal domains pose challenges in model development [19]. The principal objectives of agroforestry models include the ability to replicate above- and belowground dynamics concerning light, water, and nutrient interactions; diverse potential yields encompassing food, fiber, and fuel; and provisioning of ecosystem services such as excess nutrient capture, soil erosion mitigation, and carbon sequestration [20]. Preferably, process-based models, rather than empirical ones, are favored for agroforestry systems owing to their ability to simulate the intricate dynamics of tree–crop interactions and facilitate extrapolations beyond available data for parameterization [21–23]. Despite the richness of process-based models in the forestry and agronomy domains, their availability for agroforestry remains constrained [18,20].

Basic agroforestry models were initially adapted from preexisting crop models. For example, CROPGRO [24] and STICS [25] have been employed to simulate agroforestry systems by merely diminishing the light exposure accessible to crops [26,27]. Similarly, adaptations of CROPGRO and EPIC [28] were utilized to assess the impact of windbreaks on crops by adjusting crop exposure to wind and radiation [29,30]. Additionally, the WIMISA model integrates belowground water competition between trees and crops [31]. Nevertheless, none of these basic models forecast tree growth or simulate crop productivity across numerous seasons. Certain process-based models have been specifically developed to accommodate agroforestry systems. Among agroforestry models, WaNuLCAS [32] stands out as the most commonly and effectively utilized model and is capable of integrating light, water, and nitrogen competition throughout an entire system rotation. While successfully applied in various tropical agroforestry contexts [33–36], WaNuLCAS was not originally tailored for temperate systems. As another example, Yield-SAFE is a one-dimensional biophysical model designed to simulate agroforestry system productivity throughout an entire tree rotation, considering light and water interactions, coupled with a bioeconomic model for profitability assessment [37,38]. The APSIM crop model was adapted to simulate hedge growth and competition for water and light with neighboring crops in a two-dimensional context [39]. The HyPAR model [40], a fusion of the Hybrid forest model [41] and the PARCH crop model [42], has been utilized for predicting agroforestry system productivity across diverse aridity gradients [43]. The Hi-sAFe model was developed as part of the Silvoarable Agroforestry for Europe (SAFE) project. It is a three-dimensional, process-based biophysical model that integrates tree–crop interactions within agroforestry systems [19,44,45]. Additionally, models such as the AFOLU Carbon Calculator [46] and the Integrated Farm System Model [47] of the United States Department of Agriculture can be used to predict the yield and carbon sequestration potential of different agroforestry configurations under varying environmental conditions. The application of all existing agroforestry models to date has been hampered by limitations in flexibility, complexity in simulating interactions, or challenging parameterization requirements [20]. The Forest Industry Carbon Model (FICM) [48] is a yield table-derived carbon model developed in the context of the ForestLab project conducted at the University of Sopron [49] to evaluate the carbon balance of the Hungarian forestry and wood industry sector.

In Hungary, windbreaks are the most common agroforestry landscape elements, comprising rows of trees and forest strips positioned to shield fields from wind and prevent soil erosion. Gál [50,51] carried out extensive experiments on the effects of windbreaks in preventing erosion and improving crop productivity, concluding that the harsher the conditions or the drier the climate, the greater the beneficial impact on the microclimate and crop yields. Windbreaks are highly effective in preventing wind erosion, especially in the sandy soils found in the Hungarian lowlands. They also enhance soil moisture content, which is essential in the country's dry climate regions characterized by forest steppe and steppe climate. Given these positive impacts and the ongoing climate change, it can be expected that windbreaks will become increasingly important in agriculture. In Hungary, the area covered by windbreaks was more extensive in the 1970s, with around 35,000 hectares [52,53], compared to an estimated 14,000 hectares today, as reported by Király et al. [54]. An important innovation in the Hungarian agricultural subsidy system starting in 2023 is that the agricultural land occupied by agroforestry systems remains eligible for direct area-based subsidies [55]. In addition, agroforestry systems can be considered agro-ecology program elements and landscape elements. Given these favorable changes in the subsidy system, it is likely that the area of windbreaks in Hungary will expand. Thus, it is increasingly important to assess the carbon sequestration potential of these areas, as they are an additional means of land-based climate change mitigation.

In the Eighth National Communication and Fifth Biennial Report of Hungary [56], agroforestry systems are identified as potential solutions for mitigating climate change. However, the report does not provide numerical estimates of the carbon sequestration achieved by existing agroforestry systems, nor does it quantify the climate change mitigation potential of establishing additional agroforestry systems. Király et al. [54] estimated the total annual carbon sequestration realized in the aboveground biomass pool of Hungarian windbreaks to be $-33$ kt$CO_2$/year, which is equal to 0.7% of the total annual carbon sequestration of the aboveground biomass pool of all Hungarian forests, as reported by the Hungarian Greenhouse Gas Inventory [57].

Nonetheless, the potential for future carbon sequestration and climate mitigation through agroforestry measures in Hungary remains unexplored, and there is no available information on how agroforestry systems might contribute to achieving the 2030 and 2050 land-use sector (LULUCF) carbon removal targets. Recognizing this research gap, we are evaluating the impact of agroforestry systems on climate change mitigation and adaptation within the framework of the ForestLab project. For this purpose, we developed the Windbreak module of the FICM model [58,59]. The objective of our current study is to assess the impact of doubling the extent of windbreak plantations in Hungary by estimating the total amount of carbon sequestered and the total annual climate change mitigation potential up to 2050. For the modeling, we use the newly developed Windbreak module of the FICM. The assumptions behind the study objectives are as follows: (i) newly established windbreak plantations sequester a significant amount of carbon and store it in their biomass, dead organic matter, and soil pools; (ii) the establishment of new windbreak systems can be an effective climate change mitigation measure in Hungary.

## 2. Materials and Methods

### *2.1. The Specifics of the Proposed Measure*

Király et al. [54] estimated the total area and biomass carbon sequestration of windbreaks in Hungary. They reported that approximately half of the area of windbreaks is under forest management planning and is recorded in the National Forestry Database (NFD). In this study, we used their estimates of the total area of existing windbreak plantations and assumed that this area would double in the upcoming years (Figure 1).

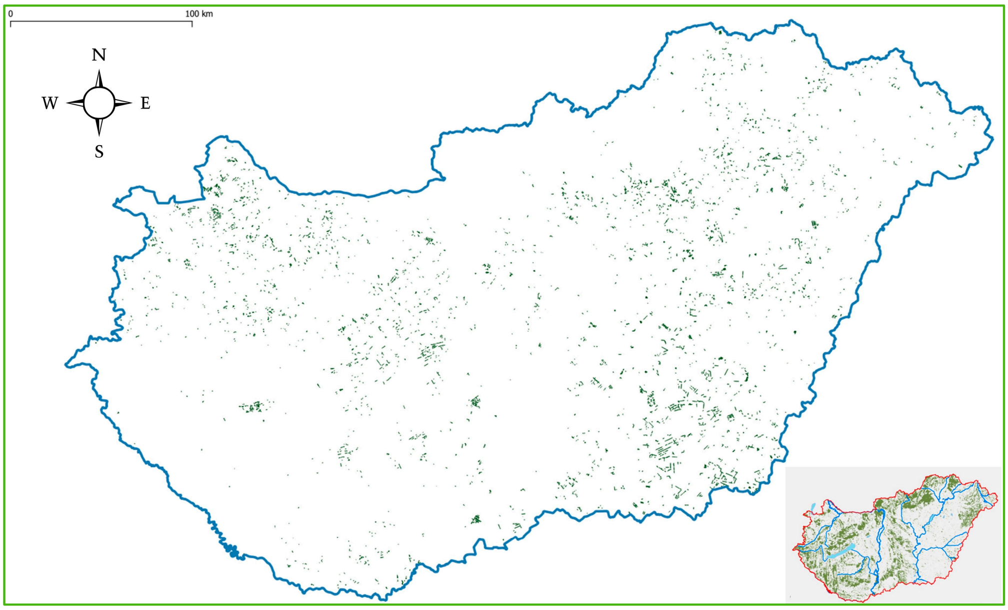

**Figure 1.** The area of windbreaks under forest management planning, as recorded in the National Forestry Database (NFD). Lower right corner: The area of all forest stands under forest management planning. Data from these forests were used for the BAU projection.

In other words, we assumed that the size of new windbreak plantations would be equal to the already existing windbreak area. Thus, it was hypothesized that a cumulative total of 14,256 hectares of windbreak plantations (Figure 2) would be established over a five-year period, spanning 2025–2029, with the initial planting distributed evenly across the five years. The introduction of a new agroforestry subsidy system in Hungary supports this hypothesis. It is also worth noting that even with the assumed initial planting, the total area of windbreaks would reach 28,512 hectares, which is still below their historical extent in the 1970s. Therefore, the assumption remains realistic.

Throughout the modeling process, we assumed that all timber harvested from these plantations between 2025 and 2050 would be utilized for firewood. The carbon balance of harvested wood products (HWPs) and substitution effects were modeled in accordance with this assumption.

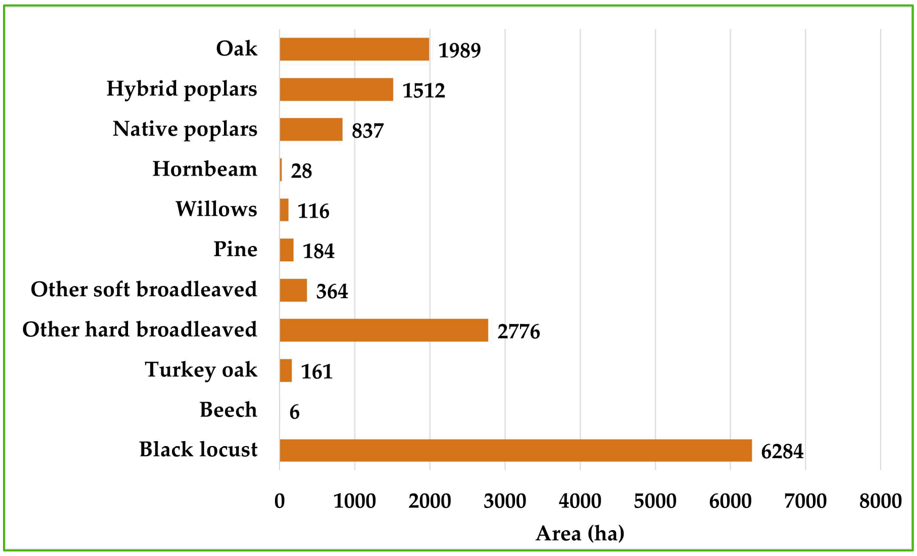

**Figure 2.** Total area and tree species distribution of the windbreak plantations assumed to be planted between 2025 and 2029.

### 2.2. Methodological Framework

In this study, we used the FICM (Figure 3), which is a country-specific carbon balance model developed in the context of the ForestLab project [48]. The model is designed to estimate the carbon balance of the forest biomass, dead organic matter (DOM), and soil pools, as well as the carbon storage, product, and energy substitution effects and net emissions arising from HWPs. The FICM model was selected for this assessment, as it is a country-specific model aligned with the Hungarian Greenhouse Gas Inventory and the NFD data. Additionally, its results would be comparable to previous assessments, such as those by Borovics et al. [48] and Király et al. [60].

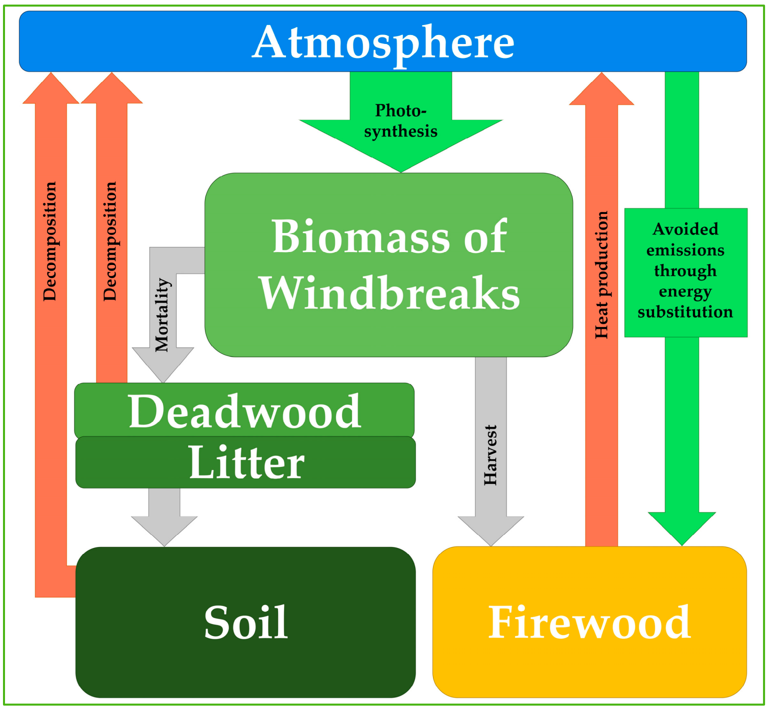

**Figure 3.** Flowchart of the FICM Windbreak module.

The FICM model uses 20 different country-specific yield tables [61], and each tree species group is modeled with the corresponding tree species-specific table, which is also used by the Hungarian Forest Authority for forest management planning purposes. Each yield table uses 6 yield classes and a specific parameter called the mean annual increment of total production at the reference age. This value is expressed in $m^3$/ha/year units and provides information on the productivity of the stand. The reference ages are 25 years and 75 years for tree species with short rotation periods and long rotation periods, respectively. Yield table-driven volume stock estimates are always corrected with the respective canopy closure values of the stands. Biomass carbon stock and carbon sink estimates are derived from volume stock data via country-specific wood density values [57] and carbon fraction values as defined by the IPCC [62,63]. The soil, dead wood, litter, and harvested wood product carbon stock change values are also estimated in accordance with the Hungarian Greenhouse Gas Inventory [57].

The FICM model estimates the magnitude of emissions avoided through product and energy substitution on the basis of the methodology given by Leskinen et al. [64]. For energy substitution, a substitution factor of 0.67 kt$CO_2$/kt $CO_2$ was used in accordance with Myllyviita et al. [65], Knauf et al. [66,67], Härtl et al. [68], and Schweinle et al. [69].

To create an FICM submodule specific to Hungarian windbreaks, we conducted an assessment based on data from the NFD, and we studied the yield class distribution and canopy closure of all forest subcompartments of the NFD with a windbreak function. The assessment is described in detail in two dedicated studies [58,59]. Figures 4 and 5 summarize the results of the assessment of Király and Borovics [58,59]. As the mean productivity and canopy closure differ for windbreaks compared with the country average, we parametrized the biomass carbon sequestration equations of the FICM using the average values specific for windbreaks.

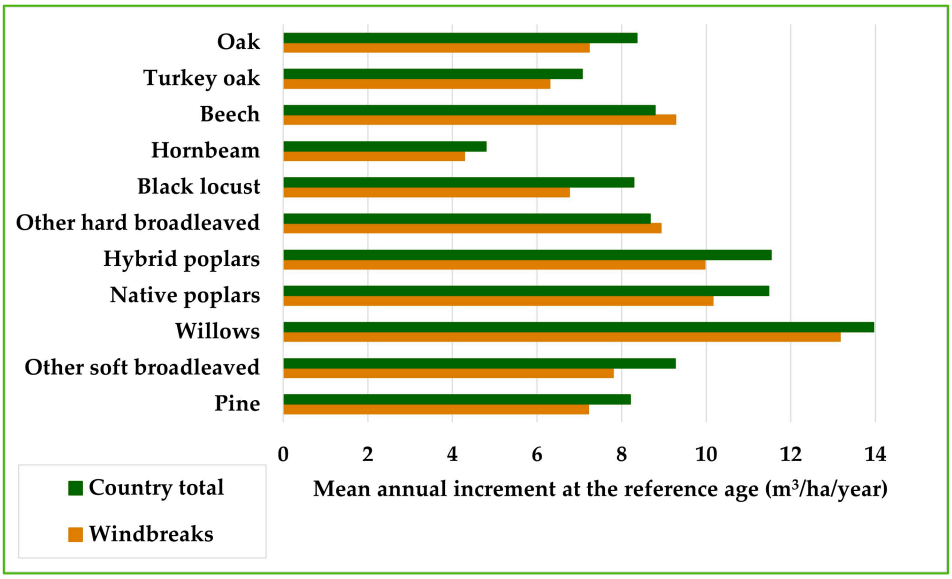

**Figure 4.** Mean annual increment of the total production at a reference age by tree species group. The average values for all forest subcompartments in Hungary (total country group) and the average values for the windbreaks are shown separately for each tree species group. Data are based on the assessments by Király and Borovics [58,59].

The original soil carbon sequestration equations of the FICM model were also changed and parametrized based on the study of Wenzel et al. [70], which is specific to field protection forest strips. The results of Wenzel et al. [70] align with the soil measurement data from Szabó et al. [71], who examined the carbon content in soils under a Hungarian windbreak plantation and in the neighboring agricultural field. Based on these data, we created the windbreak-specific module of the FICM and used this module to quantify the amount of carbon that could be sequestered by doubling the extent of windbreak plantations in Hungary.

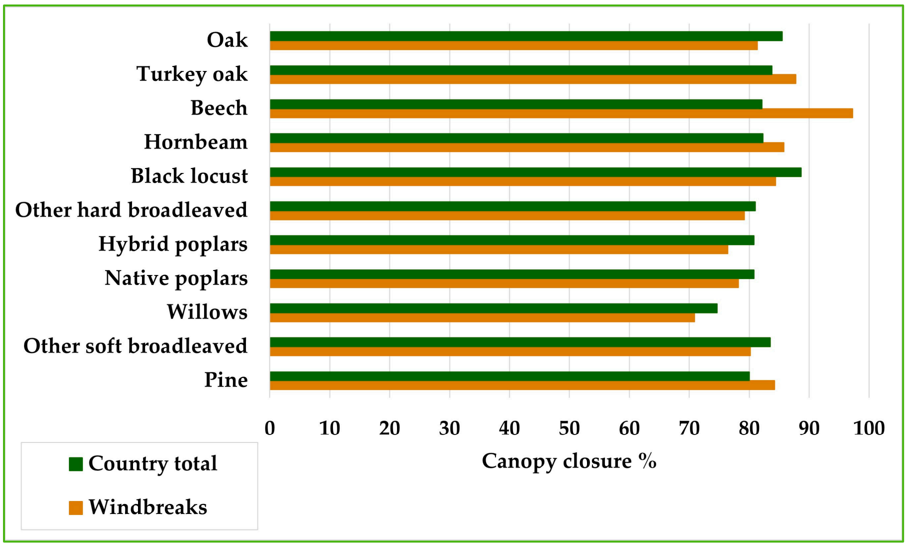

**Figure 5.** Average canopy closure by tree species group in all forest subcompartments of the country as well as in the windbreaks. Data are based on the assessments by Király and Borovics [58,59].

To assess the mitigation effect of the proposed measure, we also conducted business-as-usual (BAU) modeling for Hungary's entire forested area using the FICM model. This analysis focused on the carbon balance of forest land remaining forest land, a category also used in the Hungarian Greenhouse Gas Inventory [57]. The modeling employed BAU harvest and regeneration matrices, as defined by Kottek [61]. Based on the BAU projection, the average annual carbon sequestration for forest land remaining forest land was calculated for 2025–2050, and it was compared with the projected annual average carbon sequestration of the proposed windbreak plantations. The methodological framework is detailed in Figure 6.

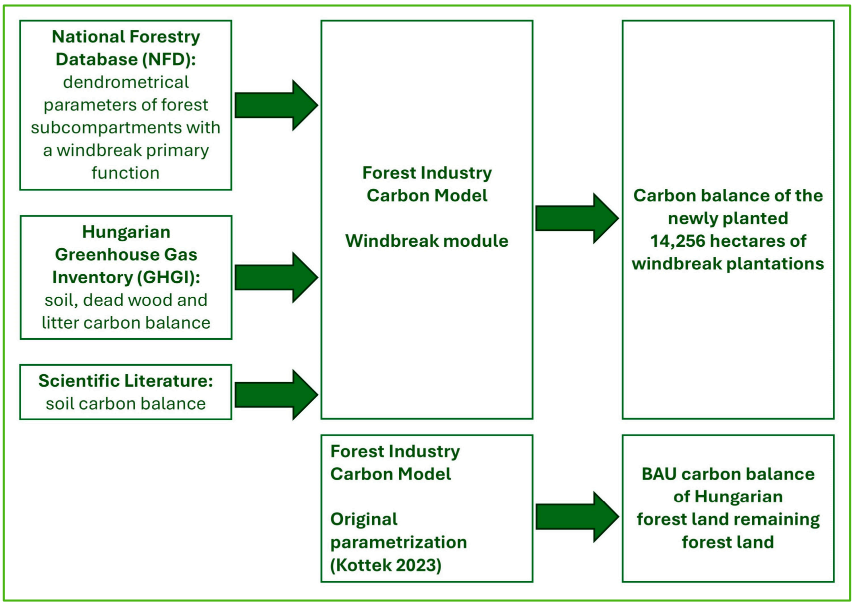

**Figure 6.** Flowchart of the methodological framework applied in this study. (BAU: business as usual) [61].

## 3. Results

A cumulative amount of 913 kilotons of carbon (kt C) is projected to be sequestered by the windbreak plantations established across a combined expanse of 14,256 hectares (Figures 6 and 7). Thus, by 2050, a mean carbon stock of 64.04 t C/ha will be reached in the new windbreak areas, while the average tree biomass carbon stock is projected to be 38.44 t C/ha at that time. Black locust (*Robinia pseudoacacia*) plantations contribute 42% of the total carbon sequestration, while oaks (*Quercus robur*, *Quercus petraea*, *Quercus pubescens*, *Quercus rubra*), other hard broadleaved species, and hybrid poplars account for 19%, 17%, and 11%, respectively, of the total carbon sequestered (Figure 7). The modeling results reveal that 60% of the carbon sequestered would be stored in the biomass pool by 2050, whereas 24% would be stored in the soil pool, and 16% would be stored in the DOM pools (litter plus dead wood) (Figure 8).

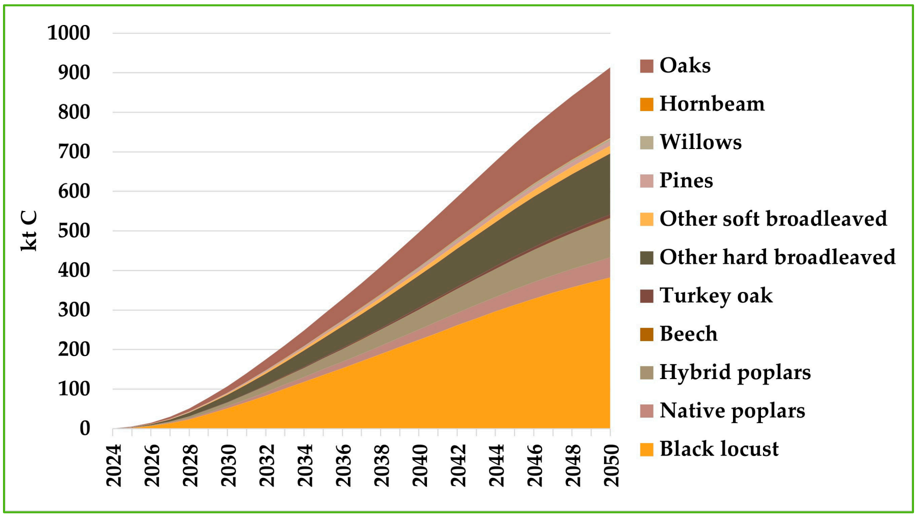

**Figure 7.** Total carbon stock accumulated in the newly planted windbreak plantations sorted by the tree species group of the plantation.

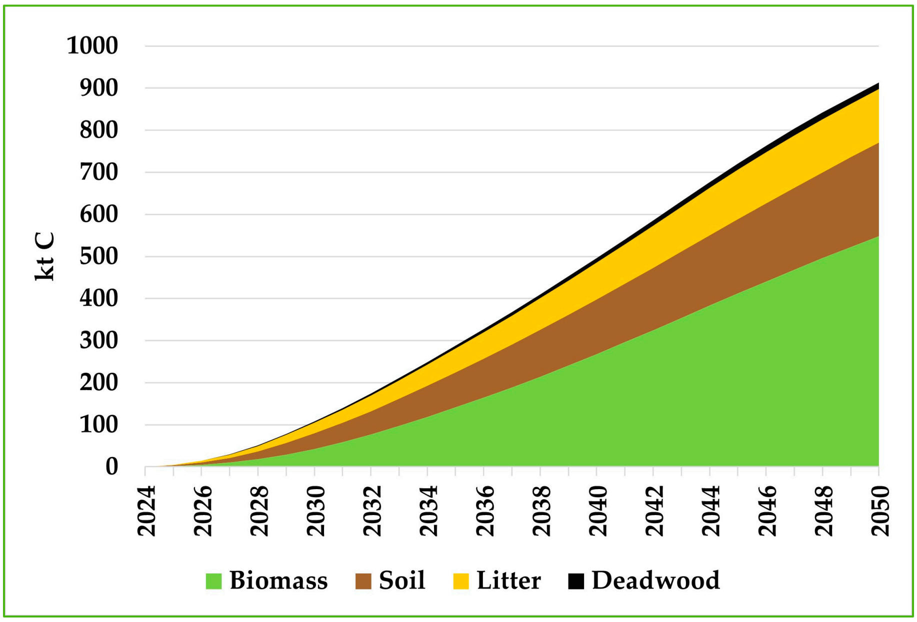

**Figure 8.** The carbon stock accumulated in the biomass, soil, litter, and dead wood pools of the newly planted windbreak plantations.

The total projected annual carbon sequestration of the windbreak plantations is estimated to range between −18 and −167 kt $CO_2$ eq (Figure 9). Meanwhile, the average annual carbon sequestration is projected to be −10.10 t $CO_2$ eq/ha/year during the 2025–2050 period. According to the model, the majority of litter and deadwood accumulation occurs within the initial 20 years, after which the stocks gradually reach saturation.

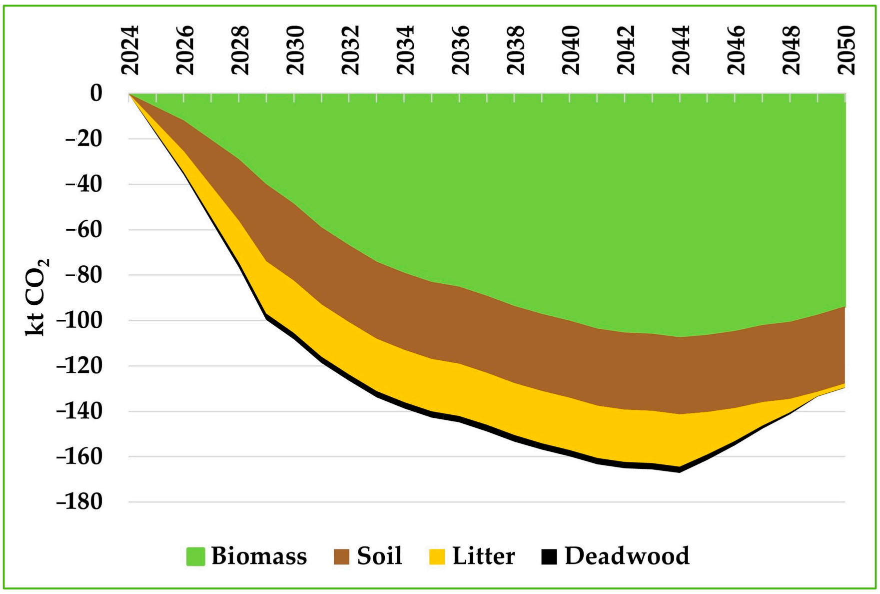

**Figure 9.** Annual carbon sequestration of newly planted windbreak plantations by carbon storage pools. (Negative values indicate carbon sequestration expressed in kt $CO_2$.).

According to our presumption, only firewood is produced from the thinning of windbreak plantations. This means that no carbon stock accumulation in the HWP pool is taking place, as firewood is assumed to be combusted in the year after harvest. Figure 10 shows the carbon content of firewood and the energy substitution effect associated with the heat production process.

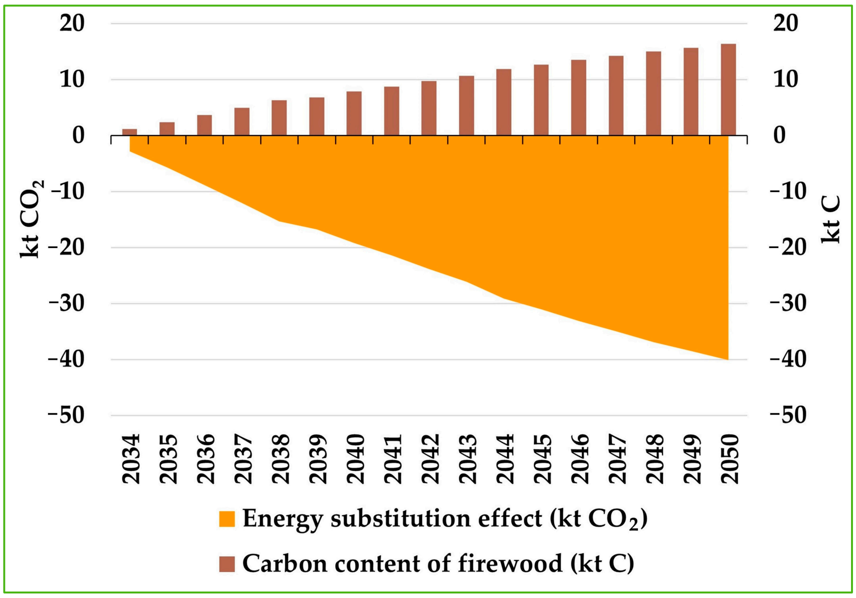

**Figure 10.** Carbon content of the produced firewood and the associated energy substitution effects. (Negative values indicate energy substitution expressed in kt $CO_2$, whereas positive values indicate the carbon stored in firewood expressed in kt C values.)

When considering the establishment of new windbreak plantations as a climate change mitigation measure, we can estimate the average annual mitigation potential for the 2025–2050 period. Figure 11 presents the mean annual climate change mitigation potential across carbon pools in kt $CO_2$ eq, where positive values indicate additional carbon sequestration compared to a scenario without this measure. According to model estimates, the newly established plantations offer an annual mitigation potential of 144 kt $CO_2$ eq, with the majority of carbon sequestration occurring in the biomass pool.

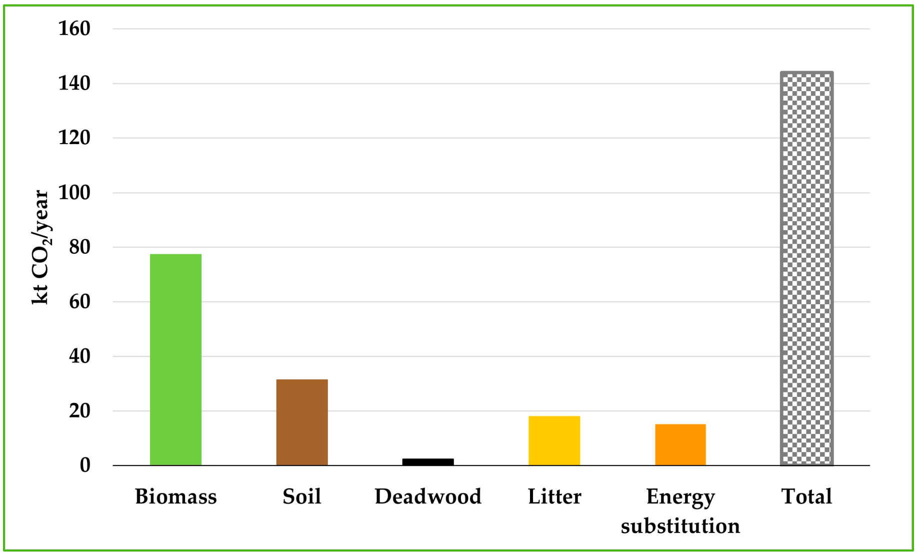

**Figure 11.** Total annual climate change mitigation potential values associated with newly planted windbreak plantations for the period of 2025–2050 sorted by carbon pools.

Figure 12 illustrates the projected carbon sequestration from the proposed windbreak plantations in comparison with the BAU projection for forest land remaining forest land. The graph does not include energy substitution effects, as these cannot be accounted for within the LULUCF sector. The results indicate that during the 2025–2050 period, the assessed measure could enhance BAU forest land carbon sequestration by an additional 5%.

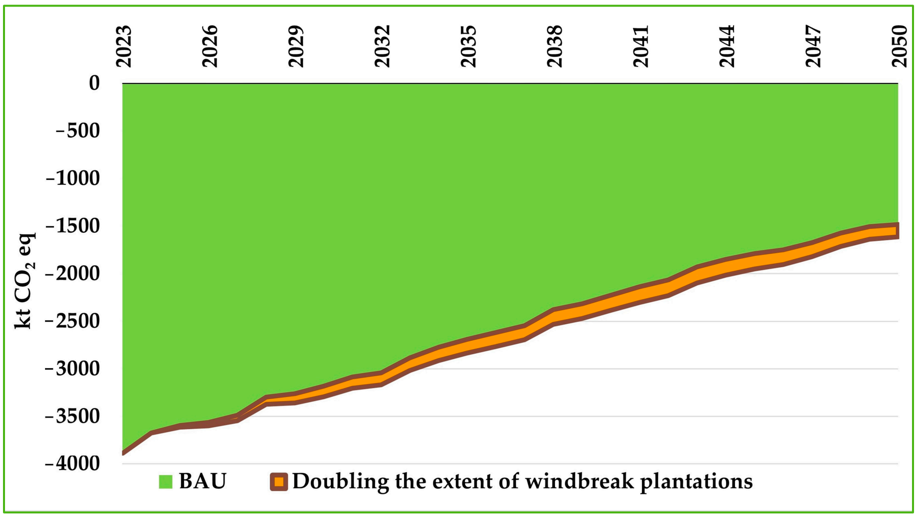

**Figure 12.** Annual projected carbon sequestration of forest land remaining forest land and the additional carbon sequestration that could be achieved by doubling the extent of windbreak plantations.

## 4. Discussion

We estimate that the total annual mitigation potential of establishing new windbreak plantations is 144 kt $CO_2$ eq, which is equivalent to 2% of the total land-use sector (LULUCF) carbon sequestration reported in the 2021 Hungarian Greenhouse Gas Inventory (GHGI) [57]. According to the GHGI, only forests and HWPs produce net carbon sequestration among the subsectors of the LULUCF sector. For the cropland subsector, a total of 119 kt $CO_2$ emissions are reported for 2021 under the LULUCF sector. These emissions originate from the soil pool and are attributable to land use changes in croplands. According to our estimate, these emissions could be offset by the plantation of 14,256 hectares of windbreaks. However, it is to be noted that the majority of emissions related to croplands are not reported under the LULUCF sector in the GHGI; instead, they are recorded within the agriculture sector. These emissions could not be offset in total by the assessed agroforestry measures.

The modeling results indicate a declining forest carbon sink for the period up to 2050 for forest land remaining forest land under BAU conditions. This underscores the need for additional climate change mitigation measures, such as the one evaluated in this study. Our findings reveal that doubling the extent of windbreak plantations could achieve an extra 5% carbon sequestration in forested areas as compared to BAU conditions.

Our results indicated an average net carbon sequestration of $-10.1$ t $CO_2$ eq/ha/year in newly established windbreak plantations. This aligns with the findings of Kay et al. [15], who estimated the carbon sequestration potential of suitable agroforestry practices in Europe to range between $-0.33$ and $-26.73$ t $CO_2$ eq/ha/year. According to Ma et al. [72], agroforestry systems, on average, contain 46.1 t C/ha (95% confidence interval, 36.4–55.8 t C/ha) more carbon in tree biomass than cropland or pastureland systems without trees. These findings support our results, as we project that the average biomass carbon sequestered by 2050 will be 38.44 t C/ha, which represents the additional tree biomass carbon compared with the initial cropland. Ma et al. [72] emphasized that incorporating multiple tree species in agroforestry systems is crucial for increasing carbon sequestration levels. Therefore, examining the effects of tree species diversity on carbon sequestration and storage in windbreaks would also be important in Hungary.

Our results show that black locust is the most important tree species in the context of carbon sequestration associated with windbreaks, accounting for more than 40% of the total projected carbon sink. This is attributable to its significant portion of the presumed initial planting area, along with its fast-growing nature. In Hungary, black locust stands out as the most significant non-native tree species [73]. It serves as a suitable choice for erosion control, amelioration, and restoration of disturbed sites owing to its drought tolerance. It constitutes approximately 35% of newly afforested land [74] and accounts for 44% of the total windbreak area across Hungary [54].

According to our estimate, in addition to carbon sequestration in the biomass pool, SOC uptake and storage in the soil pool also have significant effects; moreover, carbon accumulation in the DOM pool tends to increase, followed by saturation. The importance of SOC sequestration is increasingly acknowledged within the global community [70,75], emphasizing that practices enhancing SOC will play a pivotal role in mitigating and adapting to climate change [75,76]. Given the expansive spatial coverage of agricultural production, agroecosystems possess substantial potential for SOC sequestration and biodiversity enhancement [70]. Thus, implementing strategies that foster biodiversity and SOC sequestration is imperative for agriculture to contribute to sustainable development [70]. The establishment of windbreaks serves as a noteworthy example of such endorsed measures.

In line with our findings, Szabó et al. [71], who carried out soil carbon content measurements in a windbreak plantation in the Hungarian Great Plain, found increased SOC concentrations under the trees compared to the adjacent agricultural fields. Bidló et al. [77], in their case study, compared the soil carbon content of black locust and oak afforestation in Hungary with that of nearby fields sharing similar site conditions. The study revealed that newly afforested croplands have a higher carbon content than adjacent agricultural fields, primarily due to the accumulation of litter and humus. They concluded that forest plantations, with their abundant leaf litter and humus, can considerably boost carbon storage in the soil within a relatively short time frame (5–20 years). These findings are likely applicable to windbreak plantations composed of the same tree species.

Dmuchowski et al. [14] identified SOC sequestration as the most evident contribution of agroforestry systems to climate change mitigation. Our projection revealed that 15.60 t C/ha would be sequestered in newly planted windbreaks by 2050. Shi et al. [78] assessed carbon sequestration across various agroforestry systems, including alley cropping, home gardens, silvopastures, and windbreaks, in all climate zones. Their research indicated that agroforestry systems in tropical and subtropical regions store significantly more carbon compared to those in temperate zones. In temperate regions, the soil carbon stocks were reported as follows: home gardens (10 t C/ha) > alley cropping (2.2 t C/ha) > windbreaks (0.90 t C/ha) > silvopastures (0.70 t C/ha) [14]. These values are lower than our estimate. In contrast, Baah-Acheamfour et al. [79] analyzed data from Canada and reported that hedgerows had the highest carbon storage in soil (106.5 t C/ha), followed by shelterbelts (98.4 ± 14 t C/ha) and tree-based intercropping (83.6 ± 4 t C/ha). These findings suggest that shelterbelts have a much higher carbon storage capacity. This highlights the need for further investigation into the carbon sequestration and storage capacity of windbreaks in Hungary. It is important to note that our model's parameters are not exclusively based on country-specific data, resulting in greater uncertainties in our soil carbon sequestration estimates. To refine our model with country-specific data, extensive field measurements in windbreak plantations and control of arable land parcels are necessary.

Our results show that the energy substitution effect accounts for 11% of the total annual mitigation potential projected for the period 2025–2050. This amount is equal to the emissions avoided by using firewood instead of fossil fuels [64], and its share could be increased by using timber extracted from windbreaks to produce long-lived wood products that store carbon for decades and, in the meantime, substituted for other carbon-intensive materials.

The conducted modeling shows that the FICM Windbreak module is suitable for medium-term carbon projections related to agroforestry situations. The development of this new country-specific Windbreak module within the FICM constitutes a novel contribution to evaluating potential measures for meeting climate targets and developing and assessing nationally determined contributions (NDCs) to Hungary's LULUCF sector.

A limitation of our study is the lack of extensive country-specific soil carbon sequestration data for windbreaks. To enhance the accuracy and relevance of our model, it is essential to conduct soil measurements that reflect Hungary's specific conditions. These measurements would allow for precise parameterization of the model with localized data, thereby increasing the reliability of our findings on the soil carbon sequestration potential of windbreaks in Hungary.

Moreover, the current version of the model only projects carbon sequestration in soil, dead organic matter, and tree biomass while excluding the carbon balance of herbaceous plants and shrubs. Further development is required to model alley cropping systems, where the dynamics of intercrops must be considered. We also plan to expand the FICM framework by developing additional agroforestry submodels, specifically for alley cropping systems and standalone trees in croplands. This expansion will facilitate a more comprehensive evaluation of various agroforestry practices and their potential contributions to climate change mitigation in Hungary.

## 5. Conclusions

We conclude that by harnessing the synergies between trees and agricultural activities, agroforestry systems provide multiple benefits, including carbon sequestration in living biomass, dead organic matter, and soil pools. Our results show that in Hungary, a significant climate change mitigation potential is inherent in the establishment of new windbreak plantations on agricultural field boundaries. This highlights that agroforestry practices can foster resilient and productive agricultural landscapes while contributing to national efforts to combat climate change and promote sustainable development.

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