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Fall-Winter 2025

Environmental management, land use, biodiversity

PREPARATORY STUDY FOR CARBON SEQUESTRATION MODELLING OF AGROFORESTRY IN HUNGARY ■ THE CLIMATE REGULATORY ROLE OF SÁRVÁR'S URBAN FORESTS ■ ENVIRONMENTAL FACTORS AND THE ROLE OF SENSORS IN CLIMATE MONITORING OF LIVESTOCK BUILDINGS

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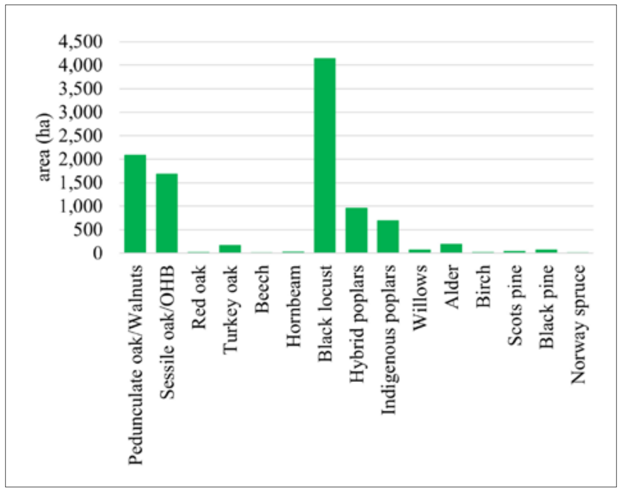

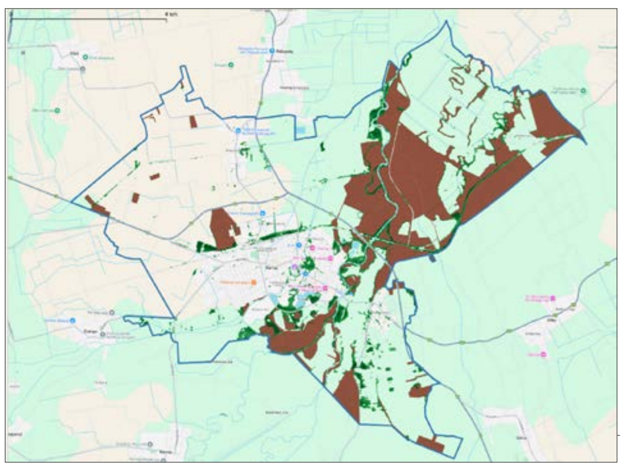

PREPARATORY STUDY FOR CARBON SEQUESTRATION MODELLING OF AGROFORESTRY IN HUNGARY – THE ASSESSMENT OF THE AVERAGE CANOPY CLOSURE OF WINDBREAKS

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ABSTRACT

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 improved agroforestry subsidy system in Hungary makes it relevant to model the carbon sequestration of windbreaks. In the frame of the ForestLab project we plan to develop a carbon sequestration model specific for Hungarian windbreaks. In this study we assess the average canopy closure of Hungarian windbreaks by tree species group based on the data of the National Forestry Database as a preparatory step of the model development. Our results show that the canopy closure of windbreaks under forest management planning in Hungary is relatively high, ranging between 74-96%. Among the examined effects the most important one is the age of the stand, which has the highest impact on the value of the canopy closure. Tree species group and production capacity are also important predictors of canopy closure.

keywords: windbreaks, shelterbelts, climate change mitigation, carbon sequestration, modelling

INTRODUCTION

In the light of the Paris Agreement and the European Green Deal climate change mitigation by means of nature-based solutions is becoming increasingly relevant (IPCC 2022). The Land Use and Forestry (LULUCF) sector has a crucial role in offsetting inevitable emissions of the Agriculture, Energy and Industry sectors. Agroforestry practices are key in upscaling carbon sequestration and storage in croplands (Borovics et al. 2017, Borovics and Király 2022, Honfy et al. 2023).

The International Centre for Research in Agroforestry (ICRAF) defines the term agroforestry as a dynamic, ecologically based natural resources management system that, through the integration of trees in farmland, diversifies and sustains production for increased social, economic and environmental benefits (Mosquera-Losada et al. 2009). The World Agroforestry Centre (WAC) highlights that in agroforestry systems woody perennials (trees, shrubs etc.) are deliberately used on the same

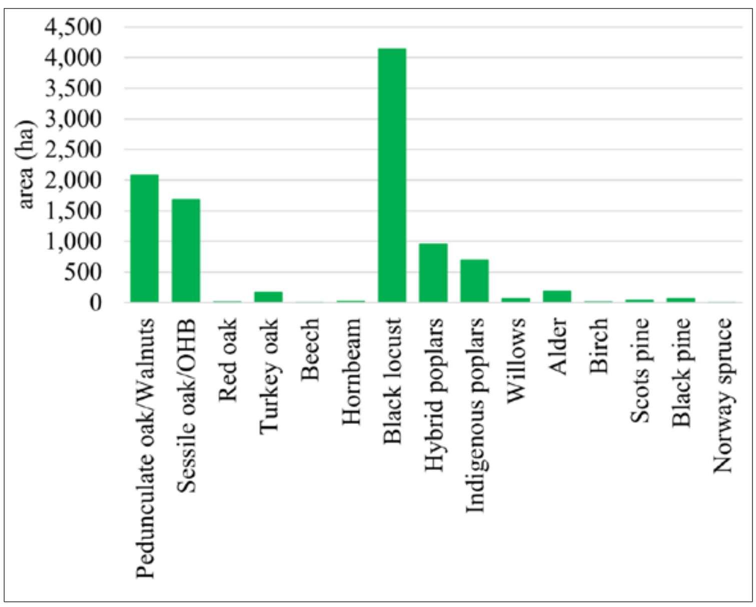

Figure 1: Area of windbreaks by tree species group as of the 2020 state of the NFD. (OHB: other hard broadleaved species).

land management unit as agricultural crops, animals, or both, either in some form of spatial arrangement or temporal sequence (Mosquera-Losada et al. 2009). Following the definitions given by the Association for Temperate Agroforestry (AFTA 1997) and Alavalapati and Nair (2001) there are currently five basic types of agroforestry practices in temperate areas: windbreaks, alley cropping, silvopasture, riparian buffers and forest farming. Nair (1993) 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.

In Hungarian agricultural landscapes, windbreaks (i.e., field protection tree rows and field protection forest strips) are common elements that protect agricultural fields from wind and soil erosion. In response to the goals of the Carbon Farming directive, 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, and agroforestry systems can be counted as agroecology program elements and as landscape elements as well (NAK 2023). Windbreaks and trees planted on grasslands are subsidized in Hungary (NAK 2023). Considering the favourable changes in the subsidy system we can foresee that these landscape elements will become important means of land-based climate change mitigation. In our previous study (Király et al. 2024) we assessed the area of windbreaks, and the carbon sequestration realised in windbreaks in Hungary. According to our estimate, the weighted mean annual carbon sequestration in the

Table 1: Weighted means of canopy closure by tree species group.

Cell No.	Weighted means of canopy closure by tree species group Current effect: F(14, 6700)=14,684, p=0,0000 Effective hypothesis decomposition					
	tree species group	canopy closure (Mean)	canopy closure (Std.Err.)	canopy closure (-95,00%)	canopy closure (+95,00%)	Number of observations
1	Pedunculate oak	77.79	0.52	76.76	78.81	1221
2	Sessile oak	79.78	0.53	78.74	80.81	1114
3	Red oak	88.64	4.11	79.49	97.79	11
4	Turkey oak	80.36	1.76	76.85	83.87	81
5	Beech	96.00				2
6	Hornbeam	80.40	2.80	74.55	86.25	20
7	Black locust	83.53	0.32	82.89	84.16	2950
8	Hybrid poplars	74.49	0.90	72.71	76.26	588
9	Indigenous poplars	76.64	0.87	74.92	78.35	473
10	Willows	76.20	2.81	70.57	81.83	55
11	Alder	81.99	1.42	79.19	84.79	129
12	Birch	75.20	6.76	56.42	93.98	5
13	Scots pine	83.21	2.83	77.34	89.07	24
14	Black pine	77.76	3.07	71.54	83.97	41
15	Norway spruce	85.00				1

Table 2: Results of the multiple regression analysis. (Numbers highlighted in red denote significant effect.)

Regression Summary for Dependent Variable: canopy closure R= ,34841950 R²= ,12139615 Adjusted R²= ,12074135 F(5,6709)=185,40 p<0,0000 Std.Error of estimate: 17,304						
N=6715	b*	Std.Err. (of b*)	b	Std.Err. (of b)	t(6709)	p-value
Intercept			263.188	26.249	10.027	0.000
age	-0.345	0.013	-0.304	0.011	-27.593	0.000
tree species group	-0.083	0.013	-0.496	0.075	-6.650	0.000
mean annual increment of total production	0.100	0.012	0.546	0.063	8.672	0.000
mixture rate	-0.020	0.012	-0.016	0.010	-1.625	0.104
stand area	0.013	0.012	0.154	0.137	1.120	0.263

aboveground biomass of windbreaks was −2.4 tCO_2/ha/year in the 2010–2020 period (Király et al. 2024). 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 (NIR 2023). 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 (Király et al. 2024).

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 windbreaks. This study is a preparatory step of the model development. In this paper we assess the average canopy closure of Hungarian windbreaks by tree species group based on the data of the National Forestry Database (NFD). Canopy closure is a necessary parameter for the use of yield tables to be able to predict future volume stock and increment of the windbreak stands.

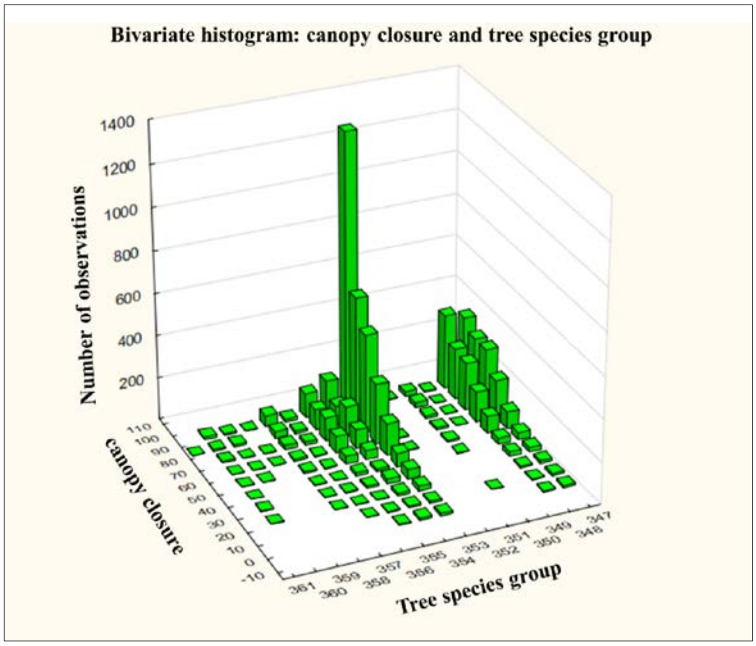

Figure 2: Bivariate histogram of the tree species group and canopy closure of windbreaks. (Tree species group codes are the following: 347 Pedunculate oak, 348 Sessile oak, 349 Red oak, 350 Turkey oak, 351 Beech, 352 Hornbeam, 353 Black locust, 354 Hybrid poplars, 355 Indigenous poplars, 356 Willows, 357 Alder, 358 Birch, 359 Scots pine, 360 Black pine, 361 Norway spruce.)

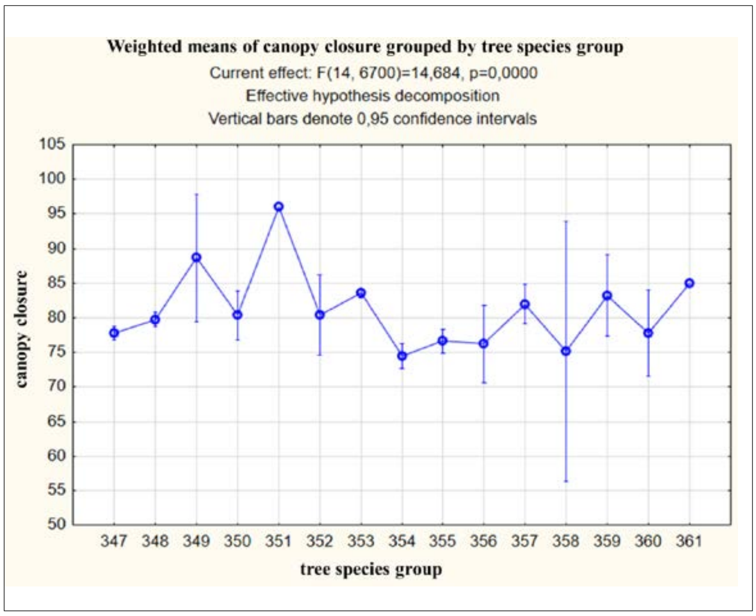

Figure 3: Weighted means of the canopy closure of windbreaks by tree species group. (Tree species group codes are the following: 347 Pedunculate oak, 348 Sessile oak, 349 Red oak, 350 Turkey oak, 351 Beech, 352 Hornbeam, 353 Black locust, 354 Hybrid poplars, 355 Indigenous poplars, 356 Willows, 357 Alder, 358 Birch, 359 Scots pine, 360 Black pine, 361 Norway spruce.)

MATERIAL AND METHODS

In our study we used the NFD, which is the official database of the Hungarian Forest Authority. NFD stores detailed data on each forest stand subject to forest management planning (Tobisch and Kottek 2013, Kottek et al. 2023). Forest management planning is based on field surveys during which the main stand attributes (such as the height, diameter, basal area, age, and canopy closure) are measured (Tobisch and Kottek 2013). Data on the standing volume are stored in tree species rows, which are the basic units of the database (Tobisch and Kottek 2013). The NFD stores data on the primary function (i.e., timber production, windbreak, nature protection, etc.) assigned to each forest sub-compartment (Király et al. 2024). We queried all stands with windbreak as the primary function from the 2020 state of the NFD at the country level. This way we obtained a whole country's windbreak forest stand group for further analysis. Thereafter we queried the tree species, area, age, canopy closure, mixture rate, and production capacity (defined as the mean annual increment of total production at the reference age of the stand) data of all stands and analysed the data using Statistica software (Version 14.0.1.25, Tulsa, OK, USA). The primary goal of the data analysis was to obtain mean canopy closure values by tree species group for the parametrisation of the carbon sequestration model under development. In addition, we also assessed the canopy closure by age, and we conducted a multiple regression analysis in order to identify variables that have significant effect on canopy closure.

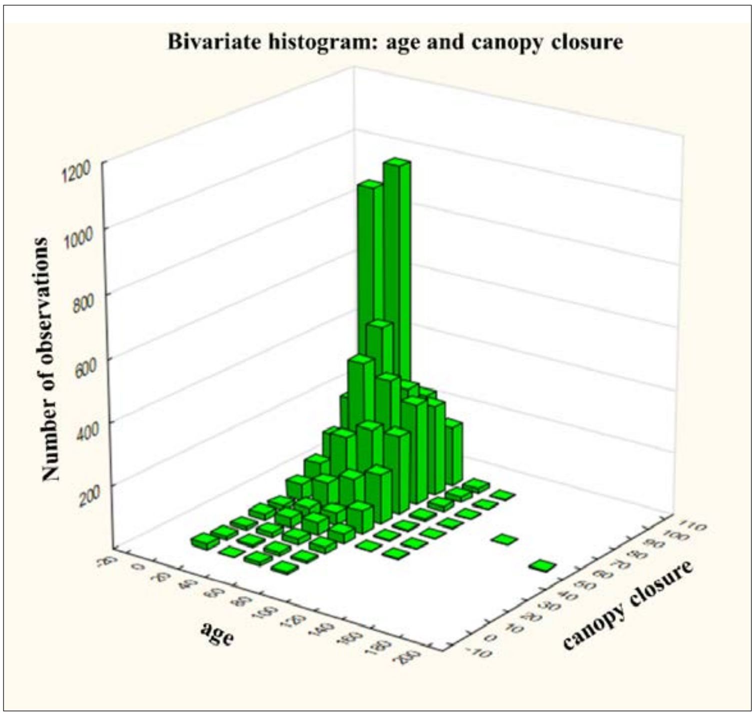

Figure 4: Bivariate histogram of the age and canopy closure of windbreaks.

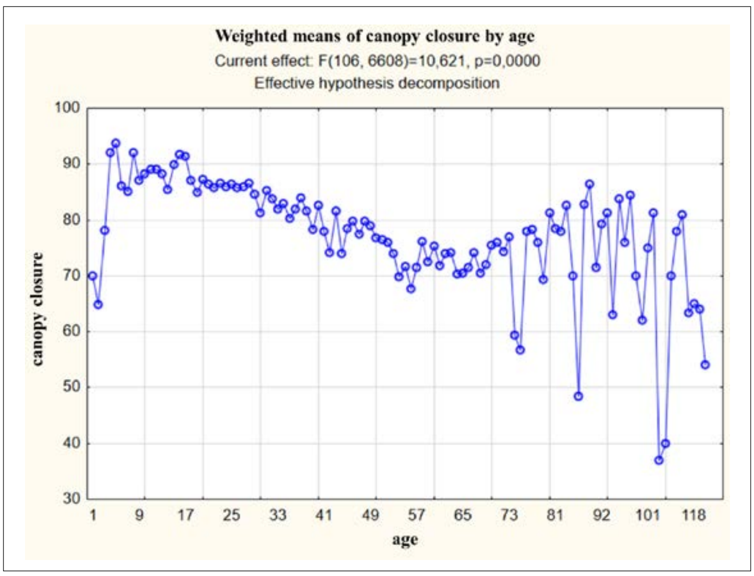

Figure 5: Weighted means of the canopy closure of windbreaks by age.

RESULTS

According to our results the majority of windbreaks are composed of black locust (*Robinia pseudoacacia*) stands, followed by pedunculate oak (*Quercus robur*), sessile oak (*Quercus petraea*), hybrid poplars, and indigenous poplars (Figure 1).

The weighted means of canopy closure by tree species group are detailed in Table 1. The highest canopy closure value was observed in beech (*Fagus sylvatica*) and red oak (*Quercus rubra*) stands. In the case of pedunculate oak, sessile oak, poplars, willows (*Salix*), birch (*Betula*) and black pine (*Pinus nigra*) the mean canopy closure was below 80%.

According to the results of the multiple regression analysis (Table 2) age, tree species group and production capacity had significant effect on canopy closure.

Our results show that tree species has a significant effect on canopy closure. Black locust, oaks and poplars represent the majority of the area of windbreaks (Figure 2). In the case of tree species represented by small area the confidence intervals of the mean are much wider (Figure 3).

According to our results the canopy closure of the windbreaks decreases with the age, however in the 1-10 age class a temporal increase was observed (Figure 4–5).

DISCUSSION

Our results show that the canopy closure of windbreaks under forest management planning is relatively high, ranging between 74-96%. Among the examined effects the most important one is the age, which has the highest impact on the value of the canopy closure. Tree species group and production capacity are also important predictors of canopy closure.

These results are in line with our previous findings related to the carbon sequestration of windbreaks which also varied highly depending on age and tree species (Király et al. 2024).

CONCLUSIONS

In this study we assessed the average canopy closure by tree species group for all windbreaks under forest management planning in Hungary. These results will be used in the parametrisation of a carbon sequestration model specific for windbreaks. As not all windbreaks are under forest management planning in Hungary it would be important to assess the canopy closure of those windbreaks which are not registered in the NFD. For this remote sensing-based assessment would be the most appropriate, as filed surveys would be too costly.

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THE CLIMATE REGULATORY ROLE OF SÁRVÁR'S URBAN FORESTS: QUANTIFYING CARBON SEQUESTRATION AND EMISSION OFFSETTING

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ABSTRACT

Urban forests and green spaces play a key role in mitigating climate change, as they simultaneously provide ecosystem services, reduce the urban heat island effect, and sequester and store significant amounts of atmospheric carbon dioxide. This study aimed to quantify the carbon sequestration, carbon storage, and product substitution potential of urban forests and other tree-covered green areas in the city of Sárvár, Hungary. Estimates of carbon stocks stored in biomass and annual carbon uptake were derived using data from the National Forestry Database (2010–2023) and the Copernicus Tree Cover Density dataset, based on methodologies from the IPCC and the Hungarian National Greenhouse Gas Inventory.

The results indicate that urban forests under Forest Management Planning (FMP) store over 80,000 tons of carbon and sequester an average of -4,950 tons of CO_2 annually, offsetting approximately 4.6% of Sárvár's total greenhouse gas emissions. When accounting for carbon sequestered by trees outside the FMP system, as well as carbon stored in harvested wood products and emissions avoided through the substitution of wood-based products and firewood, the total climate mitigation contribution of Sárvár's urban forests and tree-covered areas reaches -10,116 tons CO_2 equivalent per year—compensating for 9.3% of the city's total emissions. These findings underscore that urban forests not only hold ecological value but also serve as strategically important components of local climate strategies and nature-based climate mitigation solutions.

keywords: climate change, mitigation, urban forest, carbon stock, carbon flux, wood products, product substitution, energy substitution, CO_2

INTRODUCTION

Urban forests play a pivotal role in mitigating the impacts of climate change by providing multiple ecosystem services, reducing the urban heat island effect, and sequestering and storing significant amounts of carbon dioxide in both biomass and soil. According to the IPCC Sixth Assessment Report, the adverse effects of climate change are particularly pronounced in urban areas, where health, infrastructure, and social systems are especially vulnerable (IPCC AR6WGI 2021). The increasing frequency of extreme heatwaves and the growing occurrence of severe weather events are placing increasing pressure on urban infrastructure systems, such as transportation, water supply, wastewater management, and energy networks—resulting in economic losses, service disruptions, and reduced quality of life, especially for socially disadvantaged populations (IPCC AR6SYR 2023).

Driven by accelerating global urbanization, more than half of the world's population now lives in cities (United Nations Department of Economic and Social Affairs, 2019). The combined pressures of urbanization and global warming increasingly strain ecosystems, intensify the urban heat island effect, elevate air pollution levels, and exacerbate water quality issues (Choi et al. 2021; Strassburg et al. 2020; Feng et al. 2024). Due to high population densities and intense economic activity, urban areas are major sources of CO_2 emissions, making urbanization itself a key driver of climate change (Dhakal 2010; Hong et al. 2024).

In response, urban green infrastructure—including forests, parks, and other vegetated areas—has become an increasingly important component of both climate mitigation and adaptation strategies (Velasco et al. 2016). Urban forests are now widely recognized as nature-based solutions, contributing to climate regulation, air purification, and carbon sequestration (Goodwin et al. 2023; Ren et al. 2019; Steenberg et al. 2019). Many cities have adopted policies that promote tree planting, the preservation of existing green spaces, and the integration of vegetation into the built environment—such as green roofs and green façades (Velasco et al. 2016).

Beyond their carbon-related functions, urban forests deliver a broad range of ecosystem services that support urban sustainability. They contribute significantly to stormwater regulation by intercepting rainfall and enhancing soil infiltration, thereby reducing surface runoff and lowering the risk of urban flooding. Tree canopies help buffer the effects of intense precipitation events, while their root systems improve soil structure and water retention. Urban vegetation also contributes to air purification by filtering pollutants such as ozone (O_3), nitrogen dioxide (NO_2), and particulate matter (PM_{10} and $PM_{2.5}$), helping to improve air quality and reduce respiratory health risks—especially in densely populated areas (Borelli et al. 2023). Urban forests also provide cultural and recreational services that enhance quality of life and mental well-being. Green spaces have been shown to reduce stress, encourage physical activity, and foster social cohesion. Proximity to trees and natural areas has been associated with improved cognitive development in children and lower incidences of anxiety and depression in adults. Furthermore, urban forests contribute to aesthetic and property value enhancement, support biodiversity by providing habitat for birds and pollinators, and act as noise buffers in traffic-heavy areas. These co-benefits reinforce the multifunctional importance of urban tree-based ecosystems in creating more resilient and livable cities (Borelli et al. 2023).

While previous research has mainly focused on the total carbon stored in urban vegetation, less attention has been paid to carbon sequestration as a dynamic process, whereby vegetation actively removes carbon dioxide from the atmosphere (Sun et al. 2019; Velasco et al. 2016; Zhuang et al. 2023; Guo et al. 2024). Estimating sequestration typically relies on modeling, CO_2 flux measurements, or field sampling (Zhu et al. 2022); however, such approaches are often expensive and labor-intensive—especially at large urban scales. Tools such as the i-Tree and InVEST models have been widely used to estimate urban carbon dynamics (Babbar et al. 2021; Raum et al. 2019).

In Hungary, urban green space ecosystem services are increasingly recognized, particularly in the capital city, Budapest (Meer et al. 2014; Chen et al. 2024; Király et al. 2025). However, the ecological footprint of Budapest continues to exceed its biocapacity, mainly due to rising population and increasing per capita resource use (Kovács et al. 2022). In parallel with urbanization, many parts of the city are experiencing intensified heat island effects, pollution, and a reduction in green areas (Göndöcs et al. 2017; Tatai et al. 2023). According to recent findings on Budapest's urban forested areas, tree-covered urban vegetation offsets approximately 41,000 tons of CO_2 emissions annually—compensating for around 1% of the city's total emissions (Király et al. 2025). This is consistent with findings from other major cities (e.g., Vancouver, Changchun, Mexico City), where urban green spaces typically offset 1–2% of total municipal CO_2 emissions. Of particular interest is the role of urban tree species in delivering ecosystem services. Chen et al. (2024) evaluated the photosynthetic performance and fine particulate (PM) filtering capacity of three common species—Norway maple (Acer platanoides), European ash (Fraxinus excelsior), and silver linden (Tilia tomentosa)—and found that Tilia tomentosa exhibited the highest degree of adaptation to urban conditions. Estimates suggest that green areas in Budapest remove approximately 38 tons of fine particulate matter annually. Szabó et al. (2023) also confirmed that the surface characteristics of leaves significantly influence dust capture efficiency.

The primary objective of our research is to quantitatively assess the carbon sequestration and storage capacity of urban forests and green areas in the city of Sárvár, Hungary. Specifically, the study aims to determine the extent to which these urban forested areas contribute to climate change mitigation through carbon stored in biomass, annual carbon uptake, long-term carbon storage in harvested wood products (HWPs), and emission reductions resulting from product and energy substitution effects.

Beyond these quantitative goals, our project also has an important social objective: to raise awareness of the climate protection role of urban green areas and to promote public engagement with and support for nature-based solutions. Clearly communicable indicators of carbon sequestration and the broader climate benefits of urban forests can enhance public understanding and acceptance of green infrastructure and support the integration of ecosystem services into local climate-conscious decision-making.

MATERIAL AND METHODS

In this study, we examined the urban forest areas located within the administrative boundaries of the city of Sárvár (Figure 1). The analysis of forests under Forest Management Planning (FMP) was based on data from the National Forestry Database (NFD) covering the period between 2010 and 2023.

For tree-covered areas not classified as forests and not under FMP (e.g., parks, tree-lined avenues, gardens, etc.), the analysis was based on data from the European Union's Copernicus Earth Observation Service, specifically the Tree Cover Density (TCD 2025) dataset. This dataset delineates tree-covered areas in canopy closure-based categories at a 10×10 meter spatial resolution. These

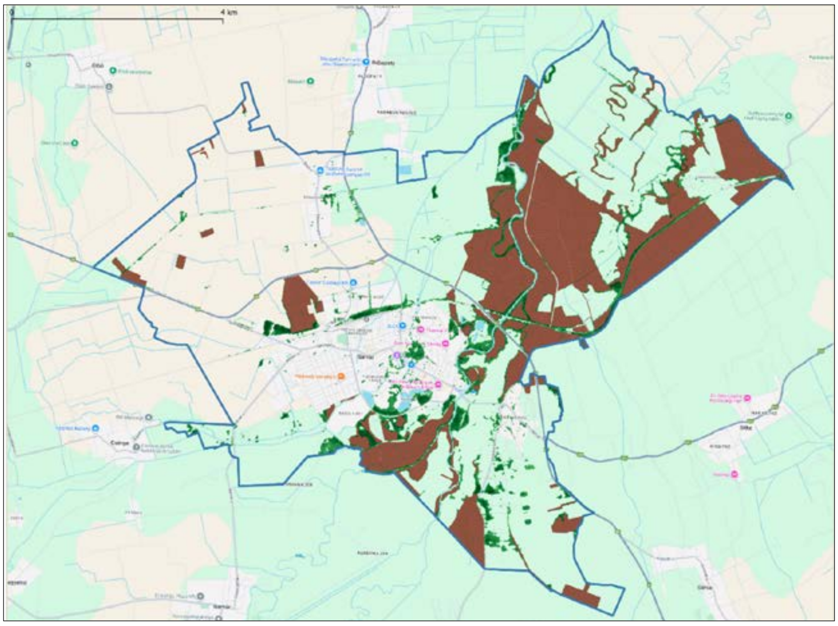

Figure 1: Overview map of the study area. Forest subcompartments under forest management planning are marked in brown, while other tree-covered areas are shown in dark green.

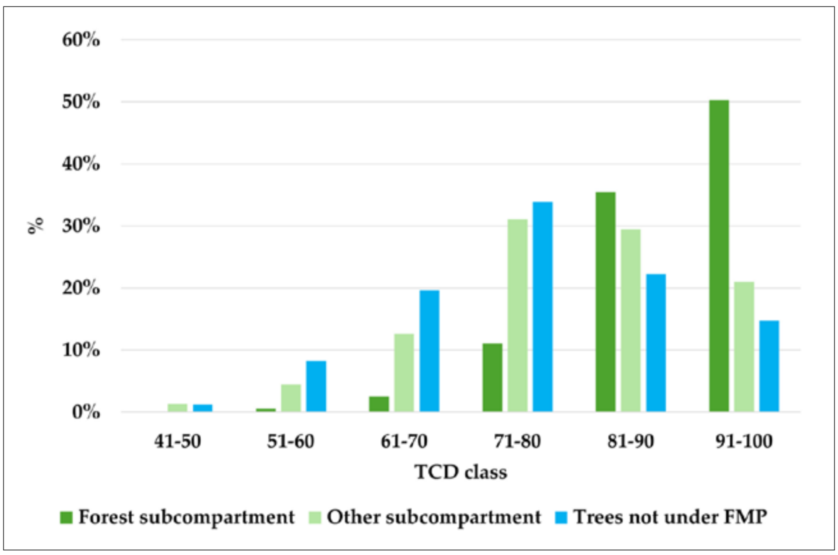

Figure 2: Distribution of canopy closure classes for managed forests and other tree-covered areas based on the Copernicus Tree Cover Density layer (TCD 2025).

data, along with carbon stock and carbon sequestration values derived from the National Forestry Database, formed the basis for estimating the carbon dynamics of tree stands outside of FMP.

To estimate carbon stock stored in biomass and annual carbon sequestration, we applied the IPCC methodological guidelines (IPCC 2006, 2019) and the Hungarian National Inventory Report (NIR 2023). Calculations were performed across 22 species groups, and we also determined average carbon storage and sequestration values per hectare. Timber harvest data were sourced from the National Forestry Database, while the distribution of wood assortments by species group was estimated according to Borovics et al. (2024), as shown in Table 1.

The product and energy substitution effects were determined following the methodology described in detail in Király et al. (2024). The energy substitution factor used was 0.67 tC/tC, while a factor of 1.2 tC/tC was applied for product substitution.

RESULTS AND DISCUSSION

The total area of urban forests under FMP within the administrative boundaries of Sárvár amounts to 1,125 hectares. The area of tree-covered urban green spaces not under FMP was estimated at 470 hectares. The managed forest areas generally exhibited higher canopy closure compared to the unmanaged tree-covered areas (Figure 2). According to our results, the total amount of carbon stored in the biomass of managed urban forests exceeds 80,000 tons, indicating that these areas

Table 1: Distribution of wood assortments by species group (source: Borovics et al., 2024).

	Oaks	Turkey oak	Beech	Hornbeam	Black locust	Hard broadleaved	Hybrid poplars	Native poplars	Willow	Soft broadleaved	Conifers
Firewood	69%	93%	59%	88%	80%	82%	8%	18%	33%	65%	14%
Industrial wood	31%	7%	40%	12%	20%	18%	91%	81%	67%	35%	86%

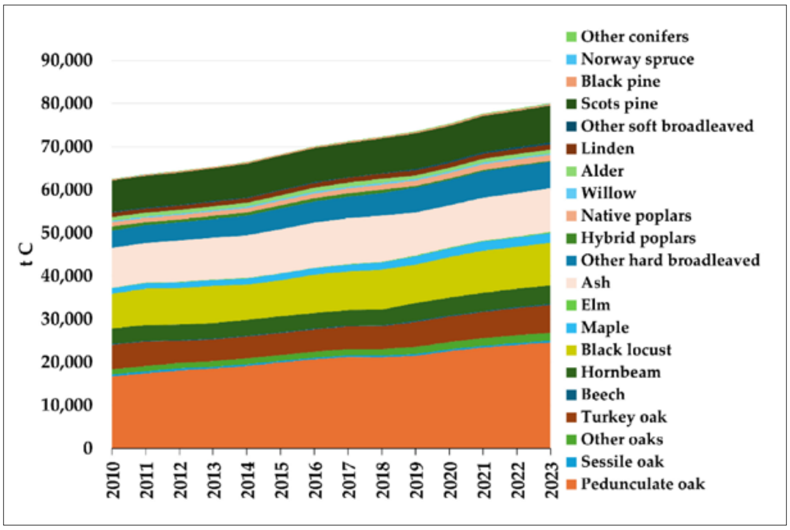

Figure 3: Carbon stored in the biomass of managed urban forests, broken down by tree species group.

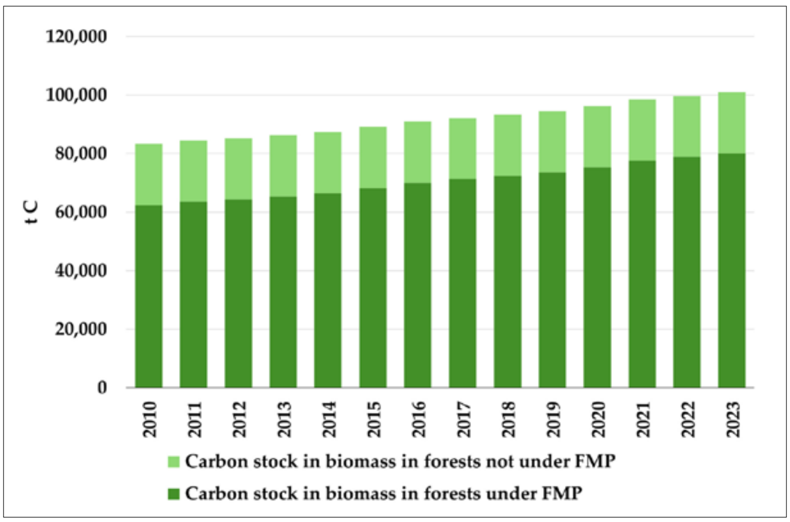

Figure 4: Carbon stock in the biomass of managed urban forests and tree-covered areas not under FMP.

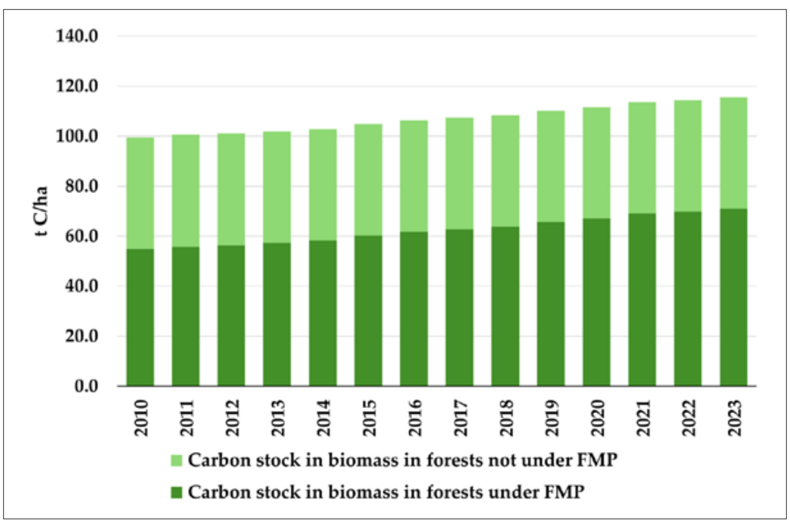

Figure 5: Average carbon stock per hectare values for the biomass of managed urban forests and for tree-covered areas not under FMP.

serve as significant natural carbon reservoirs (Figure 3). The largest carbon stocks are found in stands dominated by pedunculate oak (Quercus robur). In comparison, the estimated carbon stock in the biomass of tree-covered areas not under FMP exceeds 20,000 tons of carbon (Figure 4). The average carbon stock per hectare across both area types is illustrated in Figure 5. By 2023, the mean carbon stock per hectare surpassed 100 tons.

Figure 6 presents the annual carbon balance of managed urban forests. Carbon sequestration through biomass growth is shown as negative values (in accordance with IPCC conventions), while emissions from harvesting are shown as positive values. The amount of harvested biomass, expressed in tons of carbon, is shown in Figure 7.

The net carbon balance of urban forest areas was negative throughout the study period, meaning these areas function as net carbon sinks (Figure 8). In addition to carbon uptake through biomass growth, timber harvesting contributes further to climate change mitigation, as long-term carbon storage occurs in harvested wood products. Moreover, both product substitution and energy substitution effects of wood products and firewood help avoid further emissions, by displacing fossil fuels and carbon-intensive products and construction materials (Figure 8).

The annual average carbon sequestration in managed forest biomass was approximately -4,950 tons of CO_2, offsetting 4.6% of Sárvár's total greenhouse gas emissions, according to the city's official emissions inventory (Sárvár Municipal Government, 2020). When including the carbon stored in wood products and the emissions avoided through substitution effects, the total climate mitigation effect of Sárvár's urban forests averaged -10,116 tons of CO_2 equivalent per year, offsetting 9.3% of the city's total emissions. This amount of avoided emissions is equivalent to the annual emissions of 1,792 average Hungarian households (KSH 2025a, b), or the annual emissions of 4,334 passenger vehicles (KSH 2025c).

While Figure 8 displays the total annual net carbon balance, Figure 9 shows the same values normalized per hectare. For managed urban forest areas, the annual carbon

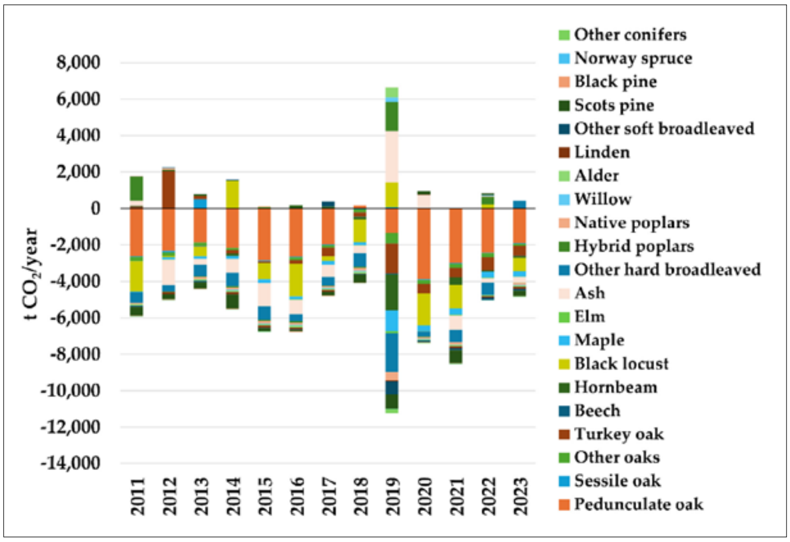

Figure 6: Annual carbon sequestration and emissions from the biomass of managed urban forests, broken down by species group. (Values are expressed in CO_2 equivalents; negative values indicate carbon sequestration, while positive values indicate emissions.)

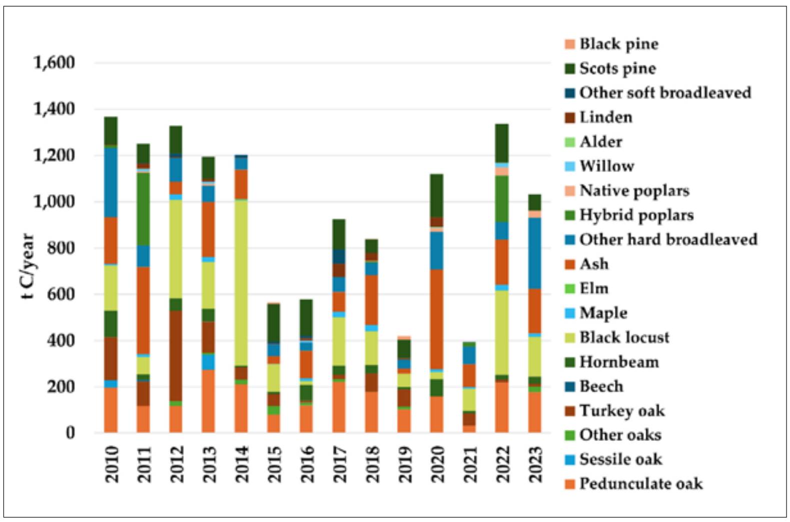

Figure 7: Amount of harvested biomass in managed urban forests, expressed in tons of carbon and broken down by tree species group.

sequestration per hectare ranged from -3.5 to -7.6 tons of CO_2/ha/year during the study period. The total net carbon balance per hectare, including substitution effects, ranged from -8.7 to -12.8 tons of CO_2/ha/year.

CONCLUSIONS AND RECOMMENDATIONS

Based on the results of this study, the urban forests of Sárvár exhibit significant climate mitigation potential, both through carbon stored in biomass and through annual carbon sequestration. Urban forest areas under FMP store over 80,000 tons of carbon, while the average annual carbon sequestration reaches -4,950 tons of CO_2, offsetting approximately 4.6% of the city's total greenhouse gas emissions. When the long-term carbon storage in wood products and the product and energy substitution effects are included, the total climate mitigation contribution of Sárvár's urban forests amounts to -10,116 tons of CO_2 equivalent per year, which compensates for 9.3% of the city's total emissions. These findings confirm that urban forests represent not only ecological value but also play a key role in the implementation of local climate strategies.

The differing carbon storage and sequestration capacities of tree species groups provide a scientific basis for species selection in future urban afforestation and tree planting programs. A targeted, informed tree species policy—aligned with ecological performance and climate adaptation potential—can further enhance the effectiveness of such efforts.

A comprehensive evaluation of the ecosystem services provided by urban green spaces—including urban heat island mitigation, air quality improvement, recreational functions, and carbon cycle contributions—is essential for evidence-based sustainable urban planning and climate-related decision-making. The case of Sárvár demonstrates that even smaller cities possess considerable potential for the application of nature-based solutions.

The results also highlight that tree-covered green spaces not under FMP play an important complementary role in the urban carbon cycle. The 470 hectares of tree-covered areas provide valuable ecological functions—such as heat mitigation, dust filtration, and recreation—which justify their systematic registration and targeted maintenance.

Based on these findings, we recommend the following:

1. Formal recognition of the climate mitigation function of urban forests and tree-covered green spaces in local strategic documents and policies.
2. Adoption of a tree species policy that supports both ecological value and climate adaptation, with a preference for climate-resilient species during planting and replacement.
3. Systematic assessment and integration of tree-covered areas not under FMP into urban green infrastructure management frameworks.
4. Active public involvement, education, and incentivization, through community-based initiatives such as "adopt-a-tree" programs and awareness campaigns.
5. Inclusion of clear and communicable carbon sequestration metrics and results in municipal environmental reports and climate strategy documents.

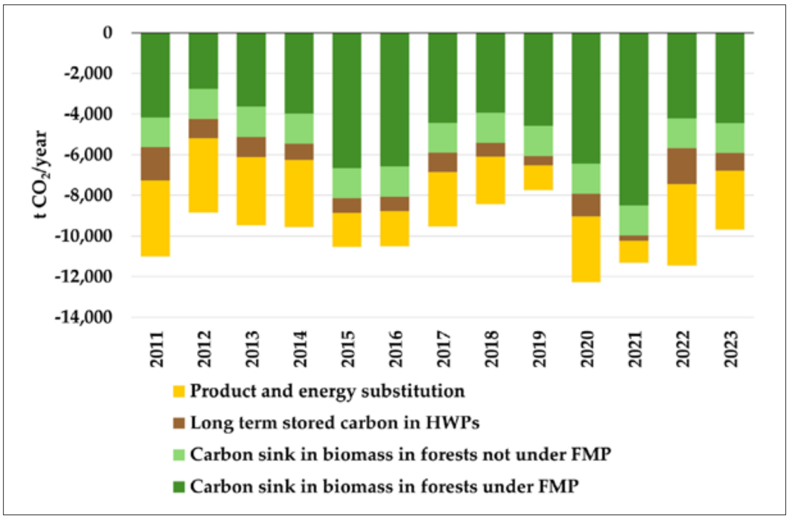

Figure 8: Total annual net carbon sequestration in the biomass of managed urban forests and tree-covered areas, including long-term carbon storage in harvested wood products and emissions avoided through product and energy substitution. Values expressed in CO_2 equivalents. Negative values indicate carbon sequestration or avoided emissions.

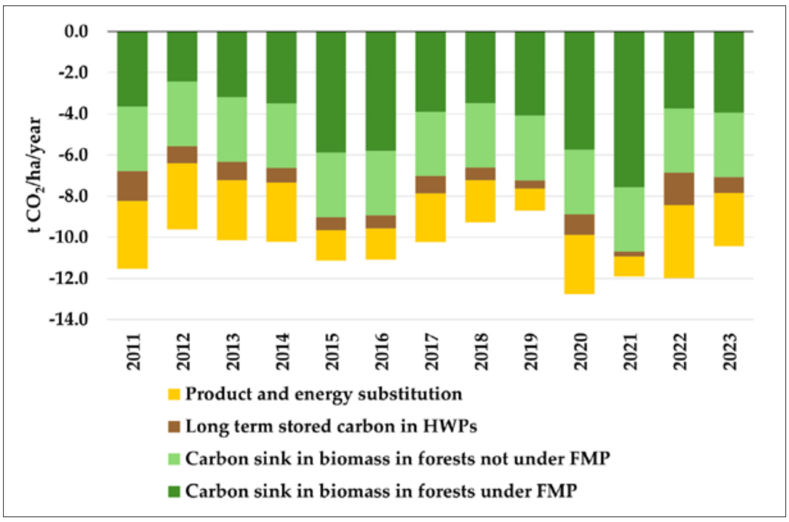

Figure 9: Annual net carbon sequestration and substitution effects per hectare in the biomass of managed urban forests and trees outside FMP. Values expressed in CO_2 equivalents. Negative values indicate carbon sequestration or avoided emissions.

Strengthening the climate protection functions of urban green spaces, engaging the public, raising awareness, and developing green infrastructure can significantly contribute to the long-term climate resilience and livability of municipalities. The case study of Sárvár demonstrates that with integrated and informed green infrastructure management, even smaller cities can achieve annual CO_2 offsetting approaching 10% of their total emissions.

As a continuation of this research, a detailed assessment of the carbon dynamics of non-managed green areas is warranted. Additionally, the climate mitigation potential of infrastructural green solutions, such as green roofs and green walls, should also be analyzed to expand the toolkit of urban climate action.

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ENVIRONMENTAL FACTORS AND THE ROLE OF SENSORS IN CLIMATE MONITORING OF LIVESTOCK BUILDINGS

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ABSTRACT

Nowadays, the key factor of competitiveness is the method and extent of data collection, at what level they are analysed, evaluated, and what interventions are carried out. Furthermore, to achieve proper livestock farming, the aim is to ensure optimal climatic conditions for the animal buildings. The factors influencing the environment and their treatment are discussed in our work. Their effects help improve farmers' competitiveness based on animal welfare considerations, maintain a continuous good animal health status, and achieve more predictable production.

Keywords: livestock farming, environmental conditions, measurement methods, sensors

INTRODUCTION

Livestock farms should provide animals with an adequate microclimate in the enclosure, as environmental factors are crucial in livestock production's qualitative and quantitative characteristics (Tóth et al. 1998), (Fenyvesi et al. 2003). Furthermore, different animal species, breeds and age groups have different environmental needs. Therefore, it is necessary to create a microclimate in which the animal's comfort can be ensured, and its keeping is optimal and satisfies its biological needs (Figure 1). The microclimate is particularly important for livestock farms, especially poultry and pig farms (Herman Ottó Intézet 2020).

Figure 1: Cattle barn equipped with fans (Source: NARIC MGI)

The most important environmental factors include:

- the temperature of the stable air,
- the relative humidity,
- gas concentration and particulate matter,
- movement of air and the lighting (Tóth 2019).

These characteristics can be monitored with individual measuring systems or so-called multisensory systems.

MEASURING BACKGROUND FOR ENVIRONMENTAL FACTORS

Temperature measurement and control

The air temperature in the animal house is influenced by the outside air temperature, the building's thermal characteristics, and the heat production of the animals. Therefore, it is recommended to measure the barn's temperature at the animals' head height to meet the animals' heat demand. The desired temperature can be reached by appropriate control of the heating or ventilation. In animal husbandry systems, the typical temperature conditions are registered with electronic, gas and steam tension temperature sensors (Műszeroldal website).
One of the easiest ways to measure temperature is when an inside thermostat controls temperature. The thermostat detects the internal temperature of the building and activates the structural elements that help change the temperature according to the set value.
It can provide a more complex solution when the outside temperature is measured in addition to the inside. In this solution, a predetermined value is selected based on the

signals of the sensors. Then, the external lower temperature air is introduced into the building while appropriate mixing is carried out (e.g., soil heat exchange tempering) (Tóth 2019).
Nowadays, computer control is mainly used. However, this solution also makes it possible to measure the humidity, temperature, and concentration of harmful gases in the outdoor and indoor air.
Depending on the animal species, inappropriate temperatures can cause heat stress in the individual and lead to the development of various diseases or even the animal's death.

Humidity measurement and control

The humidity of the outside air determines the humidity level in the livestock building, the phenomenon of evaporation in connection with feeding, watering and manure treatment, and the amount of moisture exhaled by the animals. Hygrometers, psychrometric or capacitive humidity sensors can determine the air humidity in livestock buildings (Tóth 1998).
The relative humidity value shows the relationship between the actual and maximum humidity in percentage terms. Another method that can be used for more accurate results is the simultaneous measurement of dry and wet temperatures. In this method, the measurement is conducted in the strongly flowing air with two thermometers, a dry and a water-moistened thermometer. A measuring device that can be used for this purpose is the psychrometer. In this case, the relative humidity is determined by the difference between the two types of measured temperatures (dry and wet), by calculation or by data table. In the case of a capacitive sensor, the change in the electrical permittivity of the dielectric material is measured to calculate the relative humidity values.
In a dust-contaminated environment, only the psychrometric sensor is recommended (due to the dust sensitivity of the sensors).
Maintaining relative humidity at the proper level avoids condensation on surfaces in contact with the external environment. Conversely, non-optimal humidity causes dehydration, dry cough, faster spread of pathogens, diseases, and death in severe cases.

Airspeed measurement and control

Besides the temperature and humidity characteristics described above, the comfort of the animals is ensured by the movement of the air. In closed livestock buildings, the desired air movement can be achieved by artificial ventilation, providing fresh air for the animals while removing excess vapour and gases in the atmosphere and particulate matter (Fenyvesi et al. 2003), (Herdovics et al. 2011), (Tóth 2018).

The air velocity can be measured by a rotating-cup anemometer, vane-anemometer, or thermal sensors. When measuring the air velocity with a rotating cup or vane-anemometer, the speed of the turbine wheel, which depends on the speed of the airflow, is converted into an electronically processable electrical signal using impulse transducers. The amperage varies according to the fourth power of the speed, so a low flow rate that other turbine devices cannot measure can be determined. In thermosensor air velocity meters, the sensor is heated to a significantly higher temperature than the flowing air (100-120 °C for semiconductors, 300 °C degrees or higher for metal filaments).
Platinum or tungsten fibers are used to prevent high-temperature corrosion. Improper air movement and drafts can cause colds and other concomitant illnesses.

Gas concentration measurement and control

The proportion of gases and particulate matter in the barn depends considerably on the size of the livestock, the feeding and manure treatment solutions used and the ventilation characteristics. The gases generated here can be measured using chemical reagents (hand-held air pollution meters) or more advanced electronic sensors (Figure 2). An example of such an advanced electronic sensor is the efficient and reliable gas monitoring system, the photoacoustic gas monitor. Additionally, a carbon monoxide probe can be used effectively at the maximum allowable concentration to monitor air quality. Also included are carbon dioxide sensors and gas probes for various gases, which measure ammonia, nitrogen dioxide, nitrogen oxide, chlorine gas, sulfur dioxide, hydrogen sulfide and ethylene oxide gases (Arany et al. 2018), (Senselectro website).
Ventilation in the livestock building is also important because the critical concentrations of carbon dioxide (CO_2), sulphur dioxide (SO_2), ammonia (NH_3) and dust pollution

Figure 2: Measurement of the gas content of the barn air (*Source: NARIC MGI*)

Table 1.: Emissions to air from the intensive rearing of poultry or pigs	
Air pollutant	**Production system**
Ammonia (NH_3)	Animal housing, manure storage, processing and landspreading
Odour	Animal housing, manure storage and landspreading
Dust (bioaerosols)	Animal housing, milling and grinding of feed, feed storage, solid manure storage and landspreading, heaters in buildings and small combustion installations
Methane (CH_4)	Animal housing, storage of manure and manure processing
Nitrous oxide (N_2O)	Animal housing, manure storage, processing and landspreading
NOX (NO + NO_2)	Animal housing, manure storage and landspreading, heaters in buildings and small combustion installations
Carbon dioxide (CO_2)	Animal housing, energy used for heating and transport on farm, and biogenic CO_2 that may be emitted in the field

Source: Santonja et al. 2017.

of gases hazardous to both animals and humans must be kept below the limit. Lack of proper regulation causes loss of appetite, somnolence and shortness of breath and can lead to other diseases.
The table below shows an example of emissions to air from intensive rearing of poultry or pigs production systems (Table 1).
Attention to the effects of climate change has also focused on emissions from the livestock sector. Major health risks are small particulate matter, PM 10 (10 µm or less) and PM 2.5 (2.5 µm or less). The group of air pollutants considered the most harmful by the World Health Organization (WHO), which, by binding various toxic substances, can also enter the bloodstream through the respiratory system due to its size (Sutton et al. 2011), (WHO 2013). In order to reduce air pollution, including particulate emissions, the new National Emission Limits (NEC) Directive (2016/2284 / EC) entered into force in the European Union on 31 December 2016. The new NEC Directive, which replaces previous legislation, sets emission reduction commitments for 2020 and 2030 for five primary air pollutants (sulfur dioxide, nitrogen oxides, volatile /non-methane/ organic compounds, ammonia, and particulate matter). In the past decades, ammonia emissions have been the focus of the analysis in animal husbandry. This is because ammonia in the atmosphere can be transported over long distances and then returned to the soil and surface waters by dry or wet deposition. In addition to individual solutions, we can use integrated measuring devices, which we present below.
An overview of the reported emissions (range) associated with poultry houses for ammonia, methane, nitrous oxide, dust and odour is presented in Table 2. Studies and research on odor measurement are also important areas, which are also discussed in many Hungarian publications (Béres et al. 2020a), (Béres et al. 2020b).

Table 2.: Range of reported air emission levels from poultry houses					
Type of poultry	**NH_3**	**CH_4**	**N_2O**	**PM_{10}**	**Odour (1)**
		kg per bird place per year			ou_E/s per bird
Laying hens - Enriched cage systems	0.01-0.15	0.034-0.078	0.0017-0.023	0.01-0.04	0.102-0.68
Laying hens - Non-cage systems	0.019-0.36	0.078-0.2	0.002-0.180	0.02-0.15	0.102-1.53
Pullets (cage and not cage systems)	0.014-0.21	NI	NI	0.008-0.078	0.042-0.227
Broilers	0.004-0.18	0.004-0.006 (2)	0.009 (2)-0.032	0.004-0.025	0.032-0.7
Broiler breeders	0.025-0.58	NI	NI	0.016-0.049	0.11-0.93
Turkeys (female) Whole period	0.045-0.387	NI	0.015 (2)	0.09-0.5	0.4
Turkeys (male) Whole period	0.138-0.68	NI	NI	0.24-0.9	0.71
Ducks	0.05-0.29	NI	0.015 (2)	0.01-0.084	0.098-0.49
Guinea fowl (2)	0.80	NI	0.015	NI	NI

Source: Santonja et al. 2017

(1) Odour emissions have been derived from original data expressed in ouE/s per LU
(2) COM, Best Available Techniques (BAT) Reference Document for the Intensive Rearing of Poultry and Pigs (ILF BREF), 2003
NI: no information provided

Multisensors, the integrated solutions

The multisensor is an integrated measuring device that can be expanded modularly, examining animal welfare conditions, and building management aspects. Based on developments in livestock farms, sensors measuring physical quantities that provide information from animals' living spaces have been included. This allows us to measure air temperature, humidity, ammonia and carbon dioxide, draft and noise levels (Kövesdi 2018), (Okosfarm 2021).

With the integrated measuring solutions, farmers can continuously and in real-time monitor the climate conditions affecting the animals in the livestock building. The measured data can be displayed via an internet browser and a telephone application using a software package. The software analysed the data and stored it for later use for transparency. The device can support automatic regulation based on pre-set parameters to maintain ideal conditions. It alerts and provides information to users in an emergency, providing the opportunity for correction and immediate intervention. For more accurate results, the sensor's design allows it to work at the head height of the animals. It can also be used in poultry, pig and cattle farms. The system also has a so-called remote-control function, which allows to turn on the fans and evaporators or open the vents if the data shows an outlier during gas measurement (Figure 3).

Figure 3: In case of outliers during gas measurement, the ventilation system is automatically activated (*Source: Okosfarm.hu*)

The sensor data and its information can primarily inform medium and long-term decisions.

Sensors of the future

It still takes time for the sensors to become operational in the agricultural sector, but precision livestock farming (PLF) systems have already been introduced in some Hungarian farms. With the help of PLF systems, the maximum production level corresponding to the genetic abilities of the livestock can be maintained continuously during production (Tóth 2021). Therefore, solar systems would also become increasingly popular on livestock farms and for residential use. In addition to sustainable management and renewable energy, their importance is to meet all the farm's energy needs, thus supplying the sensors with electricity. A good example of this is Hungarian cattle farms, where in several cases, we can already find buildings with solar systems (Figure 4).

Figure 4: Livestock farm with solar photovoltaic systems system in Hungary
(*Source:energiatakarek.hu*)

SUMMARY

In more developed countries, autonomous farms have emerged, where the ultimate form of intelligent agriculture and the highest level of agricultural production is realised. In these farms, modern sensor technologies are used for all work processes to monitor the condition of the environment, farm animals, plants and the operating status of various treatment equipment. Examples of such new technologies are IoT (Internet of Things), Big Data, AI (Artificial Intelligence - MI), fifth-generation (5G) technology and robots. With these technologies, all production operations on the farm can be carried out remotely. However, control and site management systems cannot be achieved without a high IT background. This will drive livestock farms towards automation and ensure sustainable development in the long term.

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