DOI: 10.34101/ACTAAGRAR/1/13673

Preparatory study for carbon sequestration modelling of agroforestry systems in Hungary: The assessment of the yield class distribution of windbreaks

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SUMMARY

The escalating carbon dioxide emissions leading to global climate change are acknowledged as a paramount environmental challenge in the twenty-first century. The significance of land use systems in stabilising carbon dioxide levels and enhancing carbon sink potential has gained noteworthy attention from both the scientific and political communities. The Intergovernmental Panel on Climate Change emphasises that agroforestry systems present vital prospects for synergising climate change adaptation and mitigation efforts, offering substantial technical mitigation potential. Windbreaks are well-known agroforestry systems in Hungary and form an important part of agricultural landscapes. The improved agroforestry subsidy system in our country makes it relevant to model the carbon sequestration potential of windbreaks. In the framework of the ForestLab project we plan to develop a carbon sequestration model specific for Hungarian agroforestry systems. In this study, as a preparatory step of the model development, we assessed the yield class distribution of Hungarian windbreaks by tree species group and identified variables that had significant effect on yield class based on the data of the National Forestry Database. Our results show that among the examined effects the most important predictor of the yield class of windbreaks was the tree species group, followed by the thickness of the productive soil layer and the hydrology of the site.

Keywords: *windbreaks; shelterbelts; climate change mitigation; carbon sequestration; modelling*

INTRODUCTION

The climate change mitigation benchmarks defined by the Paris Agreement and the European Green Deal urge significant reductions in anthropogenic greenhouse gas (GHG) emissions and an efficient offsetting of the inevitable emissions (Verkerk et al., 2022; Király et al., 2022). The capacity of the land use sector to remove carbon dioxide (CO_2) from the atmosphere and store it in the living and dead biomass and in the soils is considered key in climate change mitigation pathways (Verkerk et al., 2022). Climate change mitigation by means of nature-based solutions gains an increasing relevance (IPCC 2022). The Land Use and Forestry (LULUCF) sector has a crucial role in offsetting emissions of the Agriculture, Energy and Industry sectors (Borovics and Király, 2022; Borovics and Király, 2023).

Agroforestry is a land-use and management system that integrates the cultivation of trees or shrubs with agricultural crops or livestock, and it involves the intentional combination of agricultural and forestry practices in a sustainable and interactive manner (Nair, 2011; Borovics et al., 2017). Agroforestry systems are designed to optimize the benefits derived from both components, trees, and agricultural activities, to enhance productivity, biodiversity, and environmental sustainability (Borovics et al., 2017). Agroforestry systems provide economic, social, and environmental advantages relative to conventional farming systems, and agroforestry practices often have favourable land equivalent ratios, and thus can also pay a key role in upscaling carbon sequestration and storage in croplands (Borovics et al., 2017; Honfy et al., 2023; Király et al., 2024). There are various agroforestry practices, including alley cropping, silvopasture, forest farming, and windbreaks each tailored to specific ecological and agricultural contexts.

In Hungarian agricultural landscapes windbreaks are common elements. We define windbreaks as field protection tree rows and field protection forest strips. In response to the goals of the Carbon Farming directive, novel incentives have been implemented in the Hungarian agricultural subsidy system promoting the planting of windbreaks and single trees in croplands and grasslands. A significant innovation commencing in 2023 is that the agricultural land hosting agroforestry elements is also qualified for direct area-based subsidies, and windbreaks are eligible to be included as agroecology program elements and as landscape elements as well (NAK, 2023). The estimation of the carbon sequestration potential of windbreaks has an increasing importance as considering the favorable changes in the subsidy system we can foresee that these landscape elements will become important assets fostering land-based climate change mitigation.

The United Nations Framework Convention on Climate Change describes carbon sequestration as the method of extracting carbon from the atmosphere and depositing it in a reservoir, which can also be called a carbon pool (UNFCCC, 2006, 2007). In agroforestry systems, carbon sequestration mainly entails the absorption of atmospheric carbon dioxide during photosynthesis, the retention of the captured carbon in the biomass pool, and its transfer into detritus, and soil compartments for long-term storage (Nair et al., 2010; Nair, 2011). On average, the aboveground parts of agroforestry systems are estimated to hold roughly one-thirds of the total carbon stored, while the soil (including roots and other living biomass) are estimated to hold the two-thirds (Lal, 2010). The overall quantity of carbon stored in each carbon pool varies significantly based on various factors, such as the ecoregion, the agroforestry system type, the characteristics of the components, the age of the perennials, the site quality, and past land use

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(Nair, 2011). In our earlier study we assessed the total area and the mean annual carbon sequestration realized in windbreaks in Hungary based on the National Forestry Database (Király et al., 2024). We estimated the weighted mean annual carbon sequestration in the aboveground biomass of windbreaks to be −2.4 tCO_2/ha/year in the 2010–2020 period (Király et al., 2024). This value closely aligns with the mean annual carbon sequestration per hectare value reported for all Hungarian forests in the Greenhouse Gas Inventory (NIR, 2023; Király et al., 2024).

The estimation of tree biomass carbon sequestration can be carried out by whole-tree harvesting or by using allometric equations or yield tables (Nair, 2011; Fernández-Núñez et al., 2010). However, efforts in developing allometric equations and yield tables for agroforestry situations have generally been slow, and in many cases, these estimates use broad approximations (Nair, 2011). In Hungary three generation of country specific yield tables are available for all important forest tree species (Bondor, 1988; Peszlen, 2015). Hungarian yield tables use six yield classes defined with different productivity (yield class 1 is the most productive yield class, while yield class 6 means the least productive one). Hungarian yield tables are not specific for agroforestry; however, they can be used in the case of windbreaks if accurate canopy closure and yield class values are known.

In the frame of the ForestLab project (Borovics, 2022) which is a climate change mitigation and adaptation project carried out by the University of Sopron we plan to develop a carbon sequestration model specific for Hungarian agroforestry systems. This study is a preparatory step of the model development, where we assess the yield class distribution of Hungarian windbreaks by tree species group and identify variables that have significant effect on yield class based on the data of the National Forestry Database (NFD). Yield class is a necessary parameter for the use of yield tables which makes possible to model future volume stock and increment of the windbreak stands.

MATERIALS AND METHODS

In our study we used the official database of the Hungarian Forest Authority, the NFD stores data on the main attributes of each forest stand (also called forest subcompartment) subject to forest management planning (Tobisch and Kottek, 2013; Kottek et al., 2023). Forest management planning is based on field surveys. During the field surveys the height, diameter, basal area, age, and canopy closure of the stands are measured and yield class is also determined (Tobisch and Kottek, 2013). The NFD also defines the primary function of each forest subcompartment, which can be timber production, windbreak, nature protection, etc. (Király et al., 2024).

In this study we queried all stands with windbreak primary function from the 2020 state of the NFD at the country level, obtaining a whole country's windbreak forest stand group for further analysis. Thereafter we queried the area, geographic unit, canopy closure, climate, hydrology, soil type, thickness of productive soil layer, soil texture, age, tree species group, mixture rate, and yield class data of all stands and analyzed the data using Statistica software (Version 14.0.1.25, Tulsa, OK, USA). The primary goal of the data analysis was to obtain yield class distributions by tree species group and geographic unit for the parametrization of the carbon sequestration model under development. In addition, we also conducted a multiple regression analysis in order to identify variables that have significant effect on yield class.

RESULTS AND DISCUSSION

According to our results among the examined effects the most important predictor of the yield class of windbreaks was the tree species group, followed by the thickness of the productive soil layer and the hydrology of the site (*Table 1*).

Table 1. **Results of the multiple regression analysis**

Parameter Estimates: Sigma-restricted parameterization										
Effect	yield class (Param.)	yield class (Std.Err)	yield class (t)	yield class (p)	-95,00% (Cnf.Lmt)	+95,00% (Cnf.Lmt)	yield class (Beta (ß))	yield class (St.Err.ß)	-95,00% (Cnf.Lmt)	+95,00% (Cnf.Lmt)
Intercept	-30.97	1.92	-16.14	0.00	-34.73	-27.21				
tree species group	0.10	0.01	19.43	0.00	0.09	0.11	0.25	0.01	0.22	0.27
thickness of productive soil layer	-0.42	0.02	-17.14	0.00	-0.47	-0.37	-0.20	0.01	-0.22	-0.17
hydrology	-0.17	0.01	-15.60	0.00	-0.19	-0.15	-0.19	0.01	-0.22	-0.17
canopy closure	-0.01	0.00	-9.25	0.00	-0.01	-0.01	-0.11	0.01	-0.13	-0.09
soil texture	0.11	0.01	7.71	0.00	0.08	0.14	0.11	0.01	0.08	0.13
mixture rate	0.01	0.00	8.49	0.00	0.00	0.01	0.10	0.01	0.08	0.12
geographic unit	-0.05	0.01	-4.56	0.00	-0.07	-0.03	-0.06	0.01	-0.09	-0.03
climate	0.10	0.03	3.46	0.00	0.04	0.15	0.04	0.01	0.02	0.07
soil type	0.00	0.00	-0.65	0.52	0.00	0.00	-0.01	0.01	-0.04	0.02
area	0.00	0.01	0.48	0.63	-0.01	0.02	0.01	0.01	-0.02	0.03
age	0.00	0.00	-0.42	0.68	0.00	0.00	-0.01	0.01	-0.03	0.02

Numbers highlighted in red denote significant effect.

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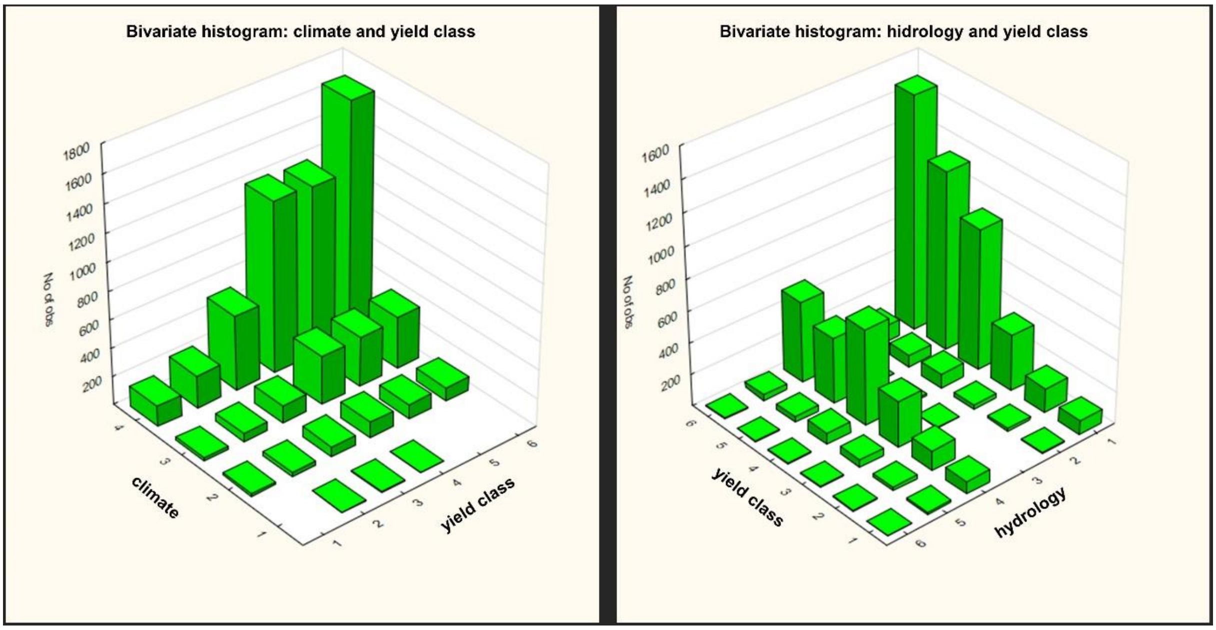
The analysis showed that the canopy closure, the soil texture, the tree species mixture rate, the geographical location, and the climate also had significant effect on the yield class of stands. However, the effect of the soil type, the area, and the age of the stand was not significant.

According to our results 31% of the area of windbreaks belongs to yield class 6, while 25–25% belongs to both yield class 5 and 4. Yield class 1–3 altogether represent the 19% of the area of windbreaks. 77% of the area of windbreaks is in forest steppe climate zone, while 18% belongs to the Sessile oak – Turkey oak climate zone (*Figure 1*). Forest steppe climate zone is the driest and the most unfavorable for the growth of forests. This explains the overrepresentation of yield class 6 among windbreaks in Hungary.

As regards hydrology of the stands, in 59% of the area no excess water is available, while 30% is under periodic water effect (*Figure 1*). In 58% of the area the soil texture is loam, and 65% of the area is on medium depth productive soil layer (*Figure 2*). The 65% of the area of windbreaks is located in the Great Plain and 13% in the Little Plain, which are the two largest and most important lowland areas of Hungary, where windbreaks are most common (*Figure 3*). Black locust (*Robinia pseudoacacia*) is the most widespread tree species among windbreaks covering 41% of the total windbreak area of the country. This can be explained by the fact that in artificially drained semi-desert habitats found in Hungary, often only the introduced black locust proves viable for successful afforestation (Borovics and Király, 2023). Black locust is a very popular and widespread tree species in Hungary due to its fast-growing nature, and high drought tolerance. It is a nitrogen-fixing species with a favorable effect on soil productivity. It has a key role in the field of plantation forestry worldwide due to its adaptability to different climatic and site conditions, and owing to its high-quality timber, and bee forage supply (Ábri and Csajbók, 2023). Black locust has also gained an increasing importance as energy woody plantation, resulting from its fast-growing nature and relatively easy and cost-effective regeneration (Szmorad and Tímár, 2014). According to our results black locust is also an important tree species of agroforestry systems, like windbreaks in Hungary. This study indicates that the average yield class of black locust in Hungarian windbreaks is yield class 5, while the mode of the data set in the case of black locust is yield class 6.

Figure 1. **Left: bivariate histogram of the climate and yield class of windbreaks. Right: bivariate histogram of the hydrology and yield class of windbreaks.**



Climate codes are the following: 1 Beech climate, 2 Hornbeam – oak climate, 3 Sessile oak – Turkey oak climate, 4 forest steppe climate. Yield class codes: 1 means the most productive yield class, while 6 means the less productive yield class.

Hydrology codes are the following: 1 independent of the effect of excess water, 2 fluctuating water supply, 3 leaking water, 4 periodic water effect, 5 permanent water effect, 6 wet to the surface.

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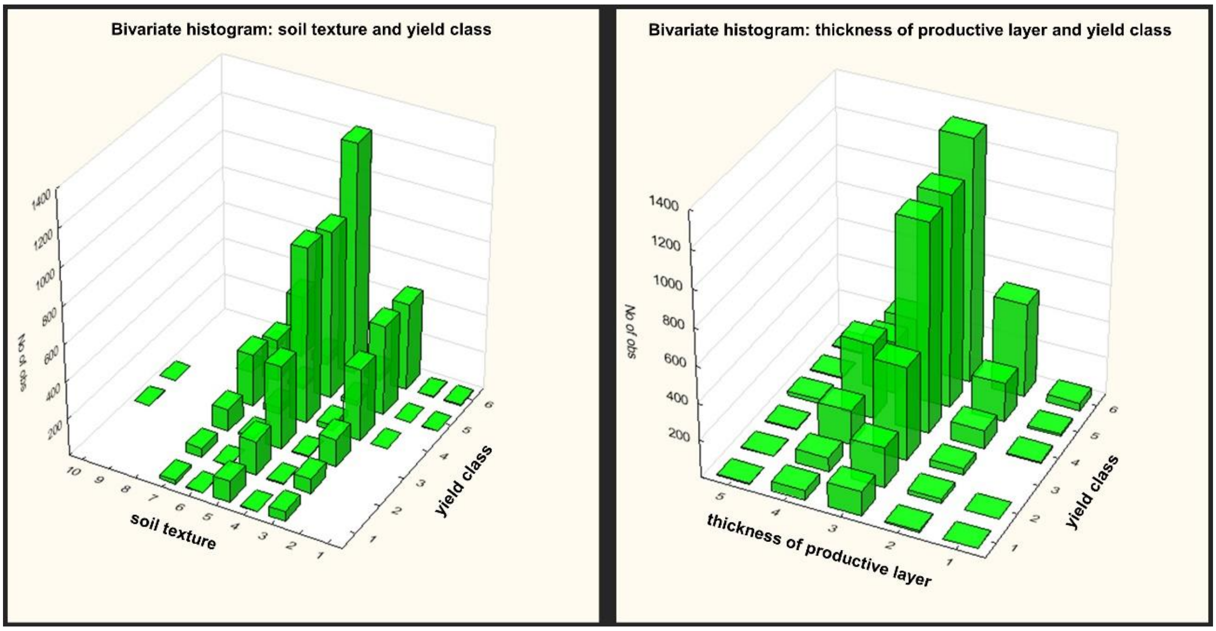
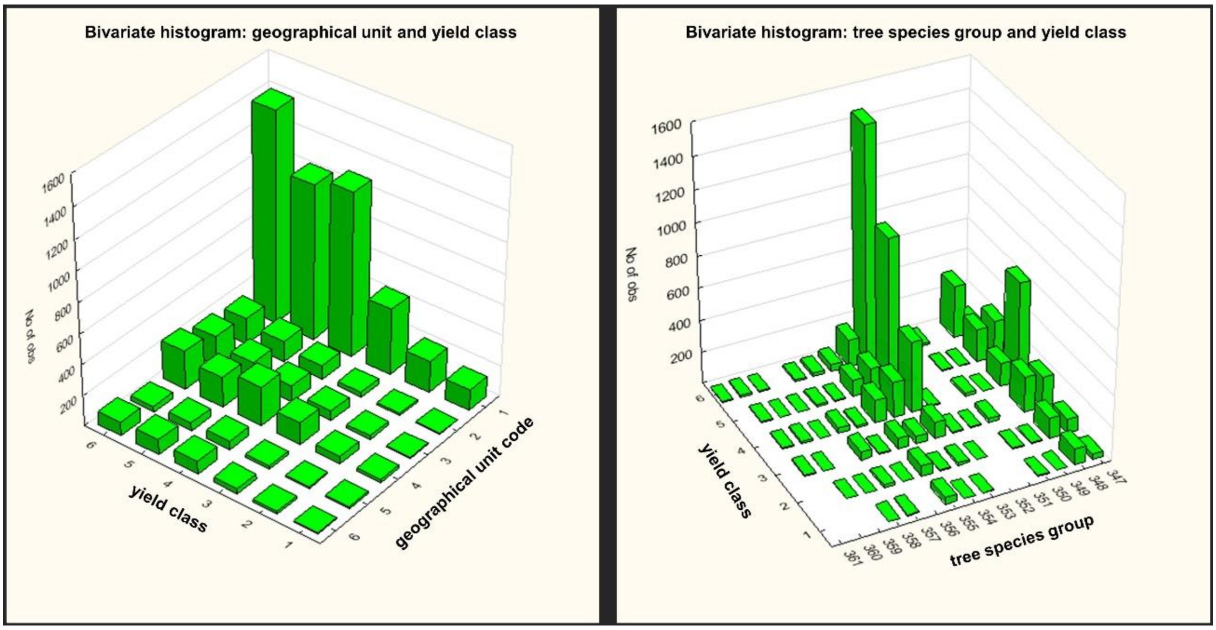
Figure 2. **Left: bivariate histogram of the soil texture and yield class of windbreaks. Right: bivariate histogram of the thickness of soil productive layer and yield class of windbreaks**



Soil texture codes are the following: 1 debris, 2 coarse sand, 3 sand, 4 sandy loam, 5 loam, 6 clay loam, 7 clay, 8 clayey sand, 9 sandy clay, 10 heavy clay. Yield class codes: 1 means the most productive yield class, while 6 means the less productive yield class.

Thickness codes are the following: 1 means the shallowest, while 5 means the deepest.

Figure 3. **Left: bivariate histogram of the geographical unit and yield class of windbreaks. Right: bivariate histogram of the tree species group and yield class of windbreaks.**



Geographical unit codes are the following: 1 Great Plain, 2 North Central mountains, 3 Transdanubian Central Mountains, 4 Little Plain, 5 West Transdanubia, 6 South Transdanubia. Yield class codes: 1 means the most productive yield class, while 6 means the less productive yield class.

Tree species group codes are the following: 347 Pedunculate oak, 348 Sessile oak, 349 Red oak, 350 Turkey oak, 351 Beech, 352 Hornbeam, 353 Black locust, 354 Hybrid poplars, 355 Indigenous poplars, 356 Willows, 357 Alder, 358 Birch, 359 Scots pine, 360 Black pine, 361 Norway spruce.

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CONCLUSIONS

In this study we assessed the yield class distribution of Hungarian windbreaks by tree species group, and we identified variables that have significant effect on yield class based on the data of the NFD. Our results show that among the examined effects the most important predictor of the yield class of windbreaks was the tree species group, followed by the thickness of the productive soil layer and the hydrology of the site. We also assessed the yield class distribution of windbreaks by tree species groups. These results will be used in the parametrization of a carbon sequestration model specific for Hungarian agroforestry systems. As not all windbreaks are under forest management planning in Hungary it would be also important to assess the dendrometrical parameters of those windbreaks which are not registered in the NFD. For this purpose, remote sensing-based assessment could be appropriate, as it is more cost effective than large-scale filed surveys.

ACKNOWLEDGEMENTS

This article was made in frame of the project TKP2021-NKTA-43 which has been implemented with the support provided by the Ministry of Culture and Innovation of Hungary from the National Research, Development and Innovation Fund, financed under the TKP2021-NKTA funding scheme.

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