

ACTA
SILVATICA
&
LIGNARIA
HUNGARICA

AN INTERNATIONAL JOURNAL
IN FOREST, WOOD
AND ENVIRONMENTAL
SCIENCES

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ACTA SILVATICA ET LIGNARIA HUNGARICA

Vol. 22, Nr. 1

Contents

Aleksandr V. LEBEDEV – Csaba MÁTYÁS:	
Variation of Bud Phenology of East European Scots pine Provenances Confirms the Inherited Clinal Pattern of their Adaptation to Climate	9
Éva KIRÁLY – Attila BOROVIKS:	
Valuing Urban Forests as Natural Capital: Climate Mitigation, Biodiversity and Recreational Ecosystem Services in a Hungarian City	25
Ábel BOROVIKS – Attila BENKE – Attila BOROVIKS – Éva KIRÁLY – Endre SCHIBERNA:	
Baseline Setting and Carbon Credit Quantification in Improved Forest Management: A Demonstrative Case Study	45
István György DEÁK – Sándor HORVÁTH:	
Intercropped Macadamia and Coffee in Agroforestry System in Zambia: a Case Study....	63
Andrea REMÉNYI:	
Reframing Material Perception: A Psychometric Model of Premium Wood Furniture Consumption	77
Richárd ROZS – Veronika ELEKNÉ FODOR – Andrea VÁGVÖLGYI:	
Comparison of Noise-Filtering Ability of Vegetation – A Literature Review	91

ACTA SILVATICA ET LIGNARIA HUNGARICA

Vol. 22, Nr. 1

Tartalomjegyzék

LEBEDEV, Aleksandr V. – MÁTYÁS Csaba:

Kelet-európai erdeifenyő származások rügy-fenológiai változatossága megerősíti az éghajlati alkalmazkodás öröklődő klinális mintázatát. 9

KIRÁLY Éva – BOROVICS Attila:

Városi erdők természeti tőke értékelése: klímavédelem, biodiverzitás és rekreációs ökoszisztéma-szolgáltatások egy magyar város példáján 25

BOROVICS Ábel – BENKE Attila – BOROVICS Attila – KIRÁLY Éva – SCHIBERNA Endre:

Baseline-meghatározás és karbonkreditszámítás klímabarát erdőgazdálkodási projektekben: egy szemléltető esettanulmány 45

DEÁK István György – HORVÁTH Sándor:

Makadámdió és kávé köztes termesztése agroerdészeti rendszerben Zambiában: esettanulmány 63

REMÉNYI Andrea:

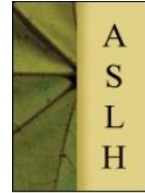
Az anyagészlelés újraértelmezése: a prémium fa bútorfogyasztás pszichometriai modellje 77

ROZS Richárd – ELEKNÉ FODOR Veronika – VÁGVÖLGYI Andrea:

Különböző növényesávok zajvédelmének összehasonlítása – szakirodalmi áttekintés. . 91



Variation of Bud Phenology of East European Scots pine Provenances Confirms the Inherited Clinal Pattern of their Adaptation to Climate



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ABSTRACT

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Phenology is a key bioindicator of climate change; however, the genetic and environmental drivers of phenological traits still remain poorly understood. The authors analyzed large-scale patterns of bud burst and bud set (i.e. of vegetation period length) in Eastern European Scots pine provenances to assess the influence of climatic factors and the role of inheritance in phenological adaptation. Phenological traits were correlated with climatic variables and modelled with linear transfer regression analyses using historical data from provenance experiments in Hungary. The results demonstrate that phenological traits of Scots pine populations exhibit a genetically determined clinal variation pattern and strong correlations between bud burst, bud set and temperature-related variables. The findings challenge opinions that emphasize plasticity in spring phenology and photoperiodic control of autumn growth cessation. The hypothesis of rapid plastic adaptation to changing climatic conditions is not supported by our results. The patterns of phenotypic diversity require a critical consideration in adaptive forest management strategies.

TANULMÁNY INFÓ

KIVONAT

Kulcsszavak:
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Kelet-európai erdeifenyő származások rügy-fenológiai változatossága megerősíti az éghajlati alkalmazkodás öröklődő klinális mintázatát. A fenológia a klímaváltozás fontos bioindikátora, de a fenológiai tulajdonságokat meghatározó genetikai és környezeti hatások szerepe kevésbé tisztázott. A szerzők az erdeifenyő rügyfakadásának és rügyképzésének (vagyis vegetációs idejének) nagytérségi mintázatát vizsgálták Kelet-Európa térségében. A cél a klímatervezők és a genetikai alkalmazkodás szerepének a feltárása volt. A vizsgálathoz egy magyar származási kísérlet egykori adatait használták fel. A fenológiai adatokat klimatikus változókkal korrelálták és lineáris transzfer egyenletekkel modellezték. Kimutatták az erdeifenyő populációk rügy-fenológiai adatainak genetikailag meghatározott, klinális változatosságát és szoros lineáris korrelációját a hőmérsékleti változókkal. Az eredmények kétségbe vonják azokat a véleményeket, amelyek szerint a fafajok rügyfakadási mintázatát jelentős mértékben a plaszticitás határozza meg, valamint hogy az őszi rügyképzés mintázata a fotoperiódussal van összefüggésben. Ugyancsak vitatható az a hipotézis is, amely szerint változó klímában a populációk plaszticitásuk révén hamar alkalmazkodnak. Az adaptív erdészeti kezelés stratégiájának kialakításában a fenotípusos változatosság figyelembevétele fontos szerepet kell kapjon.

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1 INTRODUCTION

Phenology governs the timing of transitions between dormancy and active growth for adaptation to recurring seasonal events. It plays a significant role in determining fitness, may affect competition, growth, carbon sequestration, and the functioning of the ecosystem. Changes in climate are a defining element of future ecological conditions. Climate warming influences tree phenology in boreal and temperate species, affecting their growing season (Morin et al., 2010; Way, 2011; Jing et al., 2021; Langvall – Ottosson Löfvenius, 2021). Phenology was the first widely used bioindicator of climate change. Phenological data are widely used to assess the response of trees and forests to climate change on local and global scales (Skulason et al., 2018; Montgomery et al., 2020; Risk et al., 2021; Camarero – Rubio-Cuadrado, 2025; Wu et al., 2025). The phenological responses of tree populations to climate change are considered insufficiently studied compared to growth (Aspalter et al., 2025).

Provenance tests of forest trees provide valuable information to assess the effect of environment and inheritance on phenotypes. Studies have identified parallel clines in phenology for many tree species, supporting the adaptation of these species to changing growing season conditions at the local level. The transfer to new environmental conditions can be interpreted as a simulation of climatic changes (Mátyás, 1994), allowing for the study of phenological responses (such as bud break, flowering, growth cessation, or dormancy) to assess the risk of damage (Dhar et al., 2015). Although the role of phenology may be critical to forecasting and climate mitigation, links between climate, phenology, and growth are not sufficiently understood. The literature contains conflicting evidence. Common garden studies have been conducted for over 250 years, but there is currently no holistic predictive model of clines between species and phenological events (Zeng – Wolkovich, 2024). Due to the enormous efforts and resources required for field experiments, it is not surprising that common garden studies of forest trees are often limited to traits directly relevant to forestry, such as growth rate, and overlook phenology.

Scots pine (*Pinus sylvestris* L.) is an economically and ecologically dominant tree species in Eastern European forests. Numerous studies have investigated the influence of climatic and weather factors on the growth, development, and survival of the species in this region (Meshkova, 2021; Waszak et al., 2021; Lebedev, 2023; Linkevičius et al., 2024; Lebedev – Dvoychenkov, 2025). Provenance trials indicate that Scots pine populations in the boreal zone exhibit high adaptive potential to climate change, while increased mortality is predicted at the southern edge of their distribution (Nakvasina – Prozherina, 2021; Parfenova et al., 2021; Mátyás et al., 2023; Lebedev – Mátyás, 2025). However, early investigations and tests found low variability and little differentiation in Scots pine phenology (Chmura et al., 2012; Memišević et al., 2023) due to regional approaches and less systematic sampling. The investigations also failed to address the large-scale phenological pattern of the species, especially in Eastern Europe.

This study covers most of the natural range for the species in Eastern Europe, based on a historical survey of bud phenology of provenances. The analysis aims to assess the large-scale phenological trait pattern of the species and the role of climatic factors governing it. The results are expected to contribute to the longer-term future growth and vitality of Scots pine in the region. The following key aspects were investigated: 1) the phenological variability pattern of Scots pine provenances at the study site; 2) the influence of climatic variables on phenological variation; 3) the relationship between climatic transfer distance of provenances and their bud set and bud burst phenology.

2 MATERIALS AND METHODS

2.1 Study site and tested provenances

The study location in Hungary lies outside the natural distribution of the species. Nevertheless, Scots pine was widely planted in monospecific plantations during the afforestation campaigns after the Second World War. Due to its location beyond the southern, xeric limits of the species, the site is a perfect “tolerance provocation” site for phenology responses.

The test site on brown podzolic soil is located in the Kámon Arboretum, Szombathely, Hungary (47.25°N, 16.61°E). The elevation of the site is 227 m asl. The climate is temperate continental, characterized by warm summers and moderately cold winters. In the climate period relevant for the investigations (1961–1990), the average annual temperature was 9.2°C, with means of -1.9°C in the coldest month and of 19.2°C in the warmest month. Mean annual precipitation was 651 mm, with the highest monthly rainfall occurring during the growing season. Overall, the soil and climate conditions were favorable for the growth of Scots pine.

This study used the results of a phenotypical survey of 31 Scots pine provenances from Eastern Europe, covering a latitudinal gradient from 47.2°N to 62.9°N, a longitudinal gradient from 16.5°E to 58.7°E, and an altitudinal range from 31 to 605 m asl. The seed lots were provided in 1975 by the VNIILM institute (Pushkino, Russia), where they were collected to establish the All-Union Provenance Test Network (Prokazin and Bogachev, 1975; Shutyaev – Giertych, 1997). The provenances originated from Russia (up to the Urals), Ukraine, Belarus, Latvia, Estonia, and Hungary, according to the present boundaries (*Table 1*). The seed lots were intended for parallel provenance tests in Hungary (Mátyás et al., 2023; Lebedev – Mátyás, 2025), and the surplus seeds were used for establishing a short-term phenology test.

The seeds were sown in the spring of 1976 and 1977. In 1978, the seedlings were outplanted in the Kámon Arboretum (Szombathely, Hungary) in a 0.5x1.0 m network, in unreplicated plots of 40 plants (Mátyás, 1981). The registration numbers of provenances correspond to the first publication of Shutyaev and Giertych (1997). The provenance test also contained several additional sources from Central Europe and the Mediterranean (including one provenance from Hungary), which were not part of the VNIILM experiment.

2.2 Phenological survey of provenances

The investigation of the phenotypical variation of populations included bud phenology, size, and winter discoloration of needles, juvenile growth, crown form, and needle cast infection tolerance. Adhering to the study’s basic aim, population-level bud burst, and set data were compared to determine the diversity pattern of phenology across East European populations. The plot averages were calculated from data of a minimum of 20 plants per plot.

Surveys to record bud burst were conducted weekly on 6-year-old seedlings in spring 1981. The survey date of April 10, 1981, was selected for analysis due to its best differentiating character among provenances. The average daily air temperature did not reach 15°C until this date, and the daily precipitation did not exceed 5 mm (*Figure 1*). Bud burst phenophases were recorded based on bud elongation. Depending on the development of the top bud of the plants, a score from 1 to 5 was assigned for each plant, where 1 is a closed, undeveloped bud; 5 is a green shoot without covering scales. Due to differences in survival, the first 20 plants of each provenance were scored and averaged.

The presence or absence of developed buds was recorded weekly. Per provenance one hundred nursery-grown seedlings, raised in Nisula containers, were scored. The characteristic date for bud set data was selected for September 6, 1976, on one-year-old seedlings. Bud formation progress was expressed by the percentage of one-year-old seedlings with fully

developed buds at the respective date. *Figure 2* shows the weather conditions for the vegetation season (mean daily temperature and precipitation).

2.3 Climate data and analysis

The data on phenology were analyzed decades later because the Scots pine provenance test project was suspended due to economic and political changes in both countries. Moreover, provenance location climatic data obtainable from advanced climate models were still unavailable when the surveys were conducted.

Table 1. List of Scots pine provenances investigated (MAT – mean annual temperature, MAP – mean annual precipitation)

No.	Location	Latitude, °N	Longitude, °E	Elevation, m asl	MAT, °C	MAP, mm
4	Plesetsk, Arkhangelsk Oblast	62.9	40.4	108	1.0	661
9	Totma, Vologda Oblast	60.0	43.0	126	2.2	651
15	Pryazha, Republic of Karelia	61.7	33.7	166	1.9	653
19	Lisino, Leningrad Oblast	60.0	30.4	31	4.7	658
22	Strugi Krasnye, Pskov Oblast	57.8	28.4	54	4.6	662
23	Kresttsy, Novgorod Oblast	58.3	32.5	67	4.0	683
24	Elva, Tartu County	58.2	26.5	98	4.9	657
25	Jelgava, Jelgava Municipality	56.5	25.2	79	5.6	667
28	Rasony, Vitsebsk Oblast	56.0	29.3	157	4.9	660
29	Lenino, Homel Oblast	52.2	31.7	154	6.5	613
35	Olevsk, Zhytomyr Oblast	50.4	27.7	226	7.1	623
37	Borisopil, Kyiv Oblast	50.2	32.2	116	8.0	565
38	Svesa, Sumy Oblast	52.0	34.0	163	6.1	673
39	Cherkasi, Cherkasy Oblast	49.6	32.0	96	8.2	566
40	Sloviansk, Donbas Region	48.8	37.6	64	8.4	520
43	Orekhovo-Zuyevo, Moskva Oblast	55.5	39.0	124	4.8	624
44	Kovrov, Vladimir Oblast	56.4	41.3	83	4.7	602
46	Pervomaysk, Nizhny Novgorod Oblast	54.9	43.8	181	4.1	561
48	Kostroma, Kostroma Oblast	58.0	42.0	156	3.6	643
54	Sosnovka, Tambov Oblast	53.2	41.3	137	5.5	556
55	Grafskaya, Voronezh Oblast	51.6	39.5	112	6.6	561
57	Nikolsk, Penza Oblast	53.8	46.0	154	5.0	523
60	Veshenskaya, Rostov Oblast	49.6	41.8	56	7.8	484
62	Kamyshin, Volgograd Oblast	50.2	45.4	154	7.2	422
66a	Kamskie Polyani, Republic of Tatarstan	55.7	51.4	52	4.6	662
67	Votkinsk, Republic of Udmurtia	57.5	54.0	244	2.4	588
69	Dyurtyuli, Republic of Bashkortostan	55.5	54.7	125	4.1	494
70	Duvan, Republic of Bashkortostan	55.7	57.9	312	2.7	516
71	Beloretsk, Republic of Bashkortostan	53.4	57.7	605	1.6	653
72	Zilair, Republic of Bashkortostan	52.4	58.7	360	3.6	366
999	Pornóapáti, Vas County, Hungary	47.2	16.5	273	9.2	633

Climate variables for the provenance sources and the test site have been generated with the ClimateEU v5.00 software package with a spatial resolution of 1 km grid, available at <http://tinyurl.com/ClimateEU>, based on methodology similar to Mahoney et al. (2022) and

Marchi et al. (2020). A total of 17 climate variables were analyzed (Table 2). These variables indicate the annual or seasonal amount of incoming heat, precipitation, and humidity. Data from the climatic period of 1961–1990 were used to characterize the weather conditions at the test site. Data from the “Map of the Sum of Air Temperatures for the Period with a Sustained Temperature Above 10°C” were used to analyze the clinal variability in phenology. The map was developed at the Main Geophysical Observatory of the Chief Administration of the Hydrometeorological Service under the Council of Ministers of the USSR (Institut Geografii AN SSSR, 1964).

The selected databases represent the most precise climate data available for the recent past. Nevertheless, a longer period representing the climate and extremes during the parent generation would have been useful to trace the impact of adaptation and evolution on the inherited responses of the progeny more exactly. Unfortunately, such data does not exist.

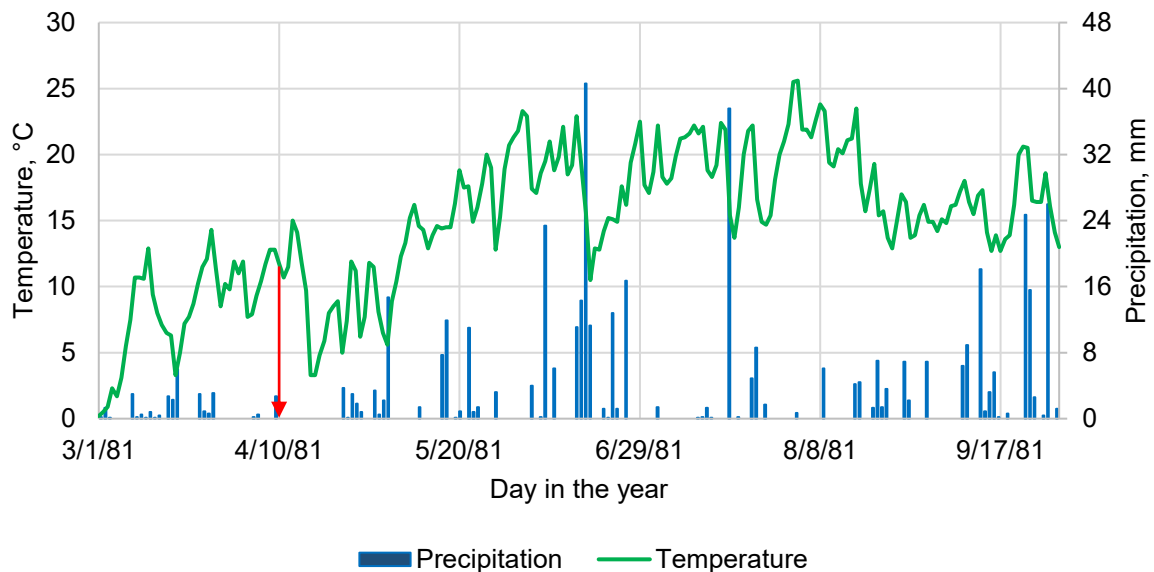


Figure 1. Average air temperature and total precipitation on individual days for the 1981 in Szombathely. The arrow indicates the selected date of assessment of bud burst

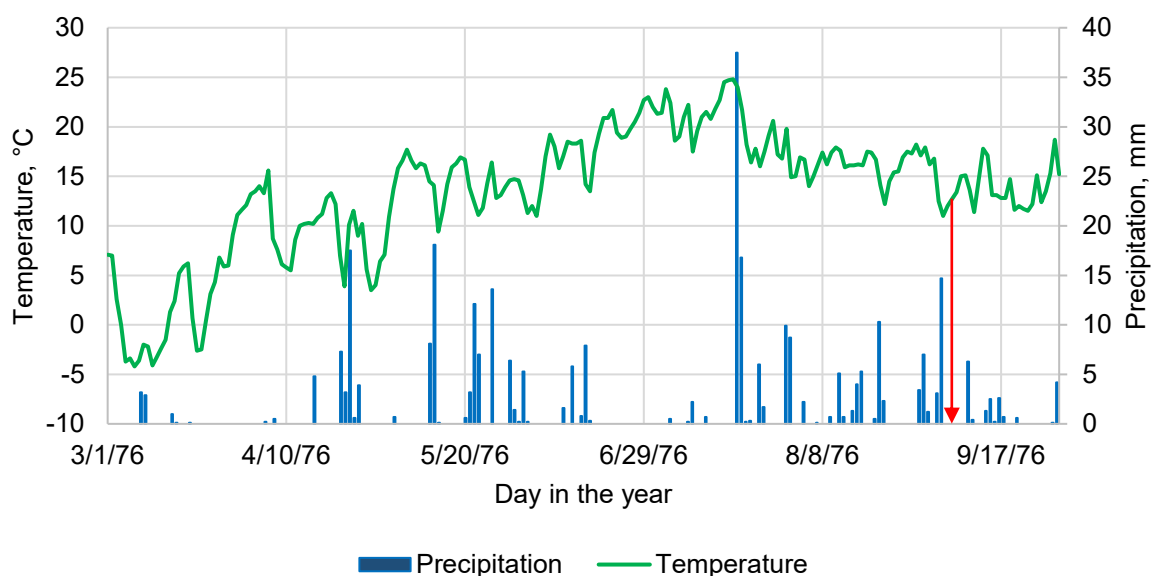


Figure 2. Average air temperature and total precipitation on individual days for the 1976 in Szombathely. The arrow indicates the selected date of assessment of bud set

Climate variables were used in their original and transformed form. To assess the phenological response of provenances to transfer to new conditions, the climate transfer distance was calculated as (Mátyás 1994):

$$\Delta X = X_s - X_p \quad (1)$$

Where:

ΔX :	climate transfer distance for climate variable X
X_s :	climate variable X for test site
X_p :	climate variable X for provenance.

Thus, local populations have a $\Delta X = 0$, and positive values of ΔX characterize the transfer of populations from colder or drier climates to warmer or wetter ones. Since most of the provenances were transferred from north to south, their temperature transfer distance is greater than 0, i.e., indicating warming.

Phenological response of provenances was related to their climate transfer distance, providing individual transfer functions for each climate variable. In this study, we used a linear regression, i.e., phenological variable = $f(\Delta X)$, where f is a linear function.

Table 2. Analyzed climate variables (ClimateEU v5.00)

Code	Definition	Units
<i>MAT</i>	Mean annual temperature	°C
<i>MWMT</i>	Mean warmest month temperature	°C
<i>MCMT</i>	Mean coldest month temperature	°C
<i>MAP</i>	Mean annual precipitation	mm
<i>MSP</i>	Mean summer (May to September) precipitation	mm
<i>AHM</i>	Annual heat-moisture index	-
<i>SHM</i>	Summer heat-moisture index	-
<i>DD_above_5</i>	Degree-days above 5°C	°C
<i>FFP</i>	Frost-free period	-
<i>Prec_wt</i>	Winter precipitation	mm
<i>Prec_sp</i>	Spring precipitation	mm
<i>Prec_sm</i>	Summer precipitation	mm
<i>Prec_at</i>	Autumn precipitation	mm
<i>Tave_wt</i>	Winter mean temperature	°C
<i>Tave_sp</i>	Spring mean temperature	°C
<i>Tave_sm</i>	Summer mean temperature	°C
<i>Tave_at</i>	Autumn mean temperature	°C

2.4 Data analysis

All statistical analyses were conducted using R software, version 4.0.3 (R Core Team, Vienna, Austria). We calculated Pearson correlation coefficients to investigate the relationships between phenological traits (bud break and bud set) and selected climatic variables at the provenance origins. Additionally, we visualized and analyzed the effect of climatic gradients on phenotypic diversity among populations. Spatial data were processed and analyzed in QGIS 3.16, utilizing standard toolkits for vector and raster data manipulation.

3 RESULTS AND DISCUSSION

3.1 Spatial and temporal pattern of phenological diversity

Bud burst and bud set values display high inter-provenance variability (Table 3). At the test site in Hungary, bud burst varied from 2.4 (provenance No. 62) to 5.0 (provenance No. 15). Bud set varied from 10 % (provenance No. 60) to 100% (provenances No. 9 and 15). These two phenological traits display a significant positive correlation ($r = 0.719$, $p < 0.001$), indicating strong genetic links.

Table 3. Bud burst and bud set values of Scots pine provenances in the Hungarian test

No.	Location	Latitude, Longitude,		Bud burst on 10/04/1981	Bud set on 06/09/1976
		°N	°E		
4	Plesetsk, Arkhangelsk Oblast	62.9	40.4	4.6	95
9	Totma, Vologda Oblast	60.0	43.0	4.4	100
15	Pryazha, Republic of Karelia	61.7	33.7	5.0	100
19	Lisino, Leningrad Oblast	60.0	30.4	3.8	70
22	Strugi Krasnye, Pskov Oblast	57.8	28.4	3.0	70
23	Kresttsy, Novgorod Oblast	58.3	32.5	3.7	80
24	Elva, Tartu County	58.2	26.5	3.6	50
25	Jelgava, Jelgava Municipality	56.5	25.2	3.0	70
28	Rasony, Vitsebsk Oblast	56.0	29.3	3.1	70
29	Lenino, Homel Oblast	52.2	31.7	3.0	30
35	Olevsk, Zhytomyr Oblast	50.4	27.7	3.1	35
37	Borispil, Kyiv Oblast	50.2	32.2	2.6	50
38	Svesa, Sumy Oblast	52.0	34.0	2.9	50
39	Cherkasi, Cherkasy Oblast	49.6	32.0	2.9	40
40	Slovyansk, Donbas Region	48.8	37.6	2.7	40
43	Orehovo-Zuyevo, Moskva Oblast	55.5	39.0	4.0	60
44	Kovrov, Vladimir Oblast	56.4	41.3	4.0	50
46	Pervomaysk, Nizhny Novgorod Oblast	54.9	43.8	3.9	65
48	Kostroma, Kostroma Oblast	58.0	42.0	3.5	90
54	Sosnovka, Tambov Oblast	53.2	41.3	3.3	70
55	Grafskaya, Voronezh Oblast	51.6	39.5	2.7	60
57	Nikolsk, Penza Oblast	53.8	46.0	3.8	80
60	Veshenskaya, Rostov Oblast	49.6	41.8	2.5	10
62	Kamyshin, Volgograd Oblast	50.2	45.4	2.4	65
66a	Kamskie Polyani, Republic of Tatarstan	55.7	51.4	4.0	70
67	Votkinsk, Republic of Udmurtia	57.5	54.0	4.2	95
69	Dyurtyuli, Republic of Bashkortostan	55.5	54.7	3.9	90
70	Duvan, Republic of Bashkortostan	55.7	57.9	3.5	90
71	Beloretsk, Republic of Bashkortostan	53.4	57.7	4.5	80
72	Zilair, Republic of Bashkortostan	52.4	58.7	3.9	70
999	Pornóapáti, Vas County, Hungary	47.2	16.5	2.5	20

The direction and gradient of the clearly clinal pattern of bud burst across Eastern Europe display the expected configuration. As described in earlier studies, northern populations were the earliest at the test location, while southern ones were the last to break bud, consistent with their thermal conditions at origin (Chmura et al., 2012; Memišević et al., 2023). Consequently,

the isophase lines describing the budburst pattern are not aligned with latitude everywhere. For example, they are adapted to a milder climate along the Baltic coast. Both bud burst and set follow their winter temperature variables, such as January temperature. This anomalous zone forms a triangle in the southwest of the East European Plain and is truncated approximately at 60° N latitude (Figure 3). A similar anomaly appears in both traits in the southeast towards the steppe region, where isophase lines run parallel to July isotherms, i.e., to summer temperature sums. Beyond these anomalies, the phenotypic isophase lines run approximately parallel to latitudes, a pattern that also holds for the Siberian part of the range. (See the following subchapters for correlation data of phenology with climate factors.) Thus, contrary to numerous findings by other sources, the present study found the growth cessation pattern (bud set) among provenances to be similar to that of spring bud burst in East Europe (Figure 3) (Mátyás 1981).

The temporal process of bud setting was investigated in autumn 1982 and 1983. The progression from the appearance of the first buds to complete growth cessation within a population may last 30 to 40 days. Bud formation timing and bud burst depend on local weather conditions, showing 20 to 30 days of variation between years; however, the ranking of the provenances remains consistent.

Temperature conditions primarily determine the active growth phase. Latitude (photoperiod) plays no decisive role. The differences between provenances observed at a specific location are dominated by genetic adaptation; the role of plasticity (as proposed by some sources – see subchapter 3.4) could not be identified in this analysis (Mátyás 1987).

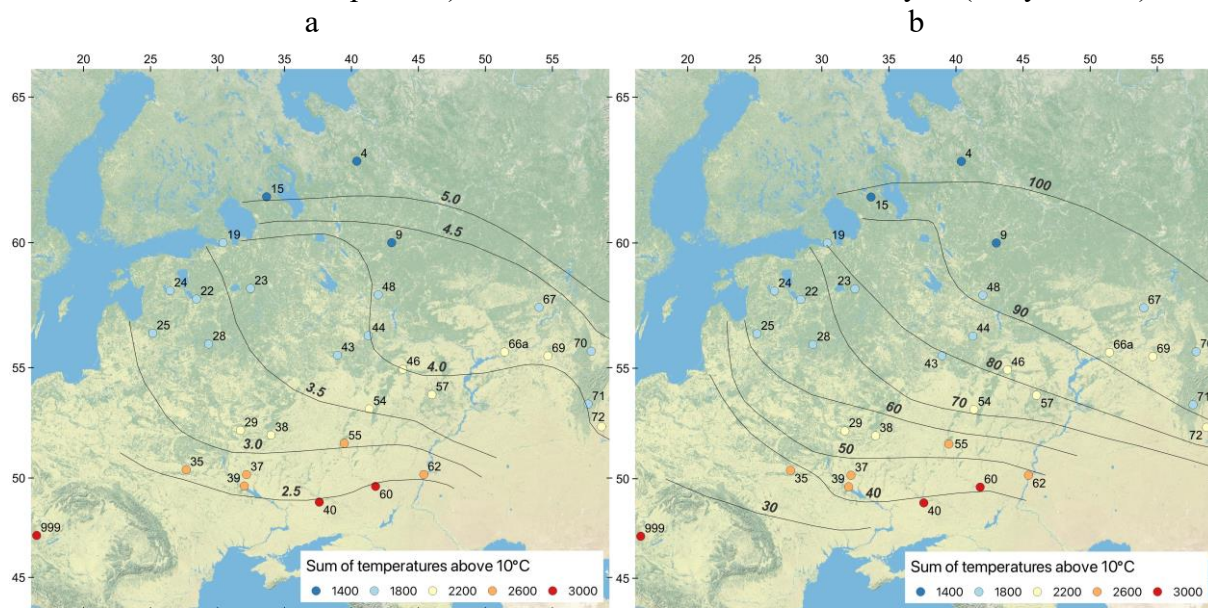


Figure 3. Clinal variation (black lines and bold italic numbers) in bud burst (a) and bud set (b) among Scots pine provenances, and annual temperature sum above 10°C at their origin. Provenance (dots) numbers explained in Table 1.

3.2 Correlation of climatic factors and phenology

We calculated Pearson correlation coefficients between climatic and phenological variables to account for ecological drivers of population differentiation. The dataset allowed us to examine trait-climate correlations across a wide range of climatic conditions in Eastern Europe. Both phenological variables showed significant negative correlations with all temperature-related variables (primarily *MAT*, *Tave_at*, *Tave_sp*, and *FFP*) and the heat-moisture index. To a lesser

extent, phenological variables also correlated with precipitation, though only *Prec_at* exhibited a significant positive correlation.

Scots pine bud phenology was most significantly influenced by mean annual temperature of the seed source (*MAT*, $r < -0.88$, $p < 0.001$). Although this climate variable is commonly used in climate change projections, it does not account for seasonal variations or periodic extreme conditions. Spring and autumn temperatures play a crucial role in the initiation and cessation of Scots pine growth (Metslaid et al., 2018; Li et al., 2021). As expected, phenological traits also showed highly significant correlations with mean spring (*Tave_sp*, $r < -0.87$, $p < 0.001$) and autumn (*Tave_at*, $r < -0.87$, $p < 0.001$) temperatures. The length of the frost-free period (*FFP*) significantly affected the phenology of the provenances as well (Figure 4). In spite of strong correlations between temperature and precipitation variables, rainfall alone shows mostly low significance with bud phenology. The low correlation with precipitation is understandable, due to sufficient rainfall in the majority of regions of Scots pine's distribution in East Europe – the few sampled provenances adapted to the drought-exposed South have negligible effect on the correlations.

It is, however, unexpected that bud burst and set are highly correlated, indicating strong genetic links between the two traits and/or similar climatic cues. The comparison of correlations of all climate variables with bud burst and bud set (Figure 4) indicates also that Scots pine phenology displays strong links both with the same spring and autumn climate variables, which is a unique finding, contradicting the recent literature (see subchapter 3.4).

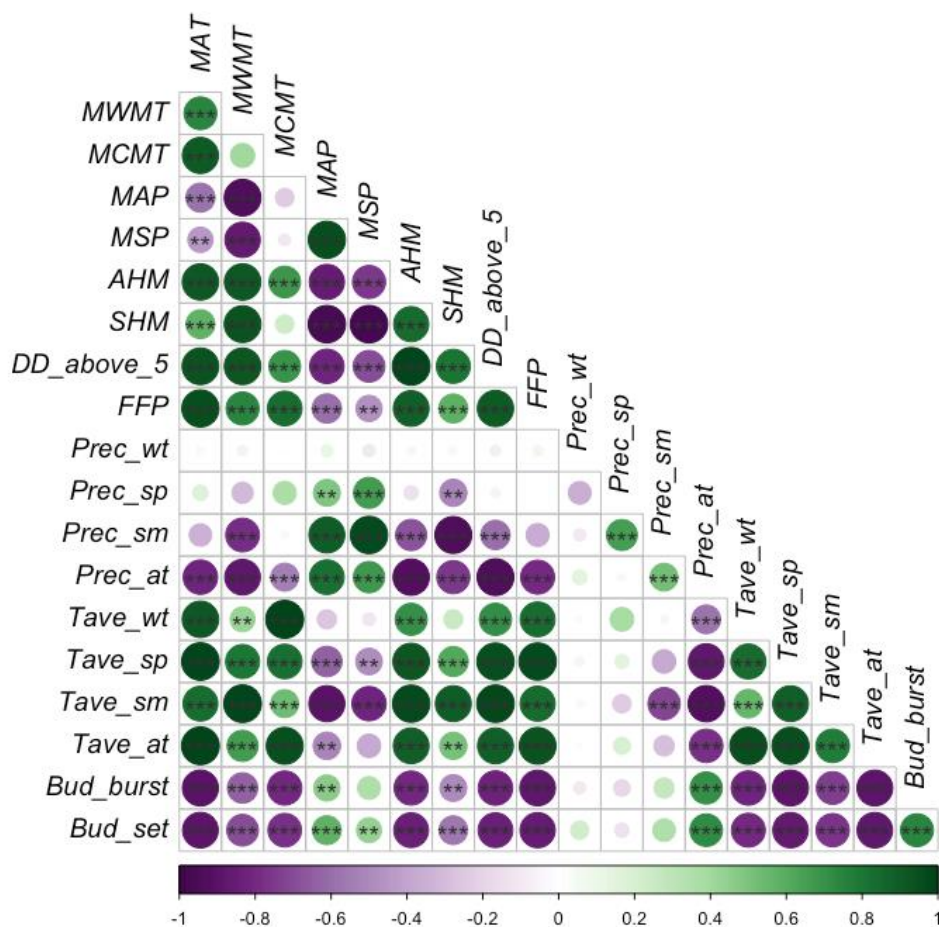


Figure 4. Correlation of climate and phenological traits of provenances. The significance level (* 0.05, ** 0.01, *** 0.001) between -1.0 and 1.0 is indicated by the size of symbols and their sign by color (positive: green, negative: purple)

3.3 Phenological pattern of provenance adaptation to climate

For the four thermal climate variables (*MAT*, *Tave_at*, *Tave_sp*, and *FFP*), which showed the most significant correlation with bud phenology, we calculated the climate transfer distances and estimated linear transfer equations for the climate variables to survey the within-species adaptive pattern across the cline of changing climatic conditions. For both phenological traits (bud burst and bud set), all linear equations were statistically significant ($p < 0.001$) and explained more than 70% of the between-population variance ($R^2 > 0.7$). This indicates strong genetic differentiation among populations according to their geographical origin, which supports their clinal character (*Figures 5 and 6*). The correlations of both phenological traits with climate found for Scots pine are similarly significant and warrant attention.

East European Scots pine provenances exhibit genetic differentiation across ecological and vegetation zones, which is reflected in the pattern of morphological and physiological trait variation. Our results, deduced from continental-scale data, support and extend the findings of Chmura et al. (2012), Ballian et al. (2019), Galdina et al. (2023), and others on the pattern of phenological variation in Scots pine. In Eastern Europe, where the topography and climate conditions across the range of Scots pine are uniform, respectively constantly changing, the pattern of phenotypic variation has a clinal character and shows high similarity to the growth traits measured in the same experiment (Shutyaev – Giertych, 1997; Mátyás et al., 2023; Lebedev – Mátyás, 2025).

3.4 Genetic differentiation and phenological adaptation of provenances

Common garden studies in many species have established similar clines in phenology; in general, the shorter the growing season, the earlier the cessation of growth (bud set). However, the evidence for genetic background in tree spring phenology is inconsistent. While spring phenology is more plastic (Aitken – Bemmels, 2016) and seems to be more strongly determined by temperature (Flynn – Wolkovich, 2018), the review by Zeng and Wolkovich (2024) of numerous species also concludes that there is no evidence of genetic (provenance) effects on spring phenology. This stands in sharp contrast to the significant clines with latitude and mean annual temperature found in autumn phenology. Research has linked these autumn clines to photoperiodic effects (Savolainen et al., 2007; Alberto et al., 2013). Zeng and Wolkovich (2024), along with other studies, suggest that a weaker and more varied plastic response is the cause of differentiation in spring phenology, while clines in autumn phenology appear stronger and more consistent across species.

Directional selection by environmental factors results in intraspecific patterns of adaptive traits, although the determinant cues may change. Therefore, the results of phenology and growth investigations may be dependent on the intensity and range of sampling. Consequently, regional studies may result in conclusions of regional validity.

It is unquestioned that thermal factors dominate in determining the active growth period. According to the general interpretation, autumn events create strong clines to avoid tissue loss from early frost at the end of the season. The high uncertainty of spring phenology found in many studies is explained by the higher unpredictability of frost risk, which triggers plastic (i.e., faster, and less genetically determined) adaptive responses to spring events. The hypothesis of Chamberlain and Wolkovich (2021) is that in the future, warming winters and late spring frosts will especially press tree species to change phenology and growth dynamics with the support of plasticity. However, the high significance of the linear regressions of both bud burst and bud set vs. thermal variables (*Figures 5 and 6*) leaves little space for plasticity; the populations follow the genetic imprint from their origin, at least at an early age. The hypothesis of fast

phenological adaptation to changing climatic conditions through plasticity cannot be supported by our results.

An example of changing determinant climatic factors in changing environments is the abrupt change in the phenotypic pattern of Scots pine populations north of latitude 60° N (e.g., around Saint Petersburg) in our study. The switching from a thermally controlled to a latitudinal pattern further north is thought to be caused by lower heat sums, which increases the regulatory role of photoperiod (Mátyás, 1981). The opinion that autumn phenology clines are determined by photoperiod (Savolainen et al., 2007) has most probably its origin in the fact that the authors investigated boreal populations in northern Scandinavia.

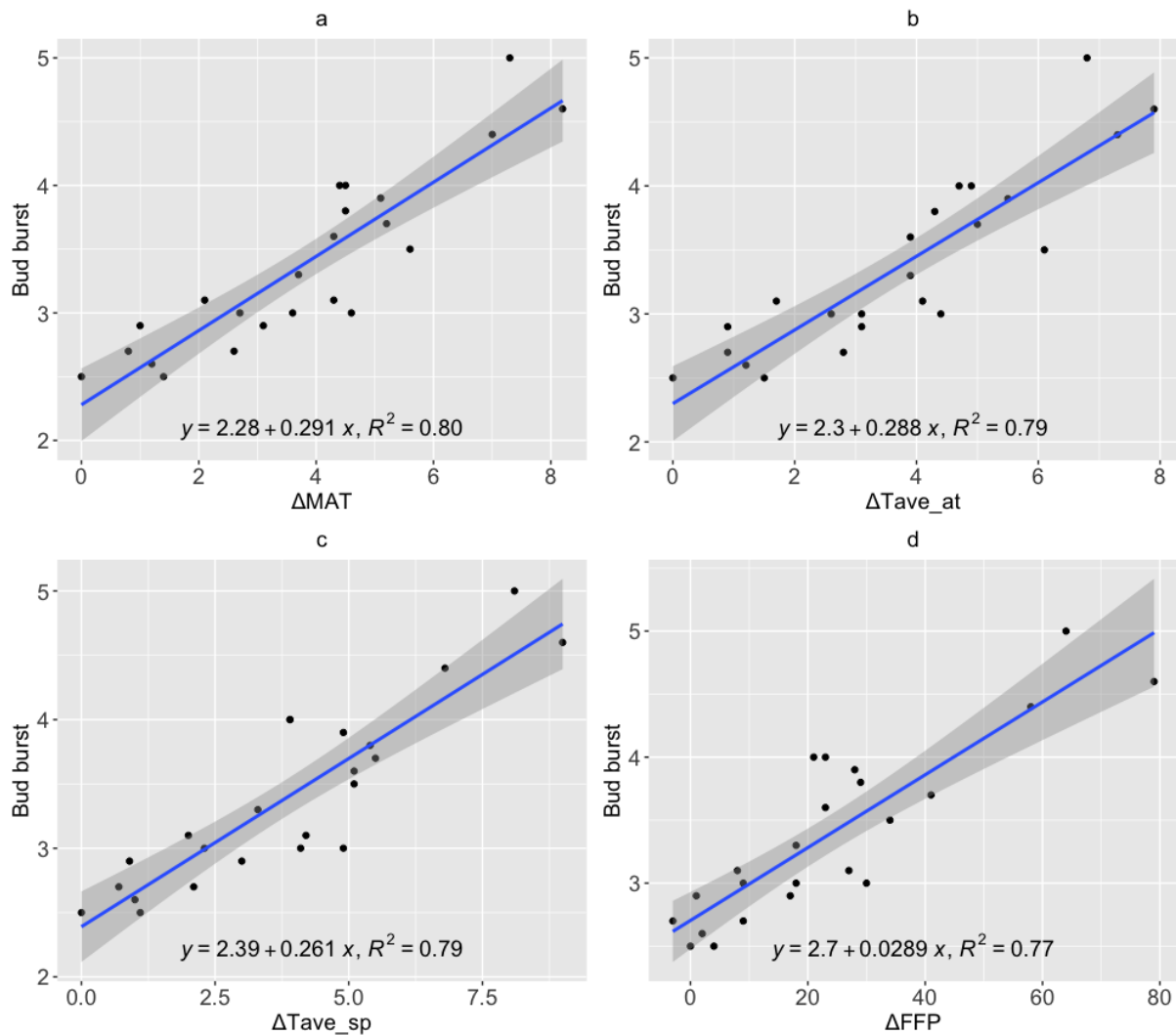


Figure 5. Linear regression between provenance bud burst value and climate transfer distance of: a) mean annual temperature, b) autumn mean temperature, c) spring mean temperature, d) frost-free period

However, our study on Scots pine shows that data for both bud burst and bud set confirm clear, genetically determined clinal variation across the eco-climatic range in Eastern Europe, and their determination and response appear similar. In this respect, the results presented on Scots pine differ from those of certain other studies, irrespective of species. One reason for this contradiction might be the limited range and non-representative sampling of populations in many studies. Distinguishing between genetic and plastic (“non-genetic”) causes for the within-species phenotypic pattern was impossible in this study, because proving the effect of plasticity

requires multiple test sites. It is most probable that there are no universally applicable laws for tree species with different distributional ranges. The climatic conditions at the test sites may also contribute to contradicting results. Climates with late springs and fast progress of heat sum may accelerate phenological phases and diminish differentiation. The fact that the majority of the rare investigations of Scots pine phenology had been conducted in the boreal zone is thought-provoking in this respect.

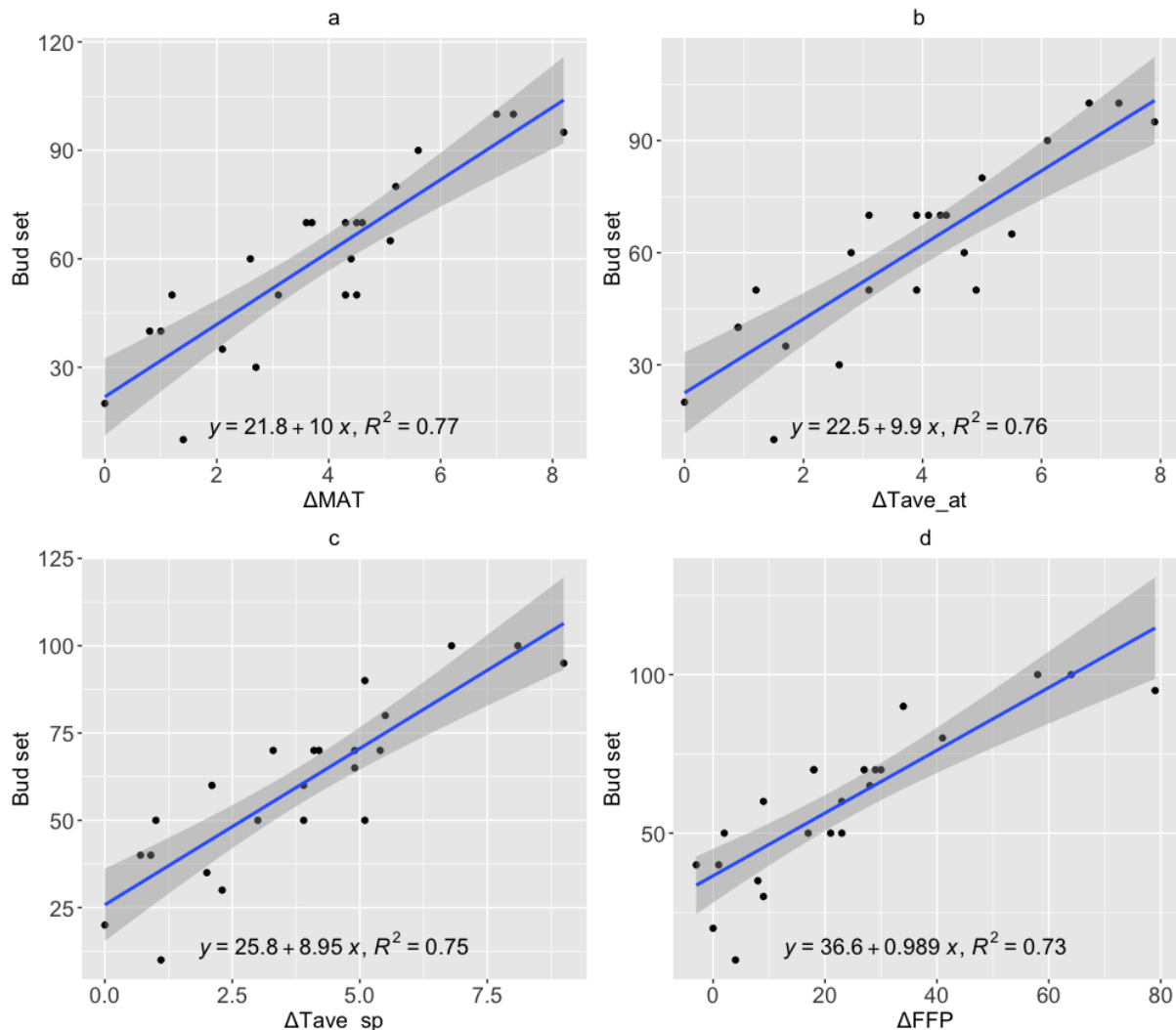


Figure 6. Linear regression between provenance bud set value and climate transfer distance of: a) mean annual temperature, b) autumn mean temperature, c) spring mean temperature, d) frost-free period

4 CONCLUSIONS

This research provides valuable insights for forecasting forest responses to climate change, emphasizing the need to integrate both adaptive genetic characteristics and phenotypic plasticity into models that project the future carbon balance and dynamics of plant communities.

In conclusion, our study demonstrates that phenological traits in Scots pine populations across Eastern Europe exhibit a clear, genetically determined clinal variation pattern. The strong correlations between bud burst, bud set, and geographic-climatic variables underscore that

phenological variability is a complex process influenced not only by local climate but also by the intrinsic genetic factors and adaptive history of populations.

In the trial, situated beyond the xeric distribution limit of the species, all transferred provenances responded with bud break and set controlled by their inherited traits. Direct damages caused by phenological maladaptation were observed only at extreme transfer distances, such as with the early flushing Murmansk provenance, which became extirpated in the trial (most probably due to spring frost damage). Other damages due to maladaptation, such as pest infestation or drought mortality, were not observed during the limited period of the investigation. The long-term consequences of unadapted phenology at sites with a rapidly changing climate are difficult to predict. However, the successive shift of climate zones in Hungary during the first decades of the 2000s already led to significant tree mortality in commercial stands of Scots pine under analog site conditions.

These findings are pivotal in the context of the anticipated global temperature rise. While previous research suggests that warming springs will be tracked more closely by trees than warming autumns, our results highlight that the pattern of phenotypic response is not uniform in tree species and certainly not valid in Scots pine. Responses are fundamentally filtered by species-specific genetic adaptation. The hypothesis of fast plastic adaptation to changing climatic conditions, as proposed by Chamberlain and Wolkovich (2021), cannot be supported by our results. The observed patterns of phenotypic diversity require a critical consideration in forest management strategies, particularly when planning the transfer (assisted migration) of propagation material to ensure resilience in future climates.

Although our findings do not allow for broad generalizations across other tree species, they provide an essential foundation for assessing the impact of genetic variation in Scots pine and for predicting the responses of southern lineages to extreme “northern” conditions. Phenology will play a key role in determining how species shift their distribution areas and how they participate in the carbon sequestration of future ecosystems. Therefore, refining predictions requires new, provenance-level phenological data.

Future studies are necessary to refine our understanding of phenological responses to environmental change by establishing experiments outside the natural ranges of the species and conducting detailed assessments of phenology in relation to growth and stress tolerance. The need for such research is underscored by the challenge of forecasted serious climate change impacts. Both the adaptive genetic characteristics of populations and phenotypic plasticity must be considered when projecting how climate change will alter dynamic forces shaping forest ecosystems.

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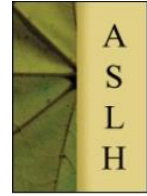
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Valuing Urban Forests as Natural Capital: Climate Mitigation, Biodiversity and Recreational Ecosystem Services in a Hungarian City



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ABSTRACT

Urban forests can support municipal climate action while delivering a broad range of additional ecosystem services. This study assesses the city of Sárvár, Hungary (1,125 ha of forests and 470 ha of other tree-covered areas) to quantify carbon-related ecosystem services and monetize selected non-market benefits. Carbon stocks and sequestration were estimated by tree species group using National Forestry Database records (2010–2023), Copernicus Tree Cover Density data, and IPCC greenhouse-gas inventory methodology. Harvested wood products and material- and energy-substitution effects were also included. Urban forests and trees stored 366,667 tons of CO₂ in 2023, corresponding to a carbon-stock value of EUR 18.8 million. When biomass dynamics, harvested wood products, and substitution effects were considered jointly, the net mitigation effect offset 9.3% of total municipal greenhouse-gas emissions. Using a benefit-transfer approach and a 2% social discount rate, the capitalized value of biodiversity-related ecosystem services amounted to EUR 11.89 million, while the capitalized recreational value reached EUR 5.95 million. Overall, the findings suggest that Sárvár's urban forests operate as multifunctional natural capital assets providing climate mitigation and welfare benefits that are directly relevant to policy design, evidence-based urban planning, and ecosystem accounting.

TANULMÁNY INFÓ

Kulcsszavak:

városi erdők
ökoszisztéma-
szolgáltatások
szénmegkötés
CO₂
Természeti tőke elszámolás

KIVONAT

Városi erdők természeti tőke értékelése: klímavédelem, biodiverzitás és rekreációs ökoszisztéma-szolgáltatások egy magyar város példáján. A városi erdők jelentős szerepet tölthetnek be a klímavédelemben, miközben számos további ökoszisztéma-szolgáltatást is biztosítanak. A tanulmány Sárvár városának példáján (1125 ha erdőterület és 470 ha egyéb fás terület) értékeli a klímamitigációs ökoszisztéma-szolgáltatásokat. A szénkészletek becslése az Országos Erdőállomány Adattár 2010–2023 adatai, illetve a Copernicus Tree Cover Density adatbázis alapján történt. Az elemzés kiterjedt a fatermékekben történő hosszú távú széntárolásra, valamint az anyag- és energiahelyettesítési hatásokra is. A sárvári városi erdők és fák 2023-ban összesen 366 667 tonna CO₂-t tároltak, ami mintegy 18,8 millió euró értékű szénkészletnek felel meg. A biomassza, a fatermékek és a helyettesítési hatások együttes figyelembevételével a nettó klímavédelmi hatás a települési üvegházhatásúgáz-kibocsátás 9,3%-át ellentételezte. A benefit transzfer értékelés szerint a biodiverzitáshoz kapcsolódó ökoszisztéma-szolgáltatások tőkésített értéke 11,89 millió euró, míg a rekreációs szolgáltatásoké 5,95 millió euró. Az eredmények azt mutatják, hogy Sárvár városi erdei jelentős klímavédelmi és jóléti értéket képviselnek.

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1 INTRODUCTION

Climate change is one of the most urgent global challenges of our time, and its impacts are particularly pronounced in urban areas (IPCC 2023). Cities have become central arenas of global challenges and opportunities in the 21st century. More than half of the world's population lives in urban areas, and a substantial share of global energy use, greenhouse gas emissions, material throughput, and waste generation originates from cities (Dhakal, 2010; United Nations, 2018; Hong et al., 2024). Cities are simultaneously major sources of greenhouse gas emissions and key arenas for implementing solutions, as urbanization-related pressures—such as the urban heat island effect, air pollution, and the loss and fragmentation of green space—require targeted interventions (Elmqvist et al., 2015; IPCC 2021; Choi et al., 2021; IPCC 2023; Feng et al., 2024). Nature-based solutions (Ren et al., 2019; Goodwin et al., 2023), including urban forests, are increasingly recognized as strategic instruments for climate action, as they provide multiple ecosystem services: they sequester and store atmospheric carbon, moderate temperature extremes, improve air quality, and enhance adaptive capacity and resilience in densely built environments (Cohen-Shacham et al., 2016; Feng et al., 2023; Fu et al., 2023; Mosisa et al., 2025).

In this study, the term ‘urban forest’ refers to all tree-covered areas within the administrative boundary of a municipality, including individual urban trees (e.g., street and yard trees), trees in parks and other public green spaces, and forest stands managed under formal forest management plans located within the municipal boundary. Under this definition, all trees within the settlement area are considered part of a single urban forest system contributing to ecosystem services and climate regulation.

Cities play a decisive role in the sustainability transition, which is understood as a comprehensive socio-economic transformation aimed at achieving environmental sustainability, social justice, and economic well-being simultaneously (Loorbach, 2010; Markard et al., 2012). From the perspective of ecological economics, economic systems must operate within the carrying capacity of nature, and natural resources should be treated not merely as production inputs but as forms of capital with intrinsic value (Costanza et al., 1997). Within this framing, cities are not only economic units but complex socio-ecological systems whose long-term viability depends on their interactions with ecological processes. Urban sustainability, therefore, requires that key ecological functions—such as carbon sequestration, temperature and water regulation, and biodiversity—are systematically integrated into planning, governance, and investment decisions (Grêt-Regamey et al., 2017). Recent urban planning concepts further emphasize the role of nature in supporting this transition. Frameworks such as biophilic cities promote the systematic integration of nature and biodiversity into urban design and governance, strengthening the relationship between people and urban ecosystems (Beatley – Newman, 2013). In parallel, practical planning guidelines such as the 3-30-300 rule propose measurable targets for urban greenery: ensuring that every resident can see at least three trees from their home, that neighborhoods reach approximately 30% tree canopy cover, and that green spaces are accessible within 300 meters (Konijnendijk, 2023). These approaches highlight the strategic importance of urban forests and tree-based green infrastructure in enhancing environmental quality and human well-being in cities (Velasco et al. 2016). Many cities have adopted policies that promote tree planting, protect existing green spaces, and integrate greenery into the built environment through green roofs and facades (Velasco et al., 2016).

Scientific and financial recognition of green infrastructure is supported by Natural Capital Accounting (NCA) approaches, which aim to integrate ecosystem services into national and local accounting and statistical systems in a measurable and trackable manner (World Bank Group, 2021; Vysna et al., 2021; UN 2024; WAVES 2025). The purpose of NCA is to ensure

that nature is not treated as a background condition in decision-making, but as a measurable and comparable asset that can be incorporated into economic planning. In the urban context, NCA can support cost–benefit analysis of green-space development, monetary evaluation of climate services, and systematic reporting of ecosystem service provision.

The System of Environmental-Economic Accounting—Ecosystem Accounting (SEEA EA; United Nations 2024) provides a methodological standard for implementing such accounts and has been assessed across multiple countries and cities. Although NCA remains in an early phase in Hungary, the monetary valuation of urban forests and green spaces—demonstrated in this study—can contribute to establishing the foundations for local-level ecosystem accounting systems and evidence-based urban governance.

To operationalize this perspective within an urban ecosystem accounting framework, it is necessary to identify key ecosystem services that capture the multifunctional contributions of urban forests. Therefore, this study focuses on three service categories particularly relevant in urban contexts: climate change mitigation services through carbon sequestration, biodiversity-related ecosystem services linked to habitat provision and ecological resilience, and recreational ecosystem services reflecting direct benefits for urban residents. Together, these services represent regulating, supporting, and cultural dimensions of urban forest benefits and provide a structured basis for assessing their societal value.

1.1 Climate-mitigation functions of urban forests

Urban forests contribute substantially to climate change mitigation by delivering ecosystem services that simultaneously reduce heat stress (Göndöcs et al., 2017) and remove and store carbon from the atmosphere through biomass accumulation and, in some contexts, soil carbon dynamics. While earlier research often focused on carbon stocks in urban vegetation, the dynamic process of sequestration—annual net uptake of atmospheric CO₂—has received comparatively less attention (Velasco et al., 2016; Zhuang et al., 2023; Guo et al., 2024). Estimating sequestration commonly relies on modelling, flux analysis, or field measurements (Zhu et al., 2022), which can be costly and labor-intensive, particularly at the metropolitan scale. Tools such as i-Tree and InVEST have therefore been widely applied to quantify carbon-related ecosystem services of urban vegetation (Raum et al., 2019; Babbar et al., 2021).

Hungary provides a useful example for illustrating the relevance of urban tree carbon sequestration in a Central European context. Recent results from Budapest indicate that urban tree vegetation offsets of about 41,000 t CO₂ annually, corresponding to approximately 1% of the city's emissions (Király et al., 2025). This value is consistent with estimates from other large cities such as Vancouver, Mexico City, and Changchun, where urban green-space sequestration typically offsets around 1–2% of total emissions (Crawford – Christen, 2015; Velasco et al., 2016; Guo et al., 2024). Beyond carbon, studies on urban trees demonstrate additional co-benefits; for example, species-specific differences in photosynthetic performance and the retention of fine particulate matter can materially influence air-quality regulation in cities (Chen et al., 2024).

1.2 Biodiversity-related ecosystem services of urban forests

Beyond climate mitigation, urban forests contribute to biodiversity conservation and associated ecosystem services by providing habitat, supporting species richness, and strengthening ecological connectivity within fragmented urban landscapes. These biodiversity functions generate both intrinsic value and indirect instrumental benefits, including enhanced ecosystem stability, increased resilience to disturbances, and the reinforcement of other ecosystem services

such as pollination, pest regulation, and cultural and recreational benefits (Wajchman-Świtalska et al., 2022; Guarino et al. 2024).

European evidence shows that biodiversity-oriented objectives are among the strongest drivers of engagement in ecosystem service provision. Meta-analytical results indicate that voluntary agreements explicitly targeting biodiversity achieve high participation rates, reflecting the importance of stewardship motivations alongside economic incentives (Mäntymaa et al., 2009; Boon et al., 2010; Mitani – Lindhjem, 2015; Ringier et al., 2025). These findings underscore that biodiversity conservation is increasingly perceived as a core forest function rather than a residual outcome of production-oriented management.

In urban contexts, biodiversity-related ecosystem services are particularly salient due to high land-use pressure, habitat fragmentation, and strong public demand for access to nature-rich environments. Biodiversity services valuation is typically conducted using stated-preference methods, most commonly contingent valuation, or choice experiments, which capture non-market values such as willingness to pay (WTP), i.e., the monetary amount individuals are willing to contribute to secure biodiversity protection and forest conservation outcomes (Kline et al., 2000; OECD 2002; Brouwer et al., 2015). Incorporating biodiversity into urban forest valuation is therefore essential within sustainability-transition frameworks, as it aligns municipal planning with biodiversity targets while also reinforcing environmental justice objectives through equitable access to biodiverse green spaces.

Given the scarcity of local stated-preference studies for municipal forest areas, biodiversity values are frequently incorporated through benefit transfer based on robust primary valuation studies and transparent adjustment procedures. In this study, benefit transfer is informed by the nationwide contingent valuation of biodiversity policy implementation conducted for Germany by Meyerhoff et al. (2012). Their results indicate annual WTP values ranging between EUR 2.3 and EUR 9.3 billion for implementing the German National Biodiversity Strategy, demonstrating that biodiversity protection yields substantial welfare benefits that clearly exceed opportunity and management costs.

1.3 Recreational ecosystem services of forests

Recreational ecosystem services are among the most directly perceived benefits that forests provide. Activities such as walking and hiking contribute to physical and mental health, stress reduction, social cohesion, and overall urban livability. In urban and peri-urban contexts, forest recreation is intricately linked to accessibility and frequent use by residents, making it a key component of sustainable urban development (Wajchman-Świtalska et al., 2022).

International evidence consistently shows that forests rank among the most highly valued landscapes for recreation, outperforming many other green-space types due to their perceived naturalness, biodiversity, and aesthetic quality (Tyrväinen – Miettinen, 2000; De Groot et al., 2012; Elmqvist et al., 2015). Meta-analyses indicate that aggregate recreational value is primarily driven by visit frequency rather than per-visit value, implying that forests located near population centers often generate the greatest overall benefits (Zandersen – Tol, 2009; Bateman et al., 2011).

The economic valuation of forest recreation has most commonly relied on the travel cost method, which infers value from the time and monetary expenses visitors incur to access recreational sites. This approach has been widely applied to urban forests, production forests, and protected areas and is considered more behaviorally robust than stated-preference methods in contexts where forest access is traditionally free of charge (Bartczak et al., 2008; Zandersen – Tol, 2009).

The most comprehensive and policy-relevant valuation of forest recreational services for Hungary was provided by Széchy and Szerényi (2023), within the national MAES-HU framework. Combining a local travel-cost case study (Pilis Biosphere Reserve) with a national-

scale benefit-transfer approach, the authors demonstrated consistency between methods. Based on this integrated assessment, they report a central estimate of 101.7 million EUR per year (2020 EUR) for the recreational ecosystem services provided by Hungary's forests, primarily through hiking and walking. The study further highlights that forests composed of native species and exhibiting higher naturalness have the highest recreational potential, while accessibility and proximity to urban populations are decisive drivers of recreational demand. These characteristics are especially relevant for urban forests, where repeated local visits can generate substantial aggregate benefits.

Building on this Hungary-specific evidence, the present study adopts the national central estimate reported by Széchy and Szerényi (2023) as the reference for valuing recreational ecosystem services in Sárvár's urban forests. Integrating recreation alongside climate-mitigation and biodiversity-related services allows for a more comprehensive assessment of the multifunctional contribution of urban forests to the sustainability transition.

1.4 Study objectives

The primary objective of this research is to provide a comprehensive, quantitative assessment of the climate-mitigation potential of urban forests and green spaces, using the city of Sárvár as a case study. The analysis aims to quantify the contribution of urban forest areas to climate change mitigation through multiple carbon-related pathways, including carbon stocks stored in living biomass, annual carbon sequestration, long-term carbon sink in harvested wood products, and additional climate benefits arising from material and energy substitution effects.

Beyond carbon accounting, the study adopts a multifunctional ecosystem-services perspective by explicitly incorporating the valuation of biodiversity-related and recreational ecosystem services provided by urban forests. In this context, the research seeks to assess the monetary value of urban forest-related ecosystem services through benefit-transfer-based economic valuation approaches. Integrating these services generates a more holistic evaluation of urban forests, aligning local assessments with broader sustainability and nature-restoration objectives.

In addition to its quantitative and methodological goals, the study has a strong societal objective focused on awareness raising and science-based communication. By translating biophysical indicators—such as carbon sequestration, biodiversity benefits, and recreational values—into well-communicable economic metrics, the research aims to enhance public understanding of the multifunctional role of urban green infrastructure. This approach supports increased social acceptance of nature-based solutions, encourages citizen engagement, and contributes to informed, climate- and biodiversity-conscious decision-making at the municipal level.

2 MATERIALS AND METHODS

2.1 Study area and spatial data

The analysis focused on urban forest areas located within the administrative boundary of the city of Sárvár, Hungary (*Figure 1*). The city of Sárvár represents a suitable case for analyzing urban forest ecosystem services in a smaller Central European municipality, in contrast to large metropolitan areas such as Budapest. The city hosts the headquarters of the Forest Research Institute of the University of Sopron, providing a local research base.

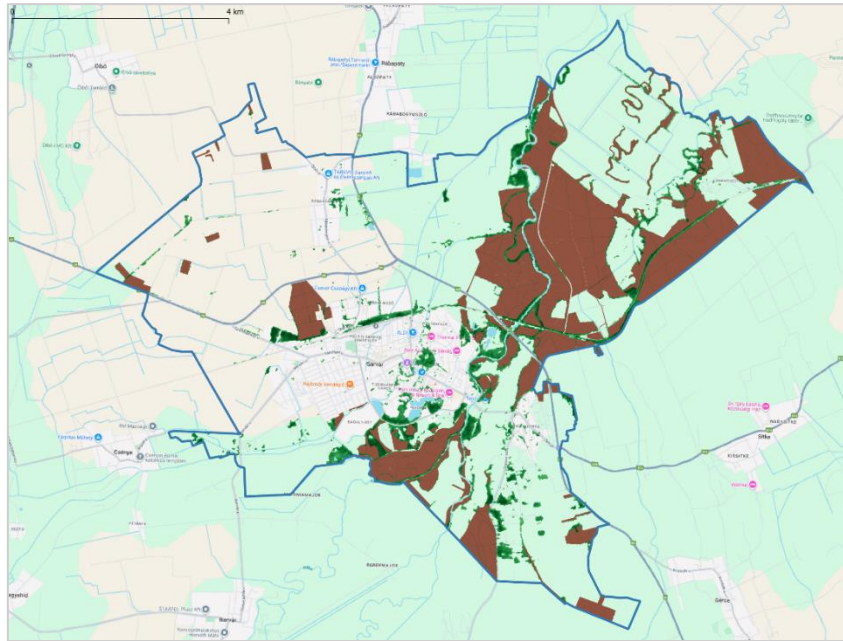


Figure 1. Overview map of the study area. Stands under forest management planning are indicated in brown, while other tree-covered areas are dark green. Source: National Forestry Database (NFD) and TCD (2025).

Forest stands under forest management planning (FMP) were identified based on records from the National Forestry Database (NFD) for the period 2010–2023. In this study, areas under FMP refer to forest stands that are officially classified as forests under Hungarian forestry legislation and are regulated by the national forestry authority. These areas are recorded in the National Forestry Database and are managed according to approved forest management plans. This category, therefore, differs from other urban tree-covered areas (e.g., parks, tree rows, gardens) that are not classified as forests within the forestry administration system. For tree-covered areas not registered as forest, spatial delineation was based on the Copernicus Land Monitoring Service Tree Cover Density dataset (TCD 2025). This dataset classifies tree cover into canopy-density classes at a spatial resolution of 10×10 m. The Copernicus-derived tree-cover map, together with carbon-stock and sequestration coefficients derived from the NFD-based forest inventory data, provided the basis for estimating carbon dynamics in non-forest tree-covered areas.

2.2 Carbon stock and carbon sequestration assessment

Estimation of carbon stocks stored in living biomass and annual carbon sequestration followed the methodological guidance of the IPCC (2006, 2019), complemented by calculation procedures applied in the Hungarian National Greenhouse Gas Inventory (NIR 2023).

Calculations were conducted for 22 tree species groups, allowing species-specific differentiation of biomass accumulation, carbon storage, and sequestration rates. In addition to species-level estimates, average per-hectare carbon stock and sequestration values were derived for urban forest areas.

Harvest data were obtained from the NFD. Assortment structure (fuelwood versus industrial roundwood) was estimated by tree species group following Borovics et al. (2024), using the proportions presented in *Table 1*.

Table 1. Assortment shares by tree-species group* (source: Borovics et al., 2024).

	Oaks	Turkey oak	European beech	Hornbeam	Black locust	Hard broadleaved	Hybrid poplars	Native poplars	Willows	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%

*Oaks: main oak species of Hungary: pedunculate oak (*Q. robur*), sessile oak (*Q. petraea*), pubescent oak (*Q. pubescens*), Hungarian oak (*Q. frainetto*), red oak (*Q. rubra*), and related species. Hard broadleaved species: a diverse group of minor hardwood species including walnuts (*Juglans* spp.), wild cherry and related *Prunus* species, wild apple and pear (*Malus*, *Pyrus*), mulberry (*Morus alba*), rowans and service trees (*Sorbus* spp.), sweet chestnut (*Castanea sativa*), plane trees (*Platanus* spp.), hackberries (*Celtis* spp.), Turkish hazel (*Corylus colurna*), and other minor hardwood species. Native poplars: indigenous poplar species: white poplar (*Populus alba*), grey poplar (*Populus × canescens*), and black poplar (*Populus nigra*). Willows: native willow species: white willow (*Salix alba*), crack willow (*Salix fragilis*), goat willow (*Salix caprea*), and regionally selected willow clones. Soft broadleaved species: birches (*Betula* spp.), horse chestnut (*Aesculus hippocastanum*), tree of heaven (*Ailanthus altissima*), Indian bean tree (*Catalpa bignonioides*), and other minor soft species. Conifers: primarily Scots pine (*Pinus sylvestris*) and black pine (*Pinus nigra*), Norway spruce (*Picea abies*), and other conifer species such as Douglas-fir (*Pseudotsuga menziesii*), firs (*Abies* spp.), cedars (*Cedrus* spp.), junipers (*Juniperus* spp.), cypresses, yew (*Taxus baccata*), and arborvitae (*Thuja* spp.).

2.3 Harvested wood products and substitution effects

Long-term carbon storage in harvested wood products, as well as material and energy substitution effects, were quantified following the methodological framework described by Király et al. (2024). An energy-substitution factor of 0.67 tC/tC was applied, while material substitution was calculated using a factor of 1.2 tC/tC, consistent with literature-based averages (Knauf et al., 2015, 2016; Härtl et al., 2017; Leskinen et al., 2018; Schweinle et al., 2018) for wood-based product substitution effects.

2.4 Monetary valuation of carbon-related ecosystem services

The monetary value of carbon sequestration, carbon storage, and substitution-related ecosystem services was quantified following the valuation framework proposed by Borovics et al. (2025) as follows.

$$V_{\text{seq}} = Q_{\text{seq}} \cdot P_{\text{VCM}} \quad (1)$$

$$V_{\text{stor}} = Q_{\text{stor}} \cdot P_{\text{VCM}} \quad (2)$$

$$V_{\text{sub}} = Q_{\text{sub}} \cdot P_{\text{ETS}} \quad (3)$$

Where:

- V_{seq} : value of annual net carbon sequestration services;
- V_{stor} : value of carbon storage services;
- V_{sub} : value of avoided fossil CO₂ emissions through substitution;
- Q_{seq} : annual net carbon sequestration;
- Q_{stor} : carbon storage;
- Q_{sub} : avoided fossil CO₂ emissions through substitution;
- P_{VCM} : carbon price applied to biological sequestration and storage consistent with the voluntary carbon market prices;
- P_{ETS} : ETS carbon price applied to substitution effects.

For carbon sequestration and storage services, a carbon price of 50 EUR per tCO₂ was applied, reflecting prevailing price levels in voluntary carbon markets (VCMs). In contrast, substitution effects were valued using a price of 100 EUR per tCO₂, corresponding to the average allowance price observed in the EU Emissions Trading System (Borovics – Király, 2024).

This valuation approach does not represent a WTP-based estimate of social preferences. Instead, it constitutes a market-price-based proxy valuation, grounded in observed policy-relevant carbon prices applied within existing carbon-market and regulatory contexts. The applied prices reflect revealed values embedded in climate-policy instruments, namely voluntary carbon markets for biological carbon services and compliance markets for avoided fossil emissions. Accordingly, the resulting monetary values should be interpreted as policy-consistent, market-based climate-mitigation values expressing the contribution of urban forest ecosystem services in terms directly comparable to carbon-market benchmarks and mitigation costs.

2.5 Biodiversity-related ecosystem service valuation: benefit transfer approach

Biodiversity-related ecosystem services of Sárvár's urban forests were valued using a benefit transfer approach. The objective was to derive a WTP-based annual value per hectare and its capitalized natural-capital equivalent, suitable for integration into urban ecosystem-service accounting and municipal decision-support frameworks. Due to the absence of local stated-preference studies at the municipal scale, a unit value transfer methodology was applied, combining inflation adjustment and income scaling to adapt an existing peer-reviewed valuation to the Hungarian context.

The base valuation was derived from Meyerhoff et al. (2012), who estimated societal WTP for biodiversity-related forest ecosystem services in Germany using a nationwide contingent valuation survey. The study reports an aggregate annual WTP of EUR 2.22 billion (2012 prices) for approximately 11 million hectares of forest.

The per-hectare unit value was calculated as:

$$V_{DE,2012} = \frac{WTP_{DE,2012}}{A_{DE}} \quad (4)$$

Where:

$V_{DE,2012}$:	is the German Biodiversity-related ecosystem service value per hectare per year;
$WTP_{DE,2012}$:	is the German willingness to pay for the total forested area;
A_{DE} :	is the German forest area.

To ensure temporal comparability, the 2012 German unit value was adjusted to the target price level using the Harmonized Index of Consumer Prices (HICP) for Germany:

$$V_{DE,t} = V_{DE,2012} \times \frac{HICP_{DE,t}}{HICP_{DE,2012}} \quad (5)$$

HICP data were obtained from the Federal Reserve Bank of St. Louis (FRED 2026).

Income differences between Germany and Hungary were accounted for using an income elasticity of WTP:

$$\varepsilon = 0.6 \quad (6)$$

consistent with meta-analytical evidence reported by Drupp et al. (2025). Income was represented by real GDP per capita from Eurostat (2026). The income-adjusted Hungarian unit value was calculated as:

$$V_{HU,t} = V_{DE,t} \times \left(\frac{GDP_{HU}}{GDP_{DE}} \right)^{\varepsilon} \quad (7)$$

The aggregate annual biodiversity-related ecosystem service value was calculated by scaling the income- and price-adjusted unit value to the total extent of urban forests of Sárvár. The aggregate annual biodiversity-related ecosystem service value was calculated as:

$$V_{Sárvár,t} = V_{HU,t} \times A_{Sárvár} \quad (8)$$

Where:

$V_{Sárvár,t}$ is the total annual biodiversity-related ecosystem service value;
 $V_{HU,t}$ is the adjusted WTP unit value per hectare;
 $A_{Sárvár}$ denotes the total urban forest area of the city of Sárvár.

2.6 Recreational ecosystem service valuation

Recreational ecosystem services were estimated using a national-level benefit transfer from Széchy and Szerényi (2023), who report a central estimate of EUR 101.7 million per year (2020 EUR) for recreational services (hiking and walking) provided by Hungarian forests. The national value was converted into a per-hectare unit value using a reference forest area of 2,000,000 ha and subsequently scaled to the urban forest area of Sárvár. Values were inflated from 2020 to 2024 using Hungarian HICP data from the Hungarian Central Statistical Office (2026) and converted to Hungarian forints using the 2024 annual average EUR/HUF exchange rate.

2.7 Capitalization of ecosystem service flows

To express annual ecosystem service flows as long-term natural-capital values, benefits were capitalized using a perpetuity assumption:

$$PV = \frac{V_{Sárvár,t}}{r} \quad (9)$$

Where:

PV : is the present value;
 $V_{Sárvár,t}$: is the total annual ecosystem service value;
 r : is the social discount rate of 2%.

A social discount rate of 2% was applied, reflecting the long-term public-benefit perspective typically adopted in municipal and public-sector investment appraisal.

3 RESULTS AND DISCUSSION

The total area of urban forest stands under forest management within the administrative boundary of Sárvár amounted to 1,125 hectares. The total area of urban tree-covered areas not

under forest management was 470 hectares. Areas under forest management were characterized by higher canopy closure than tree-covered areas not under forest management (*Figure 2*).

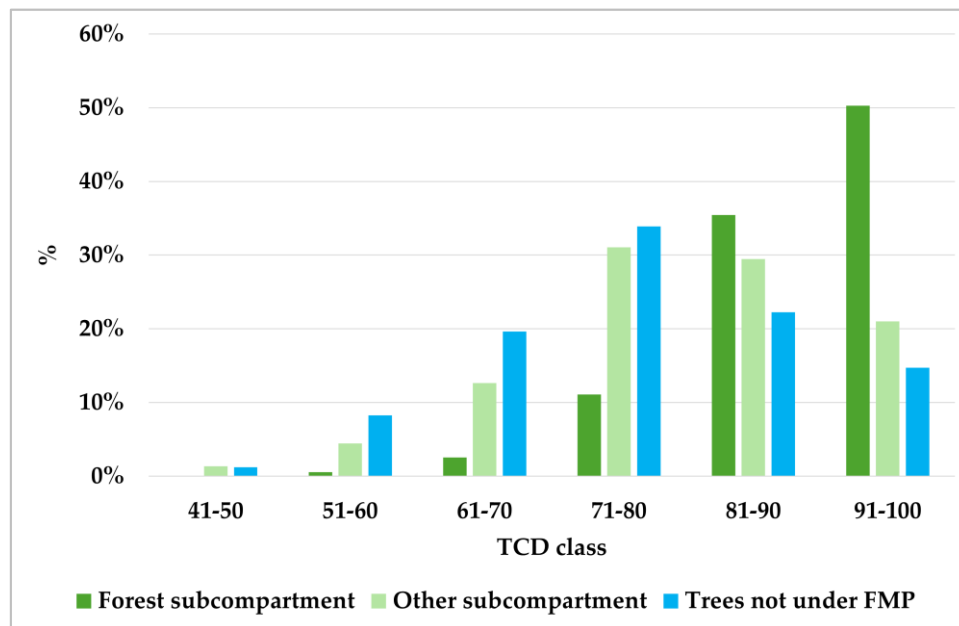


Figure 2. Distribution of urban forest areas under forest management and other tree-covered areas by canopy-closure class according to TCD (2025).

3.1 Climate mitigation-related ecosystem services

Our results indicate that urban forest stands under forest management store more than 80,000 t of carbon in above- and below-ground biomass, constituting a substantial natural carbon reservoir (*Figure 3*). The highest carbon stocks were observed in stands dominated by pedunculate oak (*Quercus robur*). Tree-covered areas not subject to forest management were estimated to store over 20,000 t of carbon in biomass; however, for these areas, tree species composition is not available. Across the study area, the average carbon stock exceeded 100 t C ha⁻¹ in 2023.

The net carbon balance of urban forest areas subject to forest management planning was negative over the study period, indicating that these forests functioned as net carbon sinks. Beyond carbon sequestration in living biomass, timber harvesting also contributed to climate-mitigation outcomes, as a portion of the harvested carbon is retained in harvested wood products. In addition, material and energy substitution effects associated with wood products and fuelwood generated further avoided emissions by replacing fossil energy carriers and carbon-intensive materials (*Figure 4*).

The average annual carbon sequestration occurring in the biomass of urban forest stands under forest management during the study period was approximately –4,950 tons of CO₂ equivalents, offsetting 4.6 % of the city's total greenhouse-gas emissions based on the emissions inventory reported by the Municipality of Sárvár (2020). The combined carbon-sequestration and emission-offsetting effect of urban forests averaged –10,116 tons of CO₂ equivalents over the study period, corresponding to 9.3 % of the city's total greenhouse-gas emissions. This offset volume is equivalent to the average annual emissions of 1,792 Hungarian households (Central Statistical Office 2025a,b) or 4,334 passenger cars (Central Statistical Office 2025c). Annual carbon sequestration per hectare in the biomass of areas under forest management ranged between –3.5 and –7.6 tCO₂ ha⁻¹ yr⁻¹ during the study period. The total average per-hectare carbon balance ranged between –8.7 and –12.8 tCO₂ ha⁻¹ yr⁻¹.

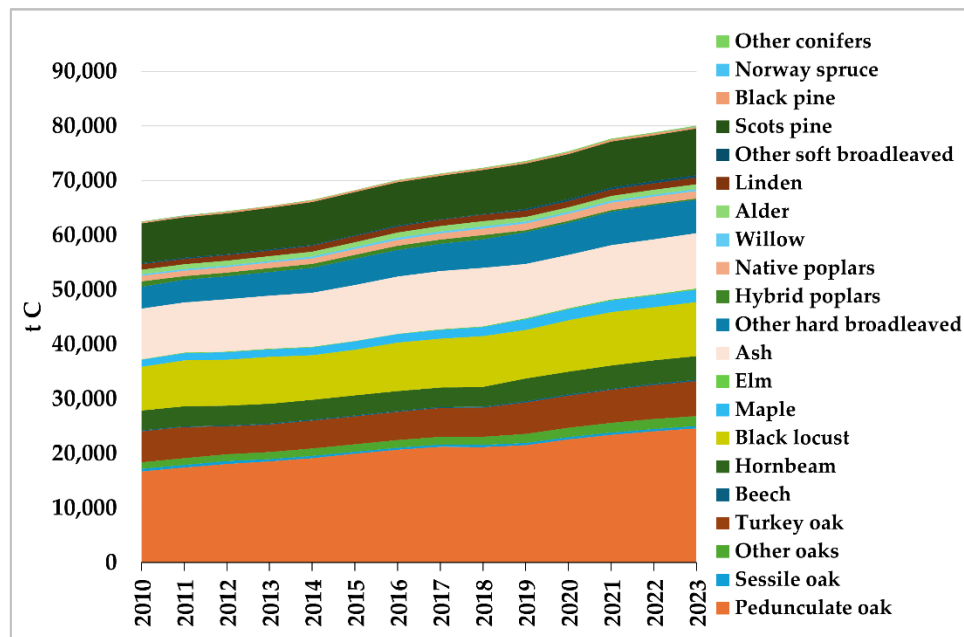


Figure 3. Carbon stored in the biomass of urban forest stands under forest management planning during the study period, disaggregated by tree-species group. Calculated based on data from the National Forestry Database (NFD).

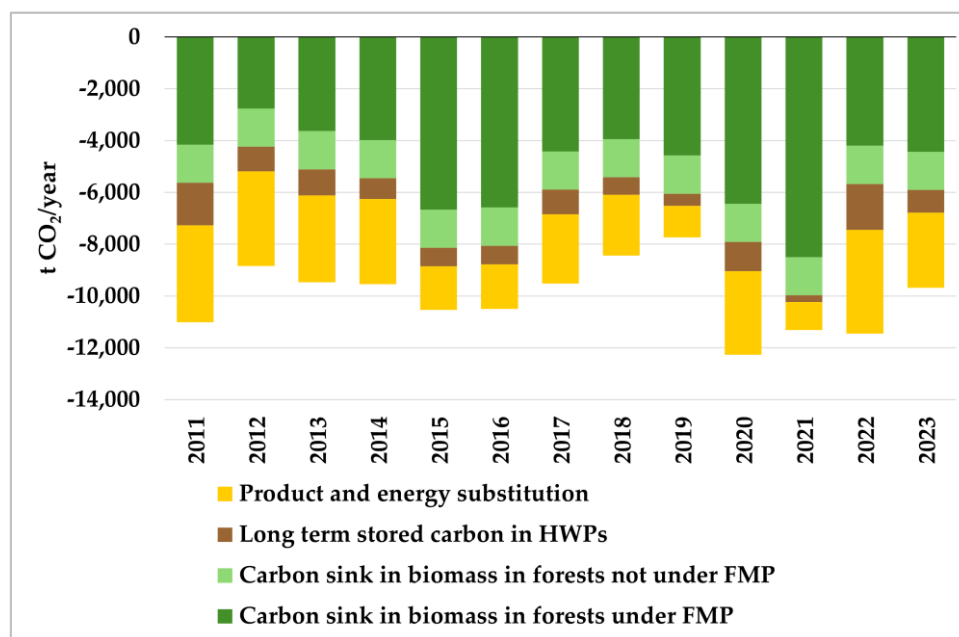


Figure 4. Net annual carbon sequestration in the biomass of urban forest areas under forest management planning (FMP) and tree-covered areas not under forest management planning, together with long-term carbon storage in harvested wood products and product- and energy-substitution effects, expressed in CO₂ equivalents. Negative values indicate carbon sequestration. Calculated based on data from the National Forestry Database (NFD).

Table 2 presents the financial valuation of climate-mitigation ecosystem services provided by urban forests and tree-covered areas in Sárvár. The results indicate that approximately 366,667 tons of CO₂ equivalents are stored in the biomass of Sárvár's urban forests and trees, representing a financial value exceeding EUR 18.8 million (HUF 7.3 billion). Annual carbon sequestration amounts to 6,423 tons of CO₂, corresponding to an annual climate-mitigation value of EUR 0.33 million (HUF 128.5 million). An additional 932 tons of CO₂ per year are

stored in newly harvested wood products originating from areas under forest management (EUR 0.05 million, HUF 18.6 million), while material and energy substitution effects associated with harvested wood result in avoided CO₂ emissions of approximately 2,761 t per year, corresponding to an economic value of EUR 0.28 million (HUF 110.4 million). Through carbon storage, continuous carbon sequestration, and long-term utilization of wood products, urban forests make a measurable financial contribution to the city's climate-neutrality objectives.

Table 2. Financial value of climate-mitigation ecosystem services provided by urban forests and tree-covered areas in Sárvár.

Description	Carbon sequestration / storage volume	Unit	Average carbon sequestration / storage volume per area	Unit	Financial value (EUR)	Financial value (million HUF)	Average financial value per area (EUR/ha)	Average financial value per area (HUF/ha)
Carbon stored in the biomass of forests and trees in Sárvár in 2023.	366,667	tons CO ₂	326	tons CO ₂ /ha	18,803,419	7,333.33	11,789	4,597,701
Carbon sequestration in the biomass of forests and trees in Sárvár, average for 2011–2023.	6,423	tons CO ₂ /yr	6	tons CO ₂ /yr/ha	329,385	128.46	207	80,539
Carbon stored in new harvested wood products originating from Sárvár's forests, average for 2011–2023.	932	tons CO ₂ /yr	1	tons CO ₂ /yr/ha	47,795	18.64	30	11,687
Avoided emissions through material and energy substitution, average for 2011–2023.	2,761	tons CO ₂ /yr	2	tons CO ₂ /yr/ha	283,179	110.44	178	69,241

3.2 Biodiversity-related ecosystem services

Using a benefit-transfer approach, unit ecosystem service values for biodiversity-related forest services were derived from the German WTP estimates reported by Meyerhoff et al. (2012). After inflation adjustment to 2024 price levels and income-based scaling to Hungarian conditions ($\epsilon = 0.6$), the resulting unit value amounts to 149 EUR ha⁻¹ yr⁻¹.

Applying this Hungary-adjusted unit value to the total urban forest area of Sárvár (1,125 ha forest and 470 ha tree-covered area) yields an aggregate annual biodiversity-related ecosystem service value of 237,871 EUR, corresponding to approximately 92.77 million HUF (Table 3). This value represents the annual societal WTP for biodiversity-related ecosystem services provided by Sárvár's urban forests.

To express the long-term asset value of this ecosystem service flow, annual benefits were capitalized assuming a perpetual provision of services and applying a social discount rate of 2%. Under this assumption, the natural capital value of biodiversity-related ecosystem services provided by Sárvár's urban forests amounts to approximately 11.89 million EUR (4.64 billion HUF).

The results indicate that even under conservative, income-adjusted WTP assumptions, biodiversity-related ecosystem services constitute a significant and economically meaningful asset for the municipality.

Table 3. Monetary valuation of biodiversity-related ecosystem services provided by the urban forests of Sárvár.

Category	EUR	HUF	EUR/ha	HUF/ha
Total annual biodiversity-related ecosystem service value	237,871	92,769,496	149	58,163
Capitalized biodiversity-related ecosystem service value (r = 2%)	11,893,454	4,638,447,147	7,457	2,908,117

3.3 Recreational ecosystem services

Recreational ecosystem service values were estimated using a benefit-transfer approach based on the national central estimate for Hungary reported by Széchy and Szerényi (2023). The original 2020 EUR value was updated to the 2024 price, using an inflation factor of 1.4676. Accordingly, the national aggregate recreational ecosystem service value increased to approximately 149.25 million EUR per year in real 2024 prices.

Normalizing this national value by the total forest area of Hungary (2 million ha) yields a recreational ecosystem service value of 74.63 EUR ha⁻¹ yr⁻¹. Applying this unit value to the total area of urban forests in Sárvár (1,125 ha forest and 470 ha tree-covered area) resulted in an estimated annual recreational ecosystem service value of 119,027 EUR, corresponding to approximately 46.42 million HUF.

To express the long-term asset value of recreational ecosystem services, annual benefits were capitalized assuming a perpetual provision of services and applying a 2% social discount rate. Under this assumption, the capitalized recreational ecosystem service value of Sárvár's urban forests amounted to approximately 5.95 million EUR, equivalent to 2.32 billion HUF (Table 4).

Table 4. Monetary valuation of recreational ecosystem services provided by the urban forests of Sárvár.

Category	EUR	HUF	EUR/ha	HUF/ha
Annual recreation value	119,027	46,420,412	75	29,104
Capitalized recreation value (r = 2%)	5,951,356	2,321,028,901	3,731	1,455,191

Overall, the results indicate that recreational ecosystem services alone represent a substantial non-market benefit generated by Sárvár's urban forests.

3.4 Integrated valuation of urban forest ecosystem services

Taken together, the valuation results demonstrate that Sárvár's urban forests deliver a diverse portfolio of ecosystem services whose economic significance becomes particularly evident when annual service flows and long-term capitalized values are assessed jointly (Figures 5 and 6).

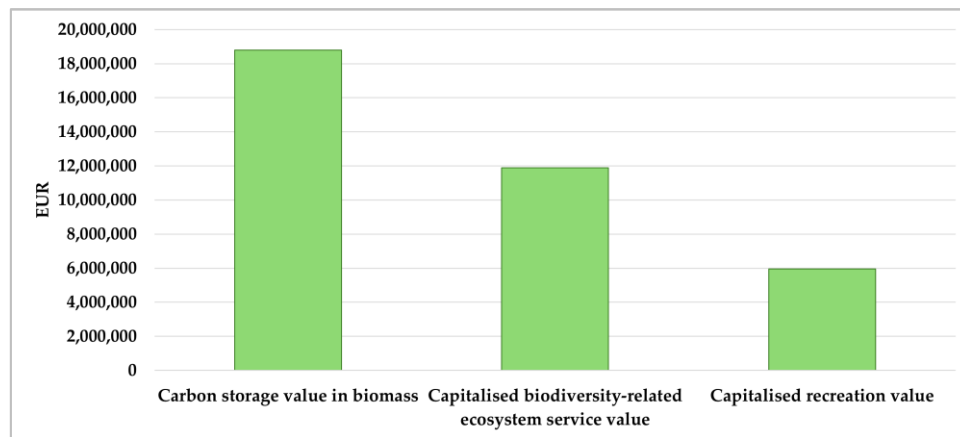


Figure 5. Comparison of capitalized ecosystem-service values provided by the urban forests of Sárvár, based on own calculations. Annual flows of recreational and biodiversity-related ecosystem services were capitalized using a perpetuity approach and a social discount rate, whereas carbon storage is not capitalized. Instead, the value of carbon storage is estimated as a stock value, calculated by multiplying the total amount of carbon stored in urban forest biomass by the prevailing voluntary carbon market (VCM) carbon price.

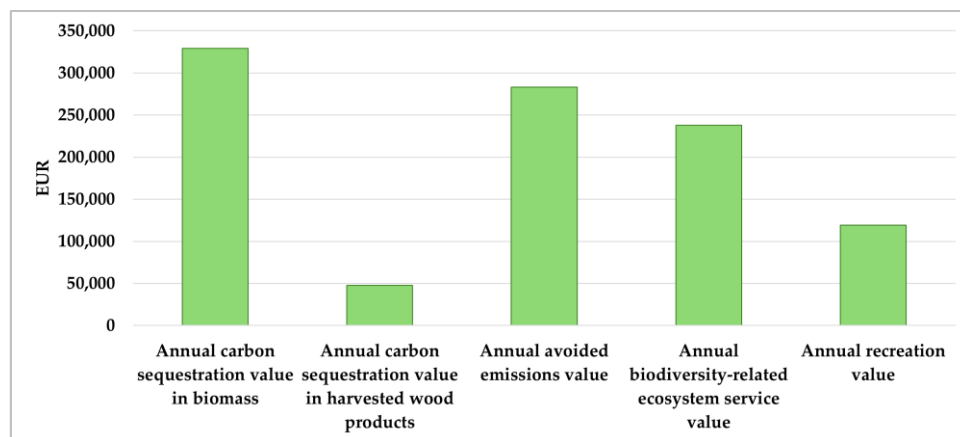


Figure 6. Annual monetary value of selected ecosystem services provided by the urban forests of Sárvár, based on own calculations.

The comparison of capitalized ecosystem-service values highlights the dominant role of climate-mitigation services in the overall natural capital stock of urban forests (Figure 5). The value of carbon stored in forest biomass clearly exceeds all other capitalized components, reaching approximately EUR 18.8 million, reflecting the long-term accumulation of carbon in standing biomass. This stock value alone is higher than the capitalized value of biodiversity-related ecosystem services (EUR 11.89 million) and more than three times the capitalized recreational ecosystem-service value (EUR 5.95 million). This pattern underscores the importance of urban forests as long-lived carbon reservoirs and highlights their relevance for long-term climate-neutrality strategies at the municipal level.

At the same time, the capitalized biodiversity and recreation values represent substantial non-market natural capital assets. Although smaller in magnitude than carbon storage, these values demonstrate that urban forests provide durable benefits related to habitat provision, species conservation, landscape quality, and human well-being. The coexistence of high carbon-storage value with significant biodiversity and recreational capital values suggests that climate mitigation in Sárvár operates in synergy with other ecosystem services.

A complementary perspective emerges when focusing on annual ecosystem-service values (Figure 6). Here, the relative importance of different services becomes more balanced. Annual climate-mitigation benefits are distributed across several components: carbon sequestration in biomass represents the largest single annual contribution, followed closely by the value of avoided emissions through material and energy substitution, while carbon sequestration in harvested wood products adds a smaller but still measurable contribution. Together, these climate-related annual flows illustrate that the mitigation effect of urban forests is not limited to biomass growth but is reinforced by sustainable wood use and substitution effects.

Beyond climate mitigation, biodiversity-related ecosystem services generate an annual value comparable in magnitude to avoided emissions, emphasizing that conservation and habitat functions provide benefits of a similar economic order to certain climate-related flows. Recreational ecosystem services, while smaller in annual monetary terms, still contribute tens of thousands of euros per year and represent direct, locally experienced benefits for residents. These services are particularly relevant from a social perspective, as they are closely linked to daily use, physical and mental health, and quality of life.

Viewed together, Figures 5 and 6 illustrate a key insight: climate-mitigation services dominate the long-term capital value of urban forests in Sárvár, whereas annual ecosystem-service flows are more evenly distributed across climate, biodiversity, and recreation. This distinction is important for policy interpretation. Carbon storage reflects the accumulated outcome of past forest development and management, while annual service flows are more sensitive to current management decisions and land-use pressures.

Overall, the integrated results confirm that Sárvár's urban forests function as multifunctional natural capital assets. They simultaneously support municipal climate objectives through carbon storage and sequestration, contribute to biodiversity conservation and ecological resilience, and provide recreational benefits with direct social relevance. The coexistence of substantial capitalized values and significant annual flows highlights the strategic importance of urban forests in local sustainability planning, demonstrating that investments in their protection and management yield returns across multiple ecosystem-service dimensions.

4 CONCLUSIONS

This study demonstrates that urban forests of Sárvár constitute a multifunctional nature-based solution with clearly measurable climate-mitigation and non-market ecosystem-service benefits at a scale relevant for municipal policy. Carbon-related services indicate a substantial natural-capital stock and a meaningful annual mitigation contribution, reaching approximately 9.3% of total municipal greenhouse-gas emissions when biomass dynamics, harvested wood products, and substitution effects are considered jointly. In monetary terms, the dominant component of the capital stock is carbon storage in biomass (EUR 18.8 million), complemented by capitalized values for biodiversity-related ecosystem services (EUR 11.89 million) and recreational ecosystem services (EUR 5.95 million).

Three overarching conclusions emerge. First, urban forests should be regarded as strategic municipal infrastructure, delivering climate regulation, biodiversity conservation, and social benefits simultaneously, rather than as residual or purely amenity-oriented land uses. Second, the results underscore the importance of a portfolio-based perspective on ecosystem services: the coexistence of climate, biodiversity, and recreational values strengthens the economic and policy rationale for urban forest protection and investment across multiple governance domains. Third, tree-covered areas not under forest management, while characterized by lower carbon

stocks than managed stands, form an integral part of the urban green-infrastructure system and should be systematically incorporated into planning, monitoring, and reporting frameworks.

4.1 Policy implications and recommendations

Based on the findings, the following policy-relevant recommendations can be formulated:

1. **Formal recognition of urban forests in local climate and sustainability strategies:** Urban forests and tree-covered areas should be explicitly embedded in municipal climate, adaptation, and sustainability strategies, supported by a limited set of stable and transparent indicators.
2. **Adaptation-oriented species and stand strategies:** Urban forest planning and renewal should prioritize climate-resilient species and stand structures that maintain long-term carbon-sink capacity while supporting biodiversity and ecosystem stability.
3. **Systematic integration of non-forest tree-covered areas:** Tree-covered areas outside formal forest management should be comprehensively inventoried and integrated into urban green-infrastructure governance to safeguard their ecosystem-service contributions.
4. **Science-based communication and public engagement:** Translating ecosystem-service outcomes into well-communicable indicators can enhance public awareness, strengthen social acceptance, and support citizen participation in urban green-infrastructure stewardship.
5. **Regular updating of ecosystem-service valuations:** Periodic revision of ecosystem-service valuations is recommended to ensure that information remains relevant for urban development, climate planning, and budgeting processes, reinforcing the treatment of green infrastructure as a long-term investment.
6. **Pilot implementation of local Natural Capital Accounting:** Applying a local-level natural capital accounting framework aligned with SEEA-EA principles would improve transparency and policy usability, enabling ecosystem-service values to be systematically incorporated into municipal decision-making.

4.2 Limitations and future research

This study focuses on a selected set of ecosystem services—climate-mitigation, biodiversity-related, and recreational services—chosen for their policy relevance, data availability, and compatibility with natural-capital accounting frameworks at the municipal scale. Consequently, the results do not capture the full range of ecosystem services provided by Sárvár's urban forests and tree-covered areas.

Some limitations that merit consideration. First, carbon-related estimates for tree-covered areas not subject to forest management planning rely on remotely sensed canopy data and forest-based coefficients, as detailed species composition and stand structure information are not available for these areas. Future research would benefit from improved urban tree inventories or high-resolution field surveys to refine carbon-stock and sequestration estimates outside the formal forest estate.

Second, biodiversity-related and recreational ecosystem services were valued using benefit-transfer approaches based on national or international primary studies. While this approach is consistent with established practice and suitable for policy screening, locally tailored stated-preference studies at the municipal or regional scale would allow more precise estimation of WTP values and reduce uncertainty associated with income adjustment and contextual transferability.

Third, some important urban ecosystem services were beyond the scope of the present analysis. Future research should extend the valuation framework to include microclimate

regulation (including urban heat-island mitigation), air quality improvement, stormwater regulation, and public health-related benefits. These services are particularly relevant in urban contexts and may increase the estimated natural-capital value of urban forests, especially when health-related outcomes are considered.

Expanding the assessment to incorporate these additional service categories, combined with improved local biophysical data and primary valuation evidence, would support the development of a more comprehensive and robust urban natural-capital account. Such advances would further enhance the usefulness of ecosystem-service valuation for evidence-based urban planning, climate adaptation strategies, and long-term sustainability governance at the municipal level.

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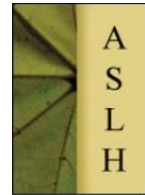
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Baseline Setting and Carbon Credit Quantification in Improved Forest Management: A Demonstrative Case Study



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ABSTRACT

Improved Forest Management (IFM) is expected to become a key component of the EU's Carbon Removal Certification Framework (CRCF), yet baseline setting, additionality assessment, and carbon-removal quantification remain methodologically challenging. This study presents a demonstrative IFM case using a 4.7-hectare Scots pine–hornbeam stand in Western Hungary, combining extended rotation with climate-adaptive regeneration. A hypothetical baseline was derived from National Forestry Database data, while carbon sequestration was modelled using the Forest Industry Carbon Model with a 15% uncertainty correction. Project-related emissions were quantified under the IPCC guidelines. Over 2024–2055, total biomass carbon increased by 99 tC, with regeneration contributing an additional 44 tC. After deducting baseline sequestration and minor implementation emissions (<1% of total removals), the project generates 201 eligible carbon credits, equivalent to 10,074 EUR (7,255 EUR at present value). The case study illustrates how CRCF-aligned IFM assessments can be conducted in practice, stressing the importance of baseline definitions, the strong net-positive carbon balance of IFM measures, and the potential economic viability of such projects under forthcoming EU carbon removal standards.

TANULMÁNY INFÓ

Kulcsszavak:

Carbon Farming
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karbonkredit
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KIVONAT

Baseline-meghatározás és karbonkreditszámítás klímabarát erdőgazdálkodási projektekben: egy szemléltető esettanulmány. A klímabarát erdőgazdálkodás (Improved Forest Management, IFM) várhatóan az EU Karbantartási Keretrendszerének (CRCF) egyik kulcselemévé válik, ugyanakkor a baseline meghatározása, az addicionalitás vizsgálata és a széneltávolítás számszerűsítése továbbra is módszertani kihívást jelent. Tanulmányunk egy IFM esettanulmányt mutat be egy 4,7 hektáros gyertyán-elegyes erdőfenyő állomány példáján Nyugat-Magyarországon, amely a vágásforduló meghosszabbítását klímavédelmi szerkezetátalakítással kombinálja. A hipotetikus baseline-t az Országos Erdőállomány Adattár adatai alapján határoztuk meg, míg a szénmegkötést a Forest Industry Carbon Model segítségével modelleztük, 15%-os bizonytalansági korrekció alkalmazásával. A projekthez kapcsolódó emissziókat az IPCC iránymutatások szerint számszerűsítettük. A 2024–2055 közötti időszakban a biomasszában tárolt szén 99 tC-vel nőtt, míg a klímavédelmi szerkezetátalakítás további 44 tC többletet eredményezett. A baseline és a kivitelezési munkálatokból származó emissziók (a teljes szénmegkötés <1%-a) levonását követően a projektben 201 elszámolható karbonkredit keletkezik, amelynek értéke 10 074 euró (jelenértéke 7 255 euró). Az esettanulmány rávilágít a baseline-meghatározás kulcsszerepére, az IFM projektek nettó pozitív szénmérlegére és gazdasági potenciáljára.

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1 INTRODUCTION

Forests play a vital role in global and European climate strategies, serving simultaneously as carbon sinks, biodiversity reservoirs, and essential ecosystem service providers. Sustainable forest management has gained strategic importance in the context of accelerating climate change, not only for maintaining ecological integrity but also for enhancing the sector's contribution to climate mitigation (Verkerk et al., 2022; IPCC 2023). Integrating nature-based solutions into climate policy has become increasingly prominent as the European Union advances toward its 2050 climate neutrality target (Korosuo et al., 2023). One of the most significant regulatory developments in this area is the forthcoming EU Carbon Removal Certification Framework (CRCF, EU/2024/3012), which establishes harmonized rules for quantifying, verifying, and certifying carbon removals across the Union (Borovics et al., 2025). Within this emerging framework, Improved Forest Management (IFM) represents a key category of Carbon Farming activities that can generate certifiable carbon dioxide removal credits. Unlike afforestation projects, IFM interventions happen in existing forests, utilizing their already substantial biomass stocks and ecological functions. IFM encompasses a broad range of silvicultural practices—such as extended rotations, climate-adaptive stand conversion, reduced-impact harvesting, assisted natural regeneration, and deadwood retention—that may increase carbon sequestration or reduce emissions relative to a defined baseline scenario. Despite their large theoretical potential, designing, quantifying, and verifying IFM projects remains methodologically complex, with uncertainties surrounding baseline determination, additionality, long-term monitoring, and economic feasibility (McDonald et al., 2021).

The CRCF aims to provide clarity by establishing standardized, science-based procedures for estimating carbon sequestration, setting regional and forest-type-specific baselines, correcting for modelling uncertainty, and accounting for project-related emissions. However, the detailed methodological guidance for IFM projects has not yet been finalized, creating a need for demonstrative analyses that explore how such projects could be assessed once the regulatory framework is in place. Case studies can play an essential role in illustrating the practical application of the CRCF principles, identifying key parameters, and highlighting the challenges and opportunities associated with IFM-based carbon credit generation.

1.1. Rules of the CRCF regulation and types of improved forest management projects

The CRCF Regulation classifies IFM projects as forestry Carbon Farming projects. At the start of an IFM project, it is necessary to estimate the project's total future carbon sequestration, which is a component of the project initiation documentation and the Certificate of Compliance.

Regular monitoring activities (at least every five years) are also required when implementing forestry projects. Whether the planned carbon sequestration has actually been achieved on site is assessed via dendrometric measurements and soil carbon measurements. Field measurements can be complemented by remote sensing-based assessments.

Carbon-dioxide units (also referred to as credits) are issued ex post; therefore, only carbon sequestration that has already been realized can generate credits. One ton of sequestered CO₂ corresponds to one carbon credit unit. Typically, the first on-site audit occurs in the fifth year of the project, after which credit issuance can occur (*Figure 1*). However, the Compliance Certificate issued at the project start already allows the forest manager to conclude a pre-agreement with a financier who will later become the owner of the generated credits, making it possible for the forest manager to receive income even before the first monitoring ends. The expected duration of IFM projects is 30 years, with an additional 10-year monitoring period. Naturally, the option to extend the project exists, which also implies extending the monitoring period.

Year	Events	Forest Manager	Certifier / Auditor	Project Developer	Certification System Owner
0	Project start	Applies for a certificate	Issues a certificate validating the eligibility of the project	Signs pre-agreement with FM Pays partial fee in advance to FM	Opens carbon account for CF project
5	First monitoring	Carries out carbon farming activity	Issues a certificate verifying the additional carbon sequestered in the first five years	Sells carbon credit on voluntary carbon market Rolling payment to FM	Registers carbon credits
:	:	:	:	:	:
30	Project end	Further maintains carbon pool	Issues a certificate verifying additional carbon sequestered over the last five years	Clearing fee balance with FM*	Registers carbon credits
40	Final monitoring		Issues a certificate verifying the storage of carbon sequestered during the project period		

*Payments methods and schedule are unclear; one option is presented here.

Figure 1. Flowchart of the CRCF certification process

The realized carbon sequestration for IFM projects must be compared against a baseline value under the CRCF regulation. The European Commission determines the baseline value in a delegated act, in the form of a detailed methodological guidance document. Currently, IFM methodological guidance is not yet available; therefore, the baseline values are also unknown. Forest type and region determine the baseline by integrating remote sensing data, field measurements, and forest stand modelling. The present study provides an example of how such a baseline could be calculated; however, the example is theoretical and hypothetical. The actual calculation method the European Commission applies will likely differ despite similarities in underlying logic and concept.

Which IFM projects will be considered eligible is unknown. Eligibility depends on unpredictable legislative decisions. *Table 1* summarizes the most important IFM project types currently known on the voluntary carbon market. It is assumed that some will be included among the IFM project types recognized under the CRCF in the future.

1.2 Study aims

This study demonstrates how an IFM project is assessable under the emerging principles of the EU CRCF. Using a real forest stand as a case example, the study illustrates the steps required for baseline determination, quantifies the net carbon sequestration achieved through extended rotation and climate-adaptive stand conversion, estimates the resulting volume of potential carbon credits, and provides an initial indication of the project’s expected carbon-credit revenues.

2 MATERIALS AND METHODS

2.1 Description of the project site

The proposed project is an extended rotation intervention complemented by climate-adaptive stand conversion. The project site is the Káld 75/C forest subcompartment, which is a part of

the Farkaserdő forest (Figures 2 and 3). The 4.7-hectare subcompartment (Figure 4) is not part of the Natura 2000 network and is designated primarily for timber production, managed under a clear-cut silvicultural system. Its naturalness is classified as a transitional forest, with no management restrictions in place.

The upper canopy layer consists almost exclusively of Scots pine (*Pinus sylvestris*), with hornbeam (*Carpinus betulus*) forming the lower canopy. Apart from the stand edges, shrub and herb layers are largely absent. The Scots pine cohort is 99 years old, while the hornbeam cohort is 69 years old. The stand has already exceeded rotation age by nine years, and its health shows a declining trend. Field inspections confirmed that the amount of deadwood and drying trees has increased compared to the state described in the most recent forest management plan.

Table 1. Types of Improved Forest Management projects on the current voluntary carbon market, which is not yet regulated by the CRCF

Project type	Description
Extended rotation	Delaying timber harvesting to maintain in-situ carbon storage and allow additional carbon sequestration from the atmosphere. To meet additionality criteria, this project type can only be implemented in harvest-mature stands where no legal barriers to final felling exist.
Climate-friendly harvesting technology	Increasing the environmental performance of harvesting operations (e.g., soil-protecting extraction), thereby reducing carbon losses from soil and biomass.
Omission of thinning / increased stand density	Discontinuing thinning to increase in-situ carbon stocks; may be combined with underplanting or measures supporting natural regeneration to enhance carbon sequestration.
Climate-adaptive stand conversion	Modifying species composition to favor native or climate-resilient species with higher carbon-sequestration potential.
Replacement of fast-growing species with slower-growing, long-lived species	Introducing long-lived native species that produce more durable biomass and improve the stand's naturalness.
Conversion to continuous-cover forestry	Ensuring continuous forest cover in areas where it was not previously required and where no legal obligation exists. Establishing mixed and uneven-aged stand structures to increase forest stability and carbon-sequestration and storage capacity.
Support for natural regeneration	Protecting naturally emerging regeneration, increasing the diversity of existing regeneration, and implementing additional measures that support climate adaptation.
Retention of deadwood	Leaving standing and laying deadwood on site in quantities exceeding legal requirements to enhance in-situ carbon storage and biodiversity.
Avoided salvage logging in damaged forests	Leaving trees on site after storm or fire damage to preserve carbon stocks.



Figure 2. Photo record of the Káld 75/C forest subcompartment



Figure 3. Deadwood and stand decline observed in the Káld 75/C subcompartment



Figure 4. Location of the Káld 75/C forest subcompartment (Source: National Forestry Map <https://erdoterkep.nebih.gov.hu/>)

To determine the current and future climatic conditions of the project site, we used the SiteViewer 3.0 (Illés et al., 2024) application, an essential decision-support tool in the planning process. Based on the climate-type layer for the recent past, the tool shows that the area fell within the hornbeam–oak climate zone during the 1981–2010 period. Under present climatic conditions (Führer et al., 2011), the site is classified as sessile oak–Turkey oak climate. The program recommends the following target stand types for the current period: Scots pine (*Pinus*

sylvestris), Turkey oak (*Quercus cerris*), grey poplar (*Populus × canescens*), and black locust (*Robinia pseudoacacia*). Scots pine dominates the existing stand on the site. The area is projected to remain within the sessile oak–Turkey oak climate zone in the near future (2041–2070), and the recommended target stand types for this period also remain Scots pine, Turkey oak, grey poplar, and black locust. Neither the climate classification nor the recommended target stand types change for the more distant future (2071–2100).

Table 2 summarizes the site conditions and the current and projected climatic characteristics of the project area. The site characteristics were also verified through on-site inspection during the planning process.

Table 2. Site-type characteristics and extent of the examined forest subcompartment.

Site	Area (ha)	Climate 2011–2040	Climate 2041–2070	Hydrology	Genetic soil type	Soil depth	Soil texture
Káld 75/C	4.7	Hornbeam–oak climate	Sessile oak–Turkey oak climate	Not affected by excess water	Rusty forest soil	Deep	Sand

2.2 Description of the Proposed Project

An extended rotation project complemented by climate-adaptive stand conversion is the proposed intervention. The planned project duration is 30 years; therefore, all projections extend to the 2055 target year.

The purpose of the extended rotation is to maintain the stand beyond its typical rotation age, to prolong in-situ carbon storage, and achieve additional carbon sequestration. The resulting carbon sequestration is considered additional because the stand would have been harvested under a Business as Usual (BAU) scenario.

Given the substantial amount of dieback within the stand, we also plan to implement gap-based regeneration on a total area of 0.47 hectares, after removing dead trees. Regeneration will be with drought-tolerant species better adapted to the climatic conditions expected at the site. As such, this intervention also qualifies as climate-adaptive stand conversion. Table 3 presents the species selected for planting. The carbon sequestration achieved through this climate-adaptive structural transformation is also considered additional, since the existing forest management plan does not prescribe such a conversion; therefore, intervention is motivated directly by the incentives of the voluntary carbon market and is implemented specifically in connection with the planned Carbon Farming project.

Table 3. Tree species planned for planting and the corresponding regenerated area.

Tree species	Share of regenerated area (%)	Area (ha)
Turkey oak (<i>Quercus cerris</i>)	40%	0.188 ha
Field maple (<i>Acer campestre</i>)	10%	0.047 ha
Field elm (<i>Ulmus minor</i>)	10%	0.047 ha
Aspen (<i>Populus tremula</i>)	20%	0.094 ha
Silver linden (<i>Tilia tomentosa</i>)	20%	0.094 ha

2.3 Establishing the baseline

Baseline determination in IFM projects is uncertain. According to the CRCF Regulation, the baseline will be established by the European Commission in a standardized manner for each forest type and region, based on the integration of remote-sensing information, field measurements, and forest-stand modelling. The baseline represents the average level of carbon sequestration that can reasonably be expected from a given forest stand under normal management conditions without any additional intervention. The detailed rules for IFM projects—including the baseline values—will be delineated in a methodological guidance document that the Commission publishes as a delegated act. As this guidance has not yet been released, the future baseline values remain unknown.

This article provides a hypothetical example of baseline determination. For this purpose, we use data from the National Forestry Database and consider Scots pine stands aged 101–120 years. We assume that the baseline corresponds to the average annual increment expressed in CO₂ equivalent for stands within this age range. *Table 4* presents the resulting baseline value calculated in this manner.

We applied the age-class average increment from the National Forestry Database as a transparent and empirically grounded proxy for the CRCF-type baseline. Importantly, under the CRCF logic, the baseline is defined in terms of carbon flow (annual net sequestration) rather than standing carbon stock; therefore, an age-class average increment expressed in CO₂ equivalent directly corresponds to the regulatory concept of a flow-based reference level. In constructing this proxy baseline, we performed explicit stratification by tree species (Scots pine) and age class (101–120 years), thereby reflecting both forest-type specificity and structural development stage. This stratified approach mirrors the CRCF principle that baselines should be differentiated by forest type and regional characteristics rather than applied uniformly across heterogeneous stands. The selected age class represents biologically and legally harvestable stands and thus approximates the business-as-usual counterfactual in an even-aged rotation system. Because the National Forestry Database relies on standardized national inventory methods and large sample sizes, the resulting increment value reflects empirically observed management conditions. While the final CRCF methodology may introduce additional stratification variables, the adopted approach provides a conceptually aligned, flow-based, and structurally differentiated approximation of a standardized CRCF baseline.

The resulting baseline value indicates a relatively small carbon sink (expressed with a negative sign, in line with IPCC greenhouse gas accounting conventions where CO₂ removals are reported as negative emissions). This modest annual sequestration rate is consistent with the biological characteristics of older stands in the 101–120-year age class, where growth typically slows compared to earlier developmental stages. Consequently, the baseline reflects a realistic and low yet still positive net carbon uptake under business-as-usual management conditions for mature Scots pine stands.

Table 4. Baseline value for Scots pine stands aged 101–120 years (negative values indicate net CO₂ sequestration in line with IPCC conventions).

Baseline unit	Baseline value
m ³ net annual increment/ha/year	0.74
m ³ net annual increment /year (for 4.7 ha)	3.48
tCO ₂ /ha/year	–0.72
tCO ₂ /year (for 4.7 ha)	–3.4

2.4 Methodology for quantifying emissions associated with harvesting, planting, and tending operations

The operations listed in *Table 5* will be performed during the planned gap-based regeneration activities. In accordance with the methodological requirements of the CRCF Regulation, we calculated the carbon dioxide, nitrous oxide (N₂O), and methane (CH₄) emissions associated with these operations. Fuel consumption related to regeneration activities was estimated following the guidelines of Erdeiné Késmárki-Gally and Rák (2020), using an approach similar to that applied by Benke et al. (2015) and Borovics et al. (2025). Emissions related to timber harvesting were quantified based on the methodology of Polgár et al. (2018). We applied the most recent conversion factors provided by the IPCC for agricultural and forestry machinery (IPCC 2006, 2019) to estimate greenhouse gas emissions from the combustion of diesel and gasoline. Fuel-consumption coefficients and emission factors are subject to parameter uncertainty, reflecting variability in machine type, engine efficiency, operational load, maintenance status, and site conditions. The applied fuel-use values are based on published national averages, and the emission factors follow IPCC default parameters commonly used in national greenhouse gas inventories.

Table 5. Planned harvesting, regeneration, and tending operations during the implementation of the IFM project, and the land-category classification of the project.

Year	Operation	Machine type	Frequency	Fuel consumption (liter)
Land category: I.				
	Removal of Scots pine and hornbeam deadwood in designated gaps	Tractor-pulled forestry trailer with crane	1× (210 m ³)	240.9
Year 1	Manual mowing and hand scything	–	1×	–
	Planting with planting spade	–	1×	–
	Row clearing	Brush cutter	4×	112.8
Year 2	Row clearing	Brush cutter	4×	112.8
	Replanting	Planting bar	1×	55
Year 3	Row clearing	Brush cutter	4×	112.8
	Replanting	Planting bar	1×	55
Year 4	Row clearing	Brush cutter	4×	112.8
Year 5	Row clearing	Brush cutter	4×	112.8
Year 6	Row clearing	Brush cutter	4×	112.8
Year 7	Row clearing	Brush cutter	4×	112.8

2.5 Calculation of carbon sequestration and carbon credit revenues

Carbon sequestration in the forest stand included in the IFM project was quantified using the Forest Industry Carbon Model (Borovics et al., 2024), which allows for the projection of carbon stocks in forest biomass, soil, dead organic matter, harvested wood products, and product-substitution effects. Using the model, we calculated carbon dioxide sequestration in aboveground and belowground biomass. We assumed equilibrium over the project period for soil, deadwood, and litter carbon pools. This conservative assumption is consistent with the provisions of the CRCF Regulation.

The projection was conducted for 2024–2055. The site productivity (yield class) of the selected tree species was determined using the SiteViewer 3.0 application, based on climatic data for the 2041–2070 period. Yield tables were assigned to each tree species according to the

same matching rules as those applied in the National Forestry Database.

The amount of eligible carbon sequestration is the quantity that forms the basis for credit issuance on the voluntary carbon market. According to the CRCF Regulation and the draft methodological guidelines, this quantity is obtained by correcting the modelled forest carbon sequestration with a factor that reflects modelling uncertainty, and then subtracting fossil fuel-based greenhouse gas emissions associated with harvesting, planting, and tending operations, as expressed in Equations (1)–(4):

$$(1) \text{ Eligible carbon sequestration} = (CR_{\text{baseline}} - CR_{\text{total}}) \times (1 - UNC) - GHG_{\text{associated}} > 0$$

$$(2) CR_{\text{baseline}} = -3,4 \frac{tCO_2}{\text{year}}$$

$$(3) CR_{\text{total}} = CR_{\text{biomass}} + CR_{\text{soil}}$$

$$(4) GHG_{\text{associated}} = GHG_{\text{fossil fuel}} + GHG_{\text{fertilizer}}$$

Where:

CR_{baseline} : is the baseline value, i.e., the assumed reference level of carbon sequestration;

CR_{total} : is the total carbon sequestration of the IFM project;

$GHG_{\text{associated}}$: denotes the additional GHG emissions associated with harvesting, regeneration, and tending operations;

CR_{biomass} : is carbon sequestration in biomass;

CR_{soil} : is carbon sequestration in soil, which in this case is assumed to be zero;

$GHG_{\text{fossil fuel}}$: represents GHG emissions from machinery used for harvesting, planting, and tending;

$GHG_{\text{fertilizer}}$: represents GHG emissions from fertilization (not relevant in this study);

UNC : is the uncertainty correction factor reflecting modelling uncertainty, set to $UNC=0.15$ in our case.

We applied an uncertainty correction factor (UNC) of 15% as a conservative expert judgement to reflect the combined modelling uncertainty associated with long-term (2024–2055) stand-level projections, mixed-species regeneration, and growth variability under changing climatic conditions. For the same Forest Industry Carbon Model, Borovics et al. (2025) report a substantially lower uncertainty deduction of approximately 3%, calculated using a statistical approach based on the relative standard deviation of modelled carbon stock changes, with uncertainty parameters derived from the Hungarian National Greenhouse Gas Inventory documentation and evaluated at a one-sided 70% confidence level. That lower value reflects uncertainties primarily associated with yield table-based modelling and field measurements under more controlled assumptions. However, in the present case study, the longer time horizon, inclusion of climate-adaptive stand conversion, and the still-unfinalized CRCF methodological rules justify applying a more precautionary deduction. To ensure transparency, we additionally provide a simple sensitivity analysis that presents carbon credits and associated revenues under alternative uncertainty factors ranging from 3% to 30%.

The eligible carbon sequestration, expressed in tons of CO₂ equivalent, determines the

number of carbon credits that can be generated. Carbon credit revenues were calculated using a carbon price of 50 EUR per tCO₂, which reflects the current price level observed for land-based voluntary carbon market (VCM) projects in Hungary, as reported by Borovics et al. (2024). The value is consistent with recent European transactions for nature-based carbon removal credits and represents a realistic market-based assumption rather than a speculative forward projection. At the same time, within the context of the emerging EU carbon removal certification system and potential credit purchasing programs, the European Commission has signalled that higher price levels may materialize in the medium term, with figures around or above 100 EUR per tCO₂. The present revenue values were derived using a real discount rate of 2%, reflecting a moderate social discount rate commonly applied in long-term climate and land-use policy assessments within the EU context.

3 RESULTS

Figure 5 shows the development of carbon stocks in the living biomass of the forest stand included in the IFM project for the projection period up to 2055. The total carbon stored in biomass increases from 527 tons to 671 tons over this time, corresponding to an overall gain of 99 tons of carbon by the end of the project. Carbon stock values are reported in tons of carbon (tC), representing the absolute quantity of carbon stored in living biomass at a given point in time. By contrast, carbon sequestration (sink) values are expressed in tons of CO₂ equivalent (tCO₂) and are reported with a negative sign, in line with IPCC greenhouse gas accounting conventions, where removals from the atmosphere are recorded as negative emissions, while increases in carbon stocks are presented as positive stock changes.

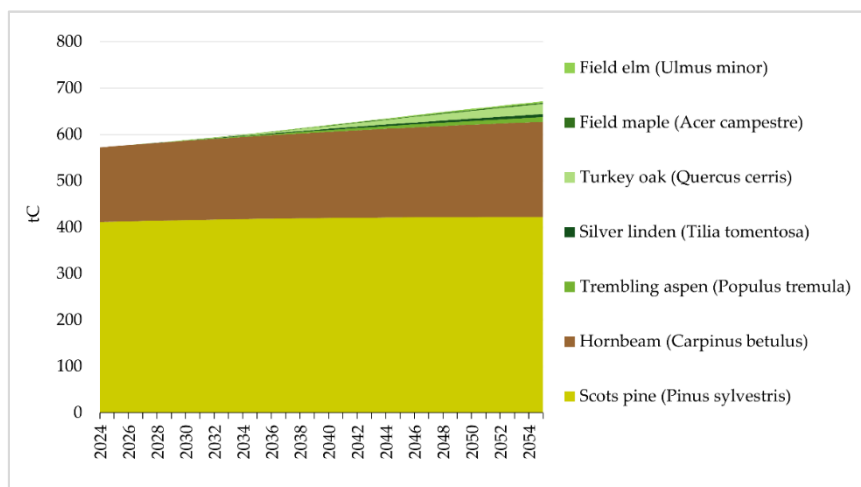


Figure 5. Development of carbon stock in the living biomass of the forest stand included in the IFM project, disaggregated by tree species, 2024–2055. (Note: Carbon stocks are reported in tons of carbon (tC) as positive stock values, in accordance with IPCC greenhouse gas reporting conventions.)

Figures 6 and 7 separately illustrate the evolution of carbon stocks and annual carbon sequestration for the tree species introduced through gap-based regeneration.

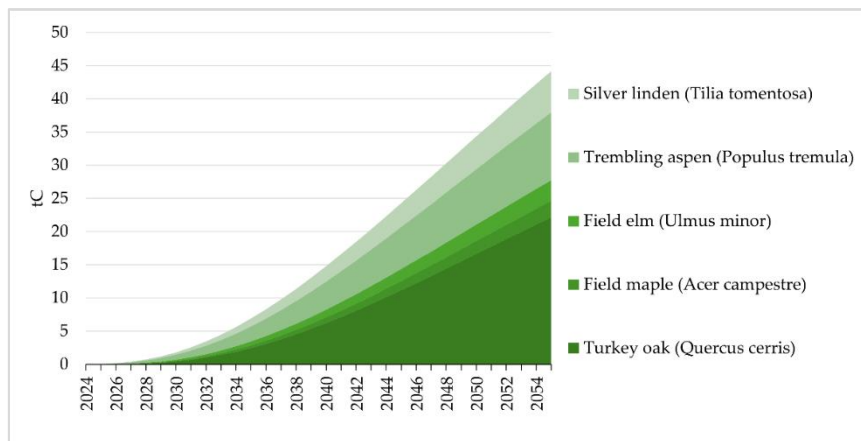


Figure 6. Development of carbon stocks of the tree species introduced through group-regeneration, 2024–2055. (Note: Carbon stocks are reported in tons of carbon (tC) as positive stock values, in accordance with IPCC greenhouse gas reporting conventions.)

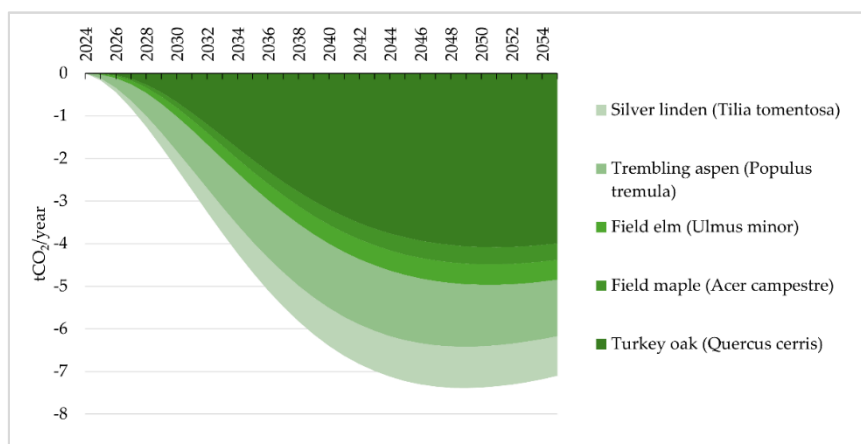


Figure 7. Development of carbon sequestration of the tree species introduced through group-regeneration, 2024–2055. (Note: Carbon sequestration is expressed in tons of CO₂ equivalent (tCO₂) and reported with a negative sign, in accordance with IPCC greenhouse gas accounting conventions, where removals from the atmosphere are recorded as negative emissions.)

Gap-based regeneration contributes a total of 44 tons of additional sequestered carbon by the end of the project period. The average annual carbon dioxide sequestration within the regenerated gaps amounts to -5.1 tCO₂ per year.

Figure 8 shows the annual total carbon sequestration alongside the greenhouse gas (GHG) emissions associated with harvesting, regeneration, and tending operations, expressed in CO₂ equivalents. The figure also displays the uncertainty correction factor applied to account for modelling uncertainty, which reduces the amount of carbon eligible for crediting. For clarity, total forest carbon sequestration is divided into the portion eligible for carbon crediting and the portion used to offset project-related emissions. According to our calculations, GHG emissions from machinery amount to 0.7% of the total carbon sequestered by 2055.

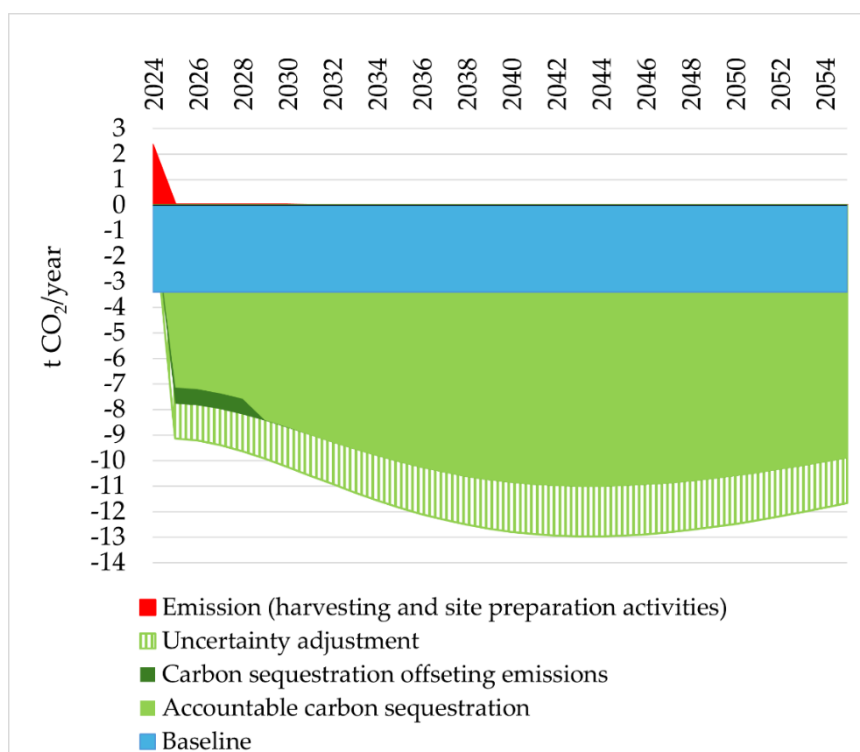


Figure 8. Eligible carbon sequestration in the IFM project, GHG emissions associated with harvesting, regeneration and tending activities, the carbon amount offsetting these emissions, and the uncertainty correction factor, 2024–2055. (Note: Carbon sequestration is expressed in tons of CO₂ equivalent (tCO₂) and reported with a negative sign in accordance with IPCC greenhouse gas accounting conventions, where removals from the atmosphere are recorded as negative emissions.)

The total revenue from carbon credits generated by the IFM project over the 2024–2055 period is estimated at 10,074 EUR, with a present value of 7,255 EUR (Figure 9).

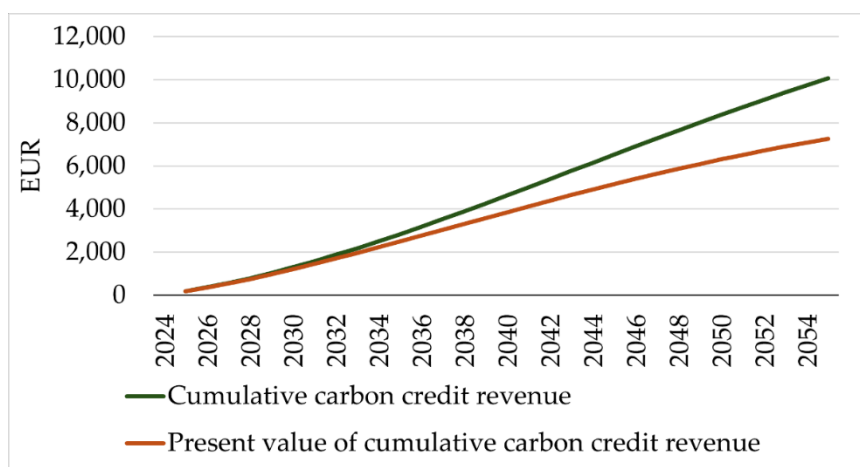


Figure 9. Cumulative carbon-credit revenue and its present value for the IFM project over the 2024–2055 period, for the 4.7-hectare project area.

Table 6 summarizes total carbon sequestration, associated GHG emissions, the resulting number of carbon credits, and the projected carbon-credit revenue. When expressed per hectare, the carbon-credit revenue equals 2,132 EUR/ha over the full duration of the project.

Table 6. Carbon sequestration, GHG emissions from harvesting, regeneration and tending operations, and the resulting carbon credits and carbon-credit revenue for the IFM project.

Site	Area (ha)	Carbon sequestration (tCO ₂)	CO ₂ emissions (kg)	N ₂ O emissions (kg)	CH ₄ emissions (kg)	Credits (units)	Credits per ha (units/ha)	Revenue (EUR)	Revenue per ha (EUR/ha)
Káld 75/C	4.7	-364	2,524.6	0.01	0.2	201	43	10,074	2,132

Figure 10 displays the present value of total carbon credit revenues at varying carbon price levels. Carbon prices are expected to increase with the entry into force of the CRCF Regulation and the launch of the regulated voluntary market. Figure 10 shows how such changes in carbon prices would influence the project's revenue (expressed in present value).

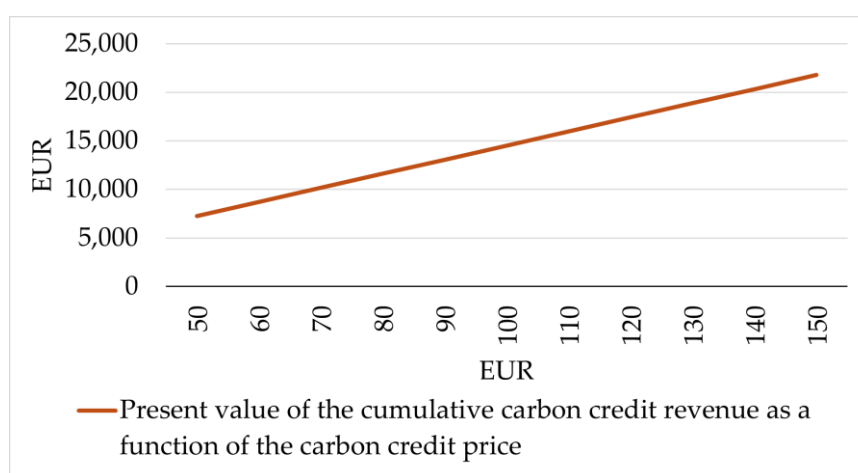


Figure 10. Present value of cumulative carbon-credit revenue under different carbon price levels for the 4.7-hectare IFM project area.

Figure 11 demonstrates that the number of eligible carbon credits and the corresponding present value of carbon credit revenues decline almost linearly as the uncertainty correction factor (UNC) increases from 3% to 30%. At the lower end of the range (3%), which corresponds to the statistically derived uncertainty level reported by Borovics et al. (2025) for the same model under more controlled assumptions, the project generates the highest number of credits and the highest present value. Applying the more precautionary 15% UNC used in this study results in a moderate reduction in both indicators; however, the project remains clearly revenue positive. The project still generates a substantial number of credits and a meaningful level of carbon credit revenue even under highly conservative assumptions (e.g., 25–30% UNC).

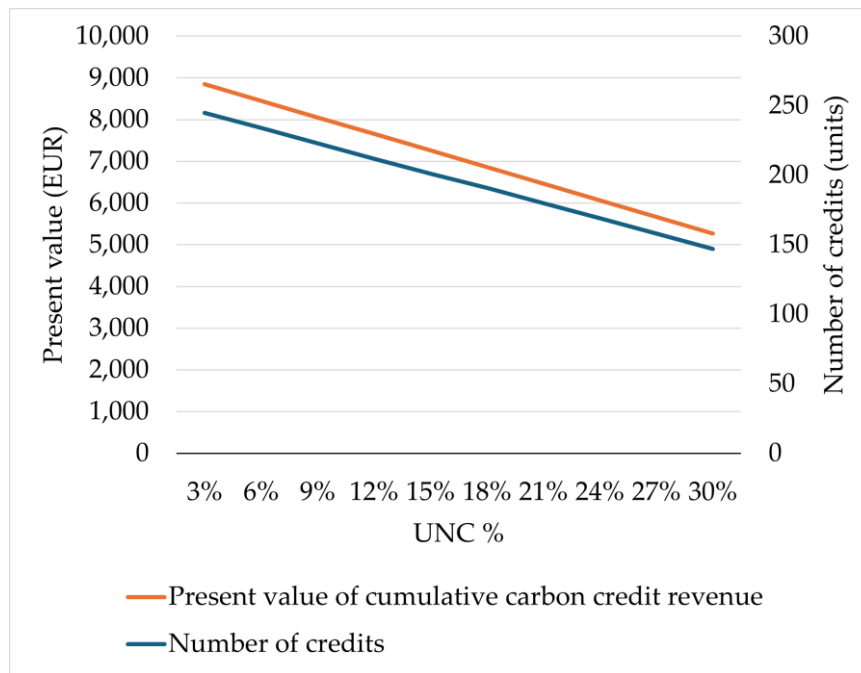


Figure 11. Sensitivity of the number of eligible carbon credits and the present value of carbon credit revenue to alternative uncertainty correction (UNC) factors (3–30%) for the 4.7-ha IFM project area.

4 DISCUSSION AND CONCLUSIONS

Improved Forest Management projects aim to optimize the carbon sequestration potential of existing forests and are expected—through the CRCF Regulation—to become an integral component of the EU’s carbon removal policy framework. Based on the findings of our case study, several key conclusions can be drawn:

(1) **Additionality and timing:** IFM projects can only be certified, and carbon sequestration can only be credited, if the implemented measures demonstrably exceed “business-as-usual” (BAU) practices and provide genuine additional carbon removals. This framework enables the inclusion of mature stands that are technically harvestable but not yet harvested. However, Scots pine stands aged 101–120 years represent an advanced developmental stage and may exhibit increasing vulnerability to climatic stress, drought events, pest outbreaks, and pathogen infections under projected future climate conditions. Although such stands may currently function as net carbon sinks, declining vitality or disturbance events could reduce growth rates or even shift the carbon balance toward net emissions. The extended-rotation approach, therefore, requires adaptive management and continuous monitoring to maintain carbon permanence.

(2) **Need for long-term commitment:** A typical project duration of 30 years, combined with an additional 10-year monitoring period, requires a substantial long-term commitment from forest owners. While essential for successful implementation, this extended period may also present challenges for landowners. Over such time horizons, disturbance risks—including windthrow, fire, bark beetle infestations, and drought-induced mortality—must be explicitly considered. Under the projected sessile oak–Turkey oak climate zone, Scots pine may face increasing physiological stress, whereas the introduced species mix (e.g., Turkey oak, field maple, field elm, aspen, and silver linden) is expected to demonstrate higher resilience to heat and water limitation. Nevertheless, no species composition is entirely risk-free under

accelerating climate change. Future CRCF methodological guidance may address such risks through buffer mechanisms, pooled risk reserves, permanence-related discount factors, or other risk-adjustment instruments similar to those applied in existing voluntary carbon market standards.

(3) The critical importance of baseline determination: Project outcomes—especially the quantity of creditable carbon removals—depend heavily on the baseline, which remains uncertain pending the adoption of the delegated act. Future methodological clarification of baseline values will strongly influence both the number of credits generated and overall project viability. In the present study, the applied baseline is explicitly hypothetical and demonstrative in nature, constructed through stratification by tree species and age class and aligned with the CRCF's flow-based accounting logic. Once the official IFM methodological guidance is adopted, additional stratification variables—such as productivity class, climatic zone differentiation, management intensity, or disturbance-risk adjustments—may be introduced, potentially requiring recalibration of baseline values and corresponding credit volumes.

(4) Economic viability and pre-financing opportunities: Our analysis indicates that IFM projects can achieve positive financial outcomes, particularly if carbon prices rise over the coming decade. The issuance of a Compliance Certificate at project initiation allows pre-financing arrangements, providing forest owners with access to funds even before the first verification audit.

(5) Carbon footprint and emissions: Project-related emissions from fossil-fuel use during harvesting, regeneration, and tending represent less than 1% of the total carbon sequestered. With appropriate planning, this confirms that IFM projects can be implemented with a strongly net-positive carbon balance.

(6) Environmental, conservation, and climate policy relevance: IFM projects simultaneously contribute to climate mitigation, biodiversity conservation, environmental protection, and sustainable forest management. Climate-adaptive stand restructuring fosters forest types better suited to future climatic conditions, thereby increasing ecosystem resilience.

(7) Role of decision-support tools: Decision-support systems such as SiteViewer 3.0 and the Forest Industry Carbon Model played a crucial role in planning and scenario development. Such digital tools are indispensable for designing scientifically robust Carbon Farming projects.

(8) Relative magnitude of carbon revenues: When interpreted in a regional economic context, the projected carbon credit revenue—approximately 71 EUR/ha/year—represents a non-negligible supplementary income stream relative to typical forest management margins in Hungary. The stumpage value of this stand's annual increment, excluding overhead and regeneration costs, is roughly 145 EUR/ha/year. Since carbon revenues do not require harvesting operations—which involve organizational tasks and management effort—and because they do not replace timber harvesting, only postpone it, this income source can be considered financially viable, depending on the landowner's individual financial objectives and preferences.

(9) Robustness of machinery-related emission estimates: Although project-related emissions from harvesting, regeneration, and tending operations account for only 0.7% of total carbon sequestration, parameter uncertainty in fuel consumption coefficients and emission factors should be acknowledged. These parameters vary depending on machine type, engine efficiency, operational load, and site conditions, and IPCC default emission factors inherently include uncertainty. However, given the relatively small absolute magnitude of machinery-related emissions compared with projected stand-level carbon sequestration, even moderate deviations in fuel consumption or emission coefficients would not materially affect the overall net carbon balance of the project. Comparable relative magnitudes of machinery-related emissions—substantially lower than total forest carbon sequestration—have also been reported by Benke et al. (2015) and Borovics et al. (2025) using similar calculation approaches, which

further supports the robustness of the present findings.

(10) Limitations and transferability: This study represents a site-specific, demonstrative case study under particular ecological, silvicultural, and regulatory assumptions. Quantitative outcomes—including baseline value, additional sequestration potential, credit volumes, and economic performance—are, therefore, context dependent and influenced by forest type, productivity class, climatic zone, rotation system, and management regime. Applying this approach to other forest types or regions would require recalibrating baseline assumptions, productivity parameters, and disturbance-risk considerations. In addition, exact numerical replication of the modelling results depends on access to the Forest Industry Carbon Model and the SiteViewer decision-support tool, as well as the yield tables and parameter settings applied. While the methodological logic is transferable, the specific quantitative outputs should be interpreted as illustrative.

Overall, IFM projects represent one of the most complex yet promising segments of the voluntary carbon market as they allow for the inclusion of far larger areas than afforestation projects alone. However, their long-term climate effectiveness depends on a robust baseline definition, adaptive risk management, and the incorporation of disturbance-related safeguards within the CRCF framework. Once the regulatory framework is finalized, their adoption is expected to increase—particularly in regions where the condition and climate sensitivity of existing forests justify such interventions.

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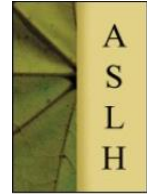
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Intercropped Macadamia and Coffee in Agroforestry System in Zambia: a Case Study





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ABSTRACT

This study examines the economic performance of an agroforestry system applied in Africa and complementary insights into its social and ecological implications, focusing on the intercropping of macadamia (*Macadamia integrifolia*) and Arabica coffee (*Coffea arabica*). The research was conducted on a 1.6-hectare area at Pamo Mangala Farm in Zambia between 2021 and 2024. During the study, we assessed and compared the effects of different planting systems on farm productivity, including homogeneous and heterogeneous layouts. The results show that intercropping can increase farm profitability through production diversification while supporting sustainable farming practices; it may also have positive effects on local employment and environmental conditions.

KIVONAT

Makadámdió és kávé köztes termesztése agroerdészeti rendszerben Zambiában: esettanulmány. Tanulmányunk egy Afrikában alkalmazott agrárerdészeti rendszer gazdasági teljesítményét vizsgálta, miközben annak társadalmi és ökológiai vonatkozásaira is betekintést nyújtott, a makadámdió (*Macadamia integrifolia*) és az arabica kávé (*Coffea arabica*) köztes termesztésére fókuszálva. A kutatás a zambiai Pamo Mangala Farmon zajlott egy 1,6 hektáros területen 2021 és 2024 között. A vizsgálat során különböző ültetési rendszerek — beleértve a homogén és heterogén elrendezéseket — gazdasági teljesítményét és termelékenységére gyakorolt hatását értékeltük és hasonlítottuk össze. Az eredmények azt mutatják, hogy a köztes termesztés a termelés diverzifikálásán keresztül növelheti a gazdaság jövedelmezőségét, miközben támogatja a fenntartható gazdálkodási gyakorlatokat; emellett feltételezhetően kedvező hatással van a helyi foglalkoztatásra és a környezeti állapotokra is.

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1 INTRODUCTION

Mounting environmental, social, and economic pressures have made agricultural diversification and sustainability critical imperatives in Sub-Saharan Africa. Declining soil fertility, erratic rainfall patterns, deforestation, and market volatility pose increasing challenges to smallholder farmers in Zambia. Such systemic vulnerabilities call for innovative land-use models combining productivity with resilience. One promising strategy is agroforestry, which integrates trees and perennial crops into agricultural systems to provide multiple outputs and ecosystem services (Garrity, 2004).

Intercropping is a form of agroforestry in which two or more crops are cultivated in proximity. It can contribute significantly to sustainable agricultural intensification. It can also improve resource use efficiency, reduce pest and disease pressure, and enhance system-level resilience (FAO 2020). In this context, the intercropping of macadamia (*Macadamia integrifolia*) and coffee (*Coffea arabica*) represents a high-potential model that aligns with Zambia's adaptation goals, livelihood diversification, and sustainable land management.

Coffee is a globally significant export commodity and a key source of rural income in many parts of Africa. However, its monocultural cultivation has led to ecological imbalances and increasing susceptibility to climate stress, pests, and diseases such as coffee leaf rust (Bunn et al. 2015). Macadamia is a climate-resilient, nitrogen-demanding perennial tree that can improve soil organic matter, reduce erosion, and sequester carbon, while also offering strong market potential due to growing global demand for tree nuts (Leakey – Asaah 2013; Dawson et al. 2014). Integrating macadamia and coffee crops can potentially enhance land-use efficiency and deliver synergistic economic, ecological, and social benefits, including increased income stability through diversified revenue streams, improved soil health via organic matter inputs from macadamia litter, and microclimatic buffering that can protect shade-sensitive coffee plants from temperature extremes (Lemos – Ribeiro, 2024). Additionally, intercropping systems can strengthen community resilience, generate local employment, and foster farmer engagement with sustainable practices (Mbow et al., 2014).

Previous studies have demonstrated the effectiveness of agroforestry systems in similar tropical environments. For example, intercropping coffee with shade trees in Central America improved yields and quality while enhancing biodiversity and carbon sequestration (Soto-Pinto et al., 2000). Integrating legumes and high-value trees in Malawi and Kenya increased household incomes and soil fertility (Ajayi et al., 2007; Kuyah et al., 2019). Such examples highlight the relevance and replicability of agroforestry models for Zambia, particularly in regions with similar agroecological zones.

This study investigates the economic, social, and ecological implications of a small-scale intercropping trial involving macadamia and coffee in Zambia. Conducted between 2021 and 2024, the present study combines empirical data collection with a multidisciplinary analytical framework and evaluates whether this system can provide a scalable and sustainable agroforestry model for smallholder farmers in Zambia and beyond. The study objective was to evaluate the viability of intercropping macadamia and coffee under Zambian conditions from two perspectives:

- Economic viability (input costs, revenues, net profit)
- Social acceptability (labour requirements, resilience).

The study addressed the following key research questions:

1. Can intercropping macadamia and coffee increase profitability compared to monocultures?
2. How does macadamia–coffee intercropping affect labour demand and employment patterns?

2 MATERIALS AND METHODS

2.1 Trial design

The field trial was performed at Pamo Mangala Farm in Zambia, on a dedicated experimental plot covering 1.6 hectares in the Miombo Woodland. The study area is at 11°08'00.0" S, 31°26'28.2" E in northern Zambia (*Figure 1*). The plot is in Zambia's Northern Province, a region characterized by a warm temperate climate and dry winters. The area receives between 800 and 1,200 mm of rainfall annually, in a single rainy season extending from November to March. Mean annual temperature is approximately 22 °C, creating conditions suitable for both coffee and macadamia cultivation (FAO 2020).



Figure 1. Location of the experimental plot (Google Earth)

The soil of the experimental area is typical Miombo woodland soil, classified predominantly as sandy loam to loamy sand Ferralsols, with low inherent fertility. Baseline soil sampling before establishment indicated acidic conditions (pH 5.2–5.6), low organic matter content (below 2%), and limited available nitrogen and phosphorus, which are characteristic of many smallholder and commercial farming areas in central and northern Zambia. Soil texture and structure were uniform across the experimental blocks, allowing for valid comparisons among planting systems.

The trial plot was systematically subdivided into four equal blocks, each measuring approximately 0.4 hectares. The subdivision was specifically designed to enable a rigorous comparative analysis of different cropping systems under similar environmental and soil conditions. Each of the four blocks was assigned a distinct planting system, facilitating direct comparison of their agronomic performance, economic viability, and ecological impacts.

The initial planting of all plots was conducted between 2019 and 2020, using one-year-old healthy seedlings sourced from certified nurseries. In total, 1,300 coffee seedlings and 300 macadamia seedlings were planted across the experimental area, distributed according to the

designed spacing for each cropping system. This setup allowed for sufficient sample sizes to assess growth rates, yield, and other parameters over the multi-year trial period.

The experimental design ensured consistency in soil preparation, fertilization, irrigation, and pest management practices across all blocks to minimize confounding factors and isolate the effects of the planting systems on performance outcomes.

2.2 Data collection

Data collection spanned agronomic, economic, and socio-ecological domains. The following parameters were measured:

- Agronomic: Yield estimates were conducted twice a year.
- Economic: Input costs (labour, seedlings, fertilizer, irrigation), yield per hectare, market prices, gross and net revenue (World Bank 2022).

2.3 Data analysis

Quantitative data were analyzed using descriptive statistics and inferential techniques, such as ANOVA, T-test, and regression analysis, to identify differences between systems.

2.4 Description of planting systems

This study evaluated four distinct planting systems to compare the agronomic, economic, and ecological performance of macadamia and coffee when grown separately and together under different spatial arrangements. Each system was designed to reflect both practical farming considerations and the potential for mechanization, yield optimization, and sustainable land use.

Homogeneous macadamia (8×4 m)

In this monoculture system, macadamia trees were planted with a spacing of 8 meters between rows and 4 meters within rows. This spacing was chosen to accommodate the large mature canopy size of macadamia trees and to allow sufficient sunlight penetration and air circulation, both essential for healthy growth and nut production. The 8×4-meter configuration was specifically designed with future mechanization in mind, providing enough room for machinery, such as tractors, to move through the orchard. The wide spacing also aimed to reduce competition for nutrients and water among trees, which is vital given macadamia's deep-rooting characteristics.

Homogeneous coffee (2×1.5 m)

The coffee monoculture system followed a traditional layout with coffee seedlings planted 1.5 meters apart within rows and 2 meters between rows. This spacing is typical for manual coffee plantations, enabling workers to access the plants for routine maintenance activities such as pruning, pest control, and harvesting. The relatively narrow 1.5-meter spacing within rows and between plants restricts the use of large-scale mechanized equipment, making this a labour-intensive system. The 2×1.5-meter spacing strikes a balance between maximizing the number of coffee plants per hectare and maintaining manageable plant productivity. The configuration supports high-density coffee planting while allowing adequate airflow and sunlight penetration.

Intercrop sparser coffee (8×3×1×1×3 m)

The modified intercrop system featured macadamia trees planted at a spacing of 8 meters between rows and 4 meters within rows, maintaining the layout necessary for mechanized operations. Within the 8-meter space between macadamia rows, coffee seedlings were arranged in a 3×1×1×3-meter pattern: the first coffee plant was located 3 meters from the base of the

macadamia tree, followed by two coffee plants each spaced 1 meter apart, and then a 3-meter gap before the next macadamia tree (*Figure 2*).

This specific configuration allowed for three coffee trees per inter-row space, evenly distributed to avoid excessive competition while optimizing light availability. The 4-meter spacing between macadamia rows remained unchanged, ensuring continued access for tractors and machinery. Despite the relatively dense coffee planting, mechanized maintenance (e.g., mowing and spraying) was still feasible, while coffee management and harvesting were expected to remain largely manual due to the crop's structural and spatial characteristics.

This layout was designed to enhance land-use efficiency, support diversified production, and maintain operational flexibility in a mixed perennial cropping system.

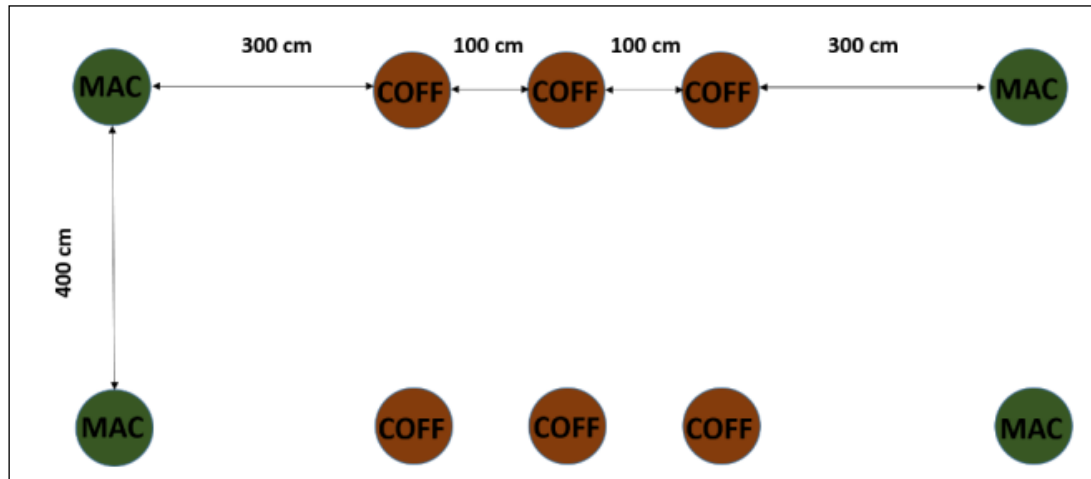


Figure 2. Sparser intercrop (Deák, 2020)

Intercrop with denser coffee (8×3×4×1 m)

This variant of the modified intercrop system was based on the initial layout where the macadamia spacing of 8×4 meters remained unchanged, yet the spacing between coffee rows was reduced. Specifically, an additional row of coffee was inserted between each existing pair of rows, effectively halving the inter-row distance for coffee to 1 meter. As a result, a coffee row was planted every 2 meters, significantly increasing the number of coffee plants per hectare compared to the original setup. The denser configuration precludes machine use; only manual maintenance and harvesting are feasible (*Figure 3*). While this layout aims to enhance coffee yield by utilizing space more intensively, it also brings increased labour demands and the need for more careful management of competition among coffee plants for light, water, and nutrients.

The above system represents a shift in priority from mechanization toward maximizing planting density and potential productivity within the available area.

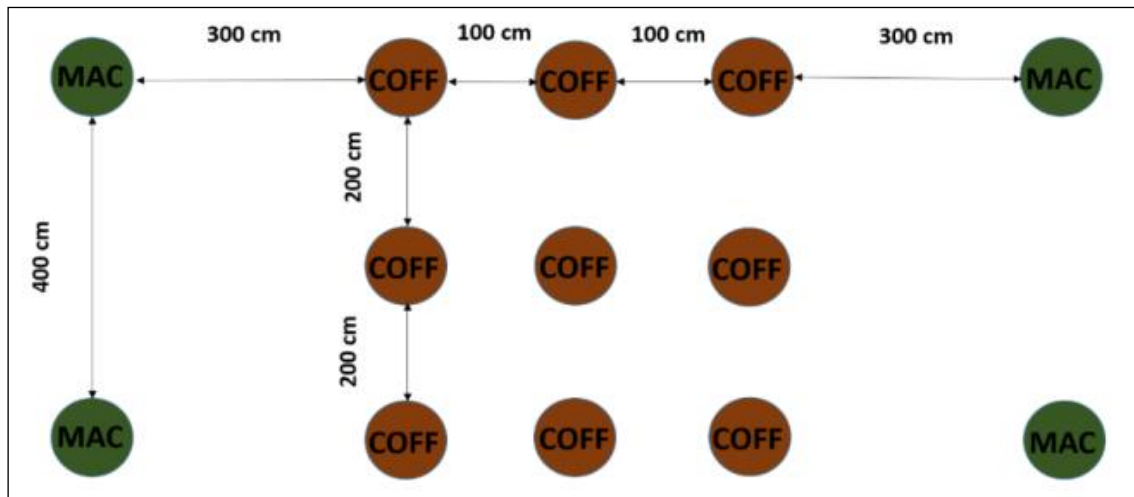


Figure 3. Denser intercrop (Deák, 2020)

2.5 Labor and material costs

Labour and material costs were monitored and recorded throughout the entire production cycle. These activities require varying levels of labour input depending on the cropping system and crop density.

Labour costs

Labour was identified as a significant component of total production costs. Labour intensity fluctuated across the different cropping systems, with the highest demands observed in the dense intercropped blocks, due primarily to the need for more frequent and meticulous management practices in systems where two crops are grown simultaneously and require additional care, such as timely pruning to avoid competition, more complex weed control, and coordinated harvesting schedules. Monoculture systems, especially homogeneous coffee plots, showed lower labour intensity as operations tend to be more straightforward with less complexity in crop management.

Labour activities throughout the production cycle included

- **Planting:** Manual planting of seedlings, which required careful spacing and depth adjustments to optimize growth conditions for both coffee and macadamia, especially in intercropped plots.
- **Weeding:** Regular manual weed removal was necessary to minimize competition for nutrients and water, with intercropped systems requiring more labour due to the complexity of managing two crop species growing in proximity.
- **Pruning:** Pruning was essential to maintaining optimal plant health and productivity. Coffee plants required routine pruning to enhance yield and quality, while macadamia trees demanded selective pruning to manage canopy structure and sunlight penetration.
- **Harvesting:** Harvest timing varied between crops and systems. Coffee harvesting is labour-intensive because ripe berries need to be selectively picked, whereas macadamia harvesting involves collecting nuts. Intercropping added complexity as coordination of labour was needed to avoid damaging either crop.
- **Material Costs:** Material inputs included essential components necessary for successful crop establishment and maintenance:
- **Fertilizers:** A mix of fertilizers—synthetic NPK (nitrogen, phosphorus, potassium) fertilizers, organic compost, and lime—was applied to improve soil fertility, support healthy crop growth, adjust soil pH, and enhance nutrient availability. The fertilizer

application rates were managed to meet the nutritional requirements of each cropping system.

- **Pesticides and Organic Treatments:** Crop protection strategies involved conventional pesticides and organic treatments to control pests and diseases. Organic treatments were favoured in the intercropped system to maintain ecological balance and protect beneficial insect populations.
- **Irrigation:** Irrigation for all experimental plots was sourced from a nearby natural stream. Irrigation was implemented across the study area using simple, low-input methods, reflecting local farming practice and the absence of mechanized irrigation infrastructure.
- **Watering methods** depended on plot accessibility and field conditions but included manual hose-based irrigation, bucket watering, or small-scale surface flooding. Simple gravity-fed drip lines were used to distribute water along crop rows in some plots; however, such systems operated without pumps or mechanical components.

The irrigation equipment required no capital investment or energy input. Consequently, irrigation did not incur equipment-related or water-related costs. Manual labour was the only input associated with irrigation, which covered water extraction from the stream and its application to the crops. Irrigation frequency and duration were adjusted according to crop type, plant developmental stage, and prevailing weather conditions.

2.6 Yield estimates and revenue projections

The yield estimates and revenue projections were developed based on observed growth patterns of coffee and macadamia trees in the trial, as well as on extensive market research on local commodity prices. Yield estimates were derived from systematic field observations conducted within the experimental plots, including regular assessments of tree growth parameters (such as plant height, canopy development, and bearing status), and recorded harvest quantities once production commenced. For coffee, yield measurements were based on harvested coffee cherry weight per plant and extrapolated to a per-hectare basis, while macadamia yield estimates relied on nut-bearing observations and harvested nut-in-shell weights. Revenue projections were calculated by combining these empirically observed yield data with average local prices. The analysis accounted for the typical maturation timelines of two crops, seasonal variability, and expected agronomic improvements over time.

Coffee yield projections:

Coffee plants generally require a few years after planting before they reach stable production levels. This study projected coffee yields to stabilize by the third year of growth, which corresponds to 2024 in the timeline. Coffee plants mature sufficiently during this growth period and produce consistent yields of coffee cherries each season. Early years showed lower output due to immature plants, while post-year-three yields were expected to remain relatively steady. Yield stabilization allows for more accurate revenue forecasting.

Macadamia yield projections:

Macadamia trees have a longer juvenile phase than coffee and typically reach their peak production several years after planting. Macadamia nut yields were projected to peak in 2026, the fifth year in our study. Peak production years are critical for ensuring the economic viability of macadamia orchards and heavily influence long-term revenue potential. The projected yield trajectory was modelled based on agronomic data and corroborated by local industry expertise.

Revenue calculations:

Revenue estimates were calculated by multiplying the expected yields by prevailing local market prices for coffee cherries and shelled macadamia nuts. The prices were sourced from reputable industry reports and market analyses to ensure realistic financial projections:

- Coffee cherries were valued at approximately 3.00 USD per kilogram, reflecting 2023 market prices.
- Shelled macadamia nuts commanded a higher price point of about 8.00 USD per kilogram.

The price points were applied uniformly across the cropping systems to maintain comparability, recognizing that fluctuations in market demand and quality could influence actual revenues. Revenue projections considered yield variability over the years, seasonal harvest volumes, and the respective contributions of each crop in intercropped systems.

3 RESULTS

3.1 Economic analysis

Between 2022 and 2026, the financial performance of the homogeneous coffee, homogeneous macadamia, and intercropping denser and spacer cropping systems showed clear divergence in efficiency and profitability trends (*Table 1*).

In 2022, all systems operated at a net loss. Coffee and macadamia monocultures generated limited revenues that could not offset initial establishment and input costs. While requiring the highest initial investment, the intercropped systems produced comparatively higher income, resulting in the lowest financial loss of the three, indicating early advantages in combined output and land-use efficiency.

In 2023, input costs began to stabilize, while yields—particularly from coffee—improved across all systems. Despite ongoing losses, the intercropped system further narrowed its financial deficit, reinforcing its greater short-term viability. Macadamia continued to mature slowly, while coffee systems struggled to achieve profitability due to modest market returns.

By 2024, the intercropped system approached financial break-even, benefiting from cumulative coffee yields and reduced operational costs. Macadamia monoculture also showed signs of financial improvement, though it still lagged. The coffee-only system remained the least profitable, hampered by market volatility and limited diversification.

In 2025, projections indicate a major turning point: the intercropped system is expected to reach a stable net profit for the first time, supported by consistent coffee output and early-stage macadamia harvests. Macadamia monoculture is also projected to enter positive financial territory. Coffee-only systems continue to reduce losses but remain economically less competitive.

By 2026, both macadamia and intercropped systems are forecast to achieve reliable profitability, with the intercropped models maintaining the strongest financial position overall. Its staggered yield cycles, shared inputs, and more efficient land use contribute to a superior long-term economic outlook.

Overall, these results confirm that despite higher early-stage costs, intercropping provides the most resilient and profitable model over a five-year horizon.

Table 1. Annual Financial Progression of Cropping Systems (2022–2026)

Year	System	Input Costs (USD)	Revenue (USD)	Net Profit (USD)
2022	Homogeneous Coffee	1,990	50	-1,940
	Homogeneous Macadamia	1,994	0	-1,994
	Intercrop Sparse Coffee	1,850	497	-1,353
	Intercrop Denser Coffee	1,900	500	-1,400
2023	Homogeneous Coffee	2,000	63	-1,937
	Homogeneous Macadamia	1,700	700	-1,000
	Intercrop Sparse Coffee	1,900	1,447	-453
	Intercrop Denser Coffee	1,800	1,900	100
2024	Homogeneous Coffee	2,000	299	-1,701
	Homogeneous Macadamia	1,600	1,700	100
	Intercrop Sparse Coffee	1,900	2,447	547
	Intercrop Denser Coffee	1,700	2,600	900
*2025	Homogeneous Coffee	2,000	800	-1,200
	Homogeneous Macadamia	1,400	2,200	800
	Intercrop Sparse Coffee	1,900	2,867	967
	Intercrop Denser Coffee	1,600	3,400	1,800
*2026	Homogeneous Coffee	2,000	1,300	-700
	Homogeneous Macadamia	1,300	2,500	1,200
	Intercrop Sparse Coffee	1,900	3,100	1,200
	Intercrop Denser Coffee	1,500	4,200	2,700

*Note: Table for 2025 and 2026 are projections based on observed trends and current market conditions.

3.2 Social and ecological impacts

Qualitative observations and field-level assessments indicated a clear overall advantage of intercropped macadamia–coffee systems compared to monoculture production. Several recurring patterns were identified across the study period.

- **Income diversification** emerged as a key social benefit of the intercropped system. The simultaneous production of two high-value crops reduced dependence on a single commodity, thereby lowering exposure to price volatility and localized yield losses. This diversification contributed to greater income stability, particularly in years characterized by fluctuating market conditions.
- **Soil quality and moisture retention** were consistently more favourable under intercropping. Improved canopy structure and increased organic matter inputs supported better soil structure and enhanced moisture conservation, leading to visibly healthier soil conditions compared to monoculture plots.
- **Reduced production risk** was another notable advantage. The intercropped system demonstrated higher resilience to climate-related disturbances, such as drought stress or pest pressure, as reduced performance of one crop could be partially compensated by the continued productivity of the other (Smith – Mwamba 2023).

Although intercropping required higher total labour inputs from a social perspective, labour demand was more evenly distributed throughout the year. This more balanced seasonal labour

requirement contributed to steadier employment opportunities, which is particularly relevant in rural areas where seasonal underemployment is common.

While the intercropped system required more labour overall, this demand was spread more evenly across the year, which contributed to steadier employment opportunities for local labourers. This year-round labour distribution was particularly appreciated in communities where seasonal unemployment is a recurring challenge.

3.3 Statistical analyses

3.3.1 Analysis of economic performance differences between cropping systems (ANOVA)

An analysis of variance (ANOVA) was applied to compare net profit outcomes among the four cropping systems—homogeneous coffee, homogeneous macadamia, sparse intercropping, and denser intercropping—over the 2022–2026 period (Table 2).

Accordingly, the null hypothesis, assuming equal mean net profitability across all systems, was rejected. These findings confirm that cropping system choice has a measurable and meaningful impact on farm-level economic outcomes, justifying further pairwise comparisons and trend analyses.

Table 2. ANOVA results for net profit differences among cropping systems

Source of variation	SS	df	MS	F	p-value
Between groups	20,745,200	3	6,915,067	8.72	0.002
Within groups	12,693,800	16	793,363		
Total	33,439,000	19			

The ANOVA results indicate statistical differences among the cropping systems ($F = 8.72$, $p = 0.002$). Therefore, the null hypothesis that all cropping systems generate equal average net profits can be rejected.

These findings confirm that the choice of planting system influences economic outcomes.

3.3.2 Comparison of net profitability between cropping systems (t-test)

Coffee Monoculture vs Macadamia Monoculture: The comparison of cumulative net profits over the study period shows that both monoculture systems remained economically constrained. Coffee monoculture generated persistent losses throughout the period, while macadamia monoculture showed gradual improvement and reached profitability only in later years. Statistical testing did not indicate a difference between the two monocultures over the full period ($p > 0.05$), reflecting their similarly delayed economic returns during the establishment phase.

Coffee monoculture vs. intercropped systems: t-test results reveal a statistical difference between coffee monoculture and both intercropped systems ($p < 0.05$). Intercropping substantially reduced early-stage losses and achieved positive net profits earlier, highlighting the clear financial advantage of diversification compared to coffee monoculture alone.

Macadamia monoculture vs. intercropped systems: The comparison between macadamia monoculture and intercropped systems did not yield statistical differences over the full period ($p > 0.05$). While intercropping showed faster profitability onset and higher cumulative gains, macadamia monoculture displayed a converging profitability trajectory by 2025–2026.

Overall, intercropping performs better than coffee monoculture while remaining statistically comparable to macadamia monoculture in terms of long-term net profitability.

Pairwise comparisons were conducted using independent sample T-tests to identify which systems differ (*Table 3*).

Table 3. Pairwise comparison of cropping systems (t-test results)

Comparison	Mean difference (USD)	t-value	p-value
Coffee vs. Macadamia	1,317	1.42	0.17
Coffee vs. Sparse intercrop	2,437	3.18	0.01
Coffee vs. Denser intercrop	3,534	4.06	0.00
Macadamia vs. Sparse intercrop	1,120	1.21	0.24
Macadamia vs. Denser intercrop	2,217	2.05	0.06

The results show statistical differences between coffee monoculture and both intercropped systems ($p < 0.05$), while differences between macadamia monoculture and intercropped systems are not statistically significant at the 5% level.

3.3.3 Temporal trends in net profit across cropping systems: regression analysis

Linear regression analysis was conducted using annual net profit data from 2022 to 2026 to assess economic trends for each cropping system (*Table 4*).

Table 4. Linear regression models for net profit trends

System	Regression equation	R ²
Homogeneous Coffee	$y = 310x - 2560$	0.89
Homogeneous Macadamia	$y = 800x - 2400$	0.94
Sparse Intercrop	$y = 640x - 1960$	0.91
Denser Intercrop	$y = 1020x - 2700$	0.96

- *Homogeneous Coffee*
Displays a modest positive trend of approximately +310 USD/year, indicating gradual improvement. However, net profit remains negative throughout the study period, underscoring structural economic limitations.
- *Homogeneous Macadamia*
Shows a strong upward trend of approximately +800 USD/year, transitioning from early losses to sustained profitability by 2025.
- *Intercrop Sparse Coffee*
Exhibits a steady positive trend of approximately +640 USD/year, outperforming both monocultures during most of the period.
- *Intercrop Denser Coffee*
Demonstrates the strongest performance with an annual increase of approximately +1,020 USD/year, achieving the highest profitability by 2026.
Across all systems, intercropping—particularly in denser configurations—reaches profitability earlier and with greater efficiency than monoculture systems (*Figure 4*).

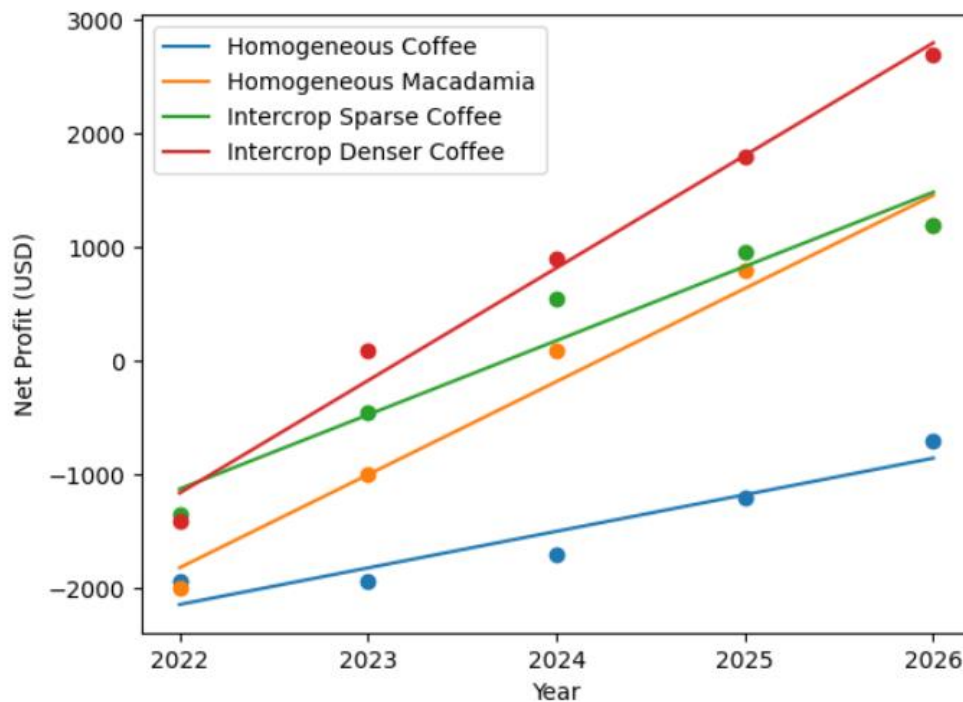


Figure 4. Regression analysis of net profit (values in USD, see also Table 4.)

4 DISCUSSION

4.1 Economic viability of intercropping systems

The economic analysis covering the 2022–2026 period clearly demonstrates the financial advantages of intercropping macadamia and coffee. Cumulative net profits amounted to approximately 4,100 USD for the denser intercropping system and 900 USD for the sparse intercropping system, compared to –7,480 USD for coffee monoculture and –894 USD for macadamia monoculture.

These results confirm that intercropping substantially mitigates establishment-phase losses and accelerates the transition to profitability. The denser intercropped system, in particular, maximized income diversification and land-use efficiency, leading to superior economic performance.

The findings are consistent with previous studies. Perdoná et al. (2015) reported improved cash flow stability and economic resilience in macadamia–coffee intercropping systems in Brazil. Taken together, the results suggest that intercropping represents a financially robust and risk-reducing production strategy under small- to medium-scale African farming conditions. However, several studies caution against overgeneralizing these benefits across contexts. Evidence suggests that the economic performance of agroforestry and intercropping is highly conditional on enabling environments—particularly reliable market outlets, supportive policies, and strong advisory/extension and technical support—without which financial gains may remain limited or uncertain (Thiesmeier – Zander, 2023; Tranchina et al., 2024). In smallholder settings, adoption and sustained performance can also be constrained by high upfront establishment costs, limited access to capital, and exposure to market uncertainty and commodity price volatility, which can erode profitability even when biophysical outcomes are positive (Stroesser et al., 2018; Abdul-Salam et al., 2022). In our case, early coffee revenues helped mitigate macadamia’s delayed income stream, confirming the value of revenue diversification. However, this advantage is highly dependent on access to reliable markets and processing infrastructure, which are often lacking in rural Zambia.

4.2 Labour dynamics and employment implications

Intercropping led to increased labour demand across seasons, especially during periods of overlapping coffee harvest and macadamia maintenance, consistent with findings that intercropping systems can require higher labour inputs throughout the growing season than sole crops in diversified smallholder farming contexts (Thierfelder et al., 2024).

While this labour demand offers employment opportunities in regions with high rural underemployment, its sustainability is questionable. Glover (2020) argues that high labour requirements can be a disincentive in smallholder systems with limited mechanization and training. Similarly, observed that without clear labour scheduling and management capacity, intercropping systems may exacerbate organizational inefficiencies.

Therefore, realizing the employment potential of such systems will require parallel investments in labour training, cooperative work arrangements, and possibly community mechanization hubs.

4.3 Socioeconomic considerations

The intercropped system offers clear potential for improving long-term rural livelihoods. However, significant socioeconomic barriers to adoption remain. High initial investment requirements, lack of access to credit, and limited extension support are major obstacles.

In addition, traditional risk-averse behaviours and preferences for short-cycle crops discourage investment in systems with delayed returns. Glover et al. (2020) emphasize that such transitions require not only technical training but also behavioural change interventions and strong cooperative networks.

The perception of macadamia and coffee as export-oriented “elite” crops further compounds these barriers. Creating inclusive value chains and promoting local processing could improve acceptability and ensure broader participation.

4.4 Trade-offs and limitations

While the benefits of intercropping are substantial, our findings highlight several compromises:

- Labour coordination becomes more complex, especially during overlapping management.
- Pest and disease management requires broader expertise.
- The data stem from a 1.6 ha trial area and only a 5-year period, which limits scalability and long-term conclusions.

Moreover, profitability projections are sensitive to market fluctuations, climate variability, and farmer behaviour—factors that often fall outside the scope of short-term (Zida et al., 2021).

5. CONCLUSIONS

In addition to aligning with broader agroecological and climate adaptation goals, intercropping macadamia and coffee can enhance financial returns, ecological resilience, and employment generation. However, success is conditional on strong support systems: farmer training, market integration, financial services and possibilities, and policy alignment. Future research should prioritize long-term trials and explore diversification under varying socioeconomic and ecological conditions.

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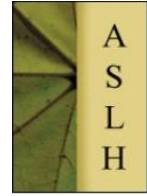
extend our special thanks to the late Wiscott Chanda, whose support and dedication were deeply appreciated. We are particularly grateful to Emanuel Chisha for his exceptional assistance in providing near-daily data, which proved instrumental to the success of this work.

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Reframing Material Perception: A Psychometric Model of Premium Wood Furniture Consumption



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ABSTRACT

Wood is an economically, culturally, and ecologically significant material that manifests through complex perceptual and psychological responses in the context of premium furniture consumption. This study introduces the Composite Material Resonance Index (CMRI). The index derives from an empirically validated impact model grounded in neuroaesthetics and identity psychology. It integrates sensory, emotional, value-based, and identity-related experiences associated with wood-based furniture consumption within a unified measurement framework. A quantitative study conducted on an international sample of 145 respondents operationalizes attachment to wood material across 11 phases and nine indices, from initial perception to integration with self-identity. The results indicate that visual proportionality, perceived naturalness, and identity resonance exert a significant influence on consumer identification, emotional engagement, and purchase intention. The CMRI serves as a strategic decision-making tool for product development, brand communication, and forest-based sustainability innovations.

TANULMÁNY INFÓ

Kulcsszavak:

Faalapú termékstratégia
Anyagészlelés
Döntéstámogatás

KIVONAT

Az anyagészlelés újraértelmezése: a prémium fa bútorfogyasztás pszichometriai modellje. A fa mint anyag gazdasági, kulturális és ökológiai jelentőséget hordoz, amely komplex érzékelési és pszichológiai reakciókban nyilvánul meg a prémium bútorok fogyasztásakor. Ez a tanulmány bemutatja a neuroesztétikai és identitáspszichológiai alapokra épülő, empirikusan validált hatásmodellből származtatott Composite Material Resonance Indexet (CMRI), amely a faalapú bútorfogyasztás során megjelenő szenzoros, érzelmi, értékalapú és identitásrezonanciához kapcsolódó tapasztalatokat egységes mérési keretben integrálja. Egy 145 válaszadóból álló nemzetközi mintán végzett kvantitatív tanulmány a faanyaghoz való kötődést tizenegy fázisban és kilenc indexben ülteti át a gyakorlatba, a kezdeti észleléstől az önazonossággal való integrációig. Az eredmények azt mutatják, hogy a vizuális arányosság, az észlelt természetesség és az identitásrezonancia jelentős hatással van a fogyasztói azonosulásra, az érzelmi elkötelezettségre és a vásárlási szándéokra. A kommunikált és tapasztalt minőség közötti szinkronitás, valamint az anyag önreprezentációs funkcióinak erősítése révén a modell és a CMRI alkalmazható stratégiai döntéstámogató eszközként a termékfejlesztés, a márkakommunikáció és az erdőalapú fenntarthatóság innovációk területén.

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1 INTRODUCTION

Wood has become a powerful symbolic (Csikszentmihalyi – Rochberg-Halton, 1981; Dormer, 1997) and identity-shaping medium (Hosey, 2012; Manna, 2025) in the premium furniture industry in the past decade. Consumers are increasingly seeking natural and sustainable materials that evoke emotional attachment and deliver an aesthetic experience (Al Darwish, 2023). The sensory complexity of wood—its touch, scent, and visual character—triggers psychological and cultural activation that transcends its physical properties (Thakral et al., 2012; Dharsono 2025).

Wood functions as a mediator of aesthetic coherence, craftsmanship, and identity resonance in the premium furniture segment. Beyond durability and design dimensions, customers search for qualities that align with their values and self-image (Karana et al., 2015; Pedgley et al., 2020). Perceptual psychology and neuroaesthetics tools offer a novel approach for interpreting this complex system of relationships (Earnshaw, 2017). Such tools enable the measurement and structured interpretation of emotional, identity-based, and aesthetic responses—allowing for the development of models that extend beyond simple market preferences and identify deeper patterns (Oliver, 2010; Manu et al., 2022). The validated Perceptual Impact Model (Reményi, 2025) was built on such principles. Through its nine psychometric indicators, the model empirically demonstrated that aesthetic cohesion levels significantly influence the allure of premium wooden furniture (Sztuka et al., 2025). And craftsmanship. The model also reveals how these align with personal values. Indices such as the Emotional Sensory Load Index (ESLI), Perceived Craft Distinctiveness Index (PCDI), Aesthetic Cognitive Activation Index (ACAI), and Identity Resonance Quotient (IRQ) were developed as parts of the model and interpret customer experience in a structured, quantitative manner.

The nine individual indicators showed significant intercorrelations and collectively described the affective and motivational responses to premium wooden furniture. In light of this, a synthesizing indicator that forms a new, complex metric by combining the previous indices was introduced. The new indicator, the Composite Material Resonance Index (CMRI), aims to create a summary value from the intersection of psychological and sensory responses, representing resonance with the material as a unified experience.

This step opens up new opportunities for design, brand communication, and product positioning. The CMRI places aesthetic, moral, and identity-related interpretations of wood within a broader framework, thus supporting conscious and differentiated product development. This study presents the theoretical foundations, computational logic, and application of CMRI using the previous dataset, examining its relationship with consumer behavior and decision-making mechanisms.

2 MATERIALS AND METHODS

2.1 Research context

The research was conducted within a well-defined perceptual and experiential investigation space, interpreted through the perspective of a targeted user group—individuals who consciously consume and interpret premium wood-based furniture. Utilizing online data collection tools, the study focused on globally emerging patterns of wood perception within a socially and culturally embedded, intellectually engaged environment. The sample predominantly consisted of highly educated, urban individuals with an openness to cultural goods and a demonstrated interest in premium product categories. Most participants exhibited a high degree of aesthetic sensitivity and were receptive to themes related to natural materials,

sustainability, and value-driven decision-making, making them especially relevant for exploring the neuroaesthetic and identity-related aspects of wood perception.

This perceptual research zone was delineated based on participant material preferences, decision-making rationales, and psychological response patterns related to wood. Mapping this interpretive domain was essential to develop and validate the eleven distinct indices that capture the various dimensions of wood perception—from sensory detection and moral significance to purchase intention. This conceptual approach also set the groundwork for the present study's new research objective: integrating these individual dimensions into a composite, synthesizing indicator.

2.2 Data collection

The research was conducted using a quantitative methodology, through an online questionnaire completed by 145 participants as part of a doctoral-level study. Respondents were selected from an international professional network comprising approximately 5,566 individuals, developed over the years through academic and research collaborations. While access to the network was random, the sampling at the entry level was deliberately targeted: only individuals who owned premium wood-based furniture were included, thereby ensuring strong thematic relevance for the study. As a result of this targeted filtering, the sample primarily consisted of highly educated, urban individuals who demonstrated openness toward design-oriented products, sustainable consumption, and objects of high aesthetic value. An additional inclusion criterion required that participants own at least one high-end, solid wood furniture item purchased within the past five years. This screening mechanism ensured that the study's target group exhibited a heightened affinity for natural materials and was well-suited for exploring neuroaesthetic and identity-related aspects of wood perception.

The responses enabled the statistical construction and empirical validation of a psychometric model consisting of eleven distinct indicators. These indicators captured complex dimensions, including multisensory engagement, aesthetic coherence, craftsmanship perception, material attachment, alignment with sustainability values, and symbolic self-identification. The resulting dataset offered sufficient statistical power ($n = 145$, $\alpha = 0.05$, CI 95%) to reliably investigate affective, cognitive, and identity-based perceptions related to material experience. The model's refined structure facilitated the detection of emotional resonance and decision-making patterns within the context of premium consumption.

The online questionnaire was distributed via the Google Forms platform, allowing for efficient international outreach. Responses were collected using a five-point Likert scale (1 = not at all characteristic, 5 = fully characteristic), with whole-number values only. Each item aligned closely with the model's core dimensions, including sensory perception, identity resonance, durability perception, moral satisfaction, aesthetic experience, and purchase intensity. The goal of the data collection process was to generate a dataset with sufficient dispersion and interpretable patterns, enabling the statistical validation of the neuroperceptual model. Participant anonymity was ensured, and all data handling procedures strictly adhered to established ethical research standards.

2.3 The applied model

The initial framework was provided by the previously developed and validated Perceptual Impact Model (see *Figure 1*), which conceptualized the emotional, aesthetic, and identity-based dimensions of wood furniture perception as a phased process. The model is structured into temporally sequenced phases, illustrating how perceptions concerning a product's provenance, material quality, and sensory attributes contribute to emotional activation and the emergence of consumer desire. At its core, the model identifies six foundational value domains—

sustainability, material and quality, durability, craftsmanship, art and design, and heritage—each functioning as a multidimensional perceptual field that facilitates both affective responses and identity construction. *Table 1* systematically outlines these phases, along with their perceptual constituents and guiding diagnostic questions.

The initial stage involves the cognitive processing of sensory stimuli, where emotional responses—such as the scent, tactility, and visual rhythm of wood—become intertwined with cultural associations and autobiographical memory (Bond et al., 2024). Empirical findings underscore the influence of multisensory input. Notably, the influence of tactile and visual features on perceptions of material authenticity and brand image (Danielsson, 2025; Wang et al., 2025). In the second phase, the model introduces the concept of perceived quality, shaped by the alignment (or misalignment) between anticipated attributes and actual product experience. This interpretation is congruent with predictive coding theory, which posits that expectations modulate sensory interpretation and that deviations from expectation directly influence perceived credibility and authenticity (Ji – Lin, 2022). At the third phase, product identification emerges, wherein the premium wooden object becomes assimilated into the individual’s self-concept, reflecting personal values, aesthetic preferences, and socio-cultural positioning (Kim – Heo, 2021). The inherent naturalness and visual individuality of wood facilitate processes of self-extension, echoing psychodynamic models of emotional attachment. This culminates in the final phase: emotional engagement, which is elicited through repeated, positive valence interactions, particularly when enhanced by artisanal craftsmanship, rich sensory stimulation, and authentic narrative frameworks.



Figure 1. The perceptual impact model. The model illustrates sequential perceptual and evaluative layers, progressing from sensory experience through identity-related appraisal to the emergence of purchase desire.

These mechanisms engage neural reward pathways (Ko, 2017; Spence, 2020), often reinforced by implicit memory traces related to material durability and the tactile familiarity of previous experiences (Harju – Lähtinen, 2021). Within this framework, emotional loyalty extends beyond conventional brand attachment, representing a deeper, identity-oriented form of commitment, particularly among consumers whose values align with slow design principles and sustainable living practices (Al Darwish, 2023).

The model ultimately converges in the emergence of purchase desire, conceptualized as the integrative outcome of preceding perceptual and affective stages. The intensity of decision-making is notably amplified when aesthetic, ethical, and sensory resonance is established between the consumer and the product (Kim – Heo, 2021). As a result, the act of purchasing transcends mere economic exchange and evolves into an expression of aesthetic identity, cultural belonging, and multisensory value integration.

Table 1. Perceptual impact model – overview table (Reményi, 2025)

Components and layers	Significance	Source	Key questions
Heritage	The symbolic meanings of wood tied to collective cultural memory evoke identity-level evaluations.	Bond et al. (2024)	Through which neurosocial mechanisms does wood trigger associations with cultural heritage, and how does this affect long-term value perception?
Art and Design	The aesthetic symmetry of design elicits visual dopamine responses and aids memory encoding.	Spence (2020)	To what extent do texture and formal proportions of wooden furniture influence aesthetic experience?
Craftsman-ship	Enhances the sense of authenticity, strengthening affective attachment to the object.	Ko (2017)	What role do traces of manual work play in forming emotional bonds and sensory evaluations?
Durability	Durability perception relies on implicit memory of prior material experiences.	Harju - Lähtinen (2021)	How do tactile and visual impressions influence perceptions of material durability?
Material and Quality	Wood’s texture and colour activate instant quality expectations via multisensory input.	Daniels-son (2025)	How rapidly is wood’s perceived quality detected in a multisensory context?
Sustainability Values	The material conveys ethical and environmental values that contribute to identity formation.	Al Darwish (2023)	How are sustainability associations integrated into mechanisms of moral judgement?
Sensory Experience	Touch, sight, and smell generate affective responses and preferences.	Wang et al. (2025)	How do wood’s sensory stimuli affect perceptions of authenticity and aesthetic character?
Perceived Quality	The alignment between marketing claims and real use shapes perceptions of quality authenticity.	Ji – Lin (2022)	How is the communicated quality integrated with the experienced quality?
Product Identification	The furniture item, as self-extension, becomes a reflection of self-image and aesthetic values.	Kim – Heo (2021)	How do naturalness and originality contribute to self-representation?
Engagement	Repeated positive experiences foster loyalty and reinforcement.	Ko (2017)	How does emotional attachment affect memory traces related to wood?
Purchase Desire	Emerges through cumulative perceptual effects when product values resonate with the individual.	Kim – Heo (2021)	What factors trigger motivational response patterns leading to purchase decisions?

2.4 Statistical methods and applied indices

The statistical procedures applied in this research aimed to map the psychological and emotional structures associated with wood-based furniture by analyzing complex response patterns. To this end, nine quantitative indices were developed, uniquely integrating perceptual, affective, identity-related, and motivational responses. The calculation of these indices is based on simplified, transparent formulas, making them applicable in both academic and industrial contexts. The indices are paired with 11 thematic questions. *Table 2* summarizes their relationships and the respective formulas. Each question corresponds to a specific psychological or neuroaesthetic dimension, which the associated index is designed to capture in a formulaic manner.

Table 2. Thematic questions and assigned indices

#	Thematic Question	Assigned Index	Calculation Formula	Explanation	Literature
1.	Heritage	1. Material Identity Alignment Index	$MIAI = -\sum(P_i \cdot \ln(A_i))$	P_i : proportion of alignment with personal values; A_i : identity relevance of the given material	Kim –Heo (2021)
2.	Art and Design	5. Aesthetic Cognitive Activation Index	$ACAI = \frac{\sum(p_i \cdot \ln(p_i))}{\ln(n)}$	p_i : frequency of design element perception; n : number of design elements	Spence (2020), De Luca – Termini (1972)
3.	Craftsmanship	2. Perceived Craft Distinctiveness Index	$PCDI = \frac{\sum n_i(n_i - 1)}{N(N - 1)}$	n_i : number perceiving craft details; N : total respondents	Stern – Schwarzbauer (2013)
4.	Durability	9. Material Attachment Stability Index	$MASI = (A_i / T_i) \cdot \ln(R)$	A_i : current attachment; T_i : time-based stability; R : brand recognition	Ko (2017)
5.	Material and Quality	7. Perceptual Integrity Synchronization Index	$PISI = \frac{\sum(C_i - T_i)^2}{n}$	C_i : communicated quality; T_i : experienced quality	Ji – Lin (2022)
6.	Sustainability Values	4. Sustainability-Value Integration Index	$SVII = \frac{\sum(S_i \cdot \ln(S_i))}{\ln(T)}$	S_i : sustainability factor value; T : number of value preferences	Al Darwish (2023)
7.	Sensory Experience	3. Emotional Sensory Load Index	$ESLI = (s - 1) / \ln(E)$	s : number of perceived sensory attributes; E : variance of emotional responses	Wang et al. (2025)
8.	Perceived Quality Product	7. Perceptual Integrity Synchronization Index	$PISI = \frac{\sum(C_i - T_i)^2}{n}$	C_i : communicated quality; T_i : experienced quality	Ji – Lin (2022)
9.	Identity Alignment	8. Identity Resonance Quotient	$IRQ = \frac{\sum(V_i \cdot \ln(V_i))}{\ln(s)}$	V_i : identity dimension scores; s : number of identity factors	Kim – Heo (2021)
10.	Commitment	9. Material Attachment Stability Index	$MASI = (A_i / T_i) \cdot \ln(R)$	A_i : current attachment; T_i : time-based stability; R : brand recognition	Ko (2017)
11.	Purchase Desire	10. Volitional Purchase Intensity Index	$VPII = \sum(P_i \cdot M_i)$	P_i : perceptual factor; M_i : motivational weight	Kim – Heo (2021), Gibson (1979)

The current study aims to integrate the relationships among these distinct dimensions into a comprehensive metric, the Composite Material Resonance Index (CMRI). The CMRI serves

as a synthesizing indicator, capturing emotional, aesthetic, and identity-based resonance with wood materials in a single, aggregated value. Its scientific foundation draws upon system-level resonance theories, integrated models of identity psychology, and frameworks of affective and cognitive appraisal (Kirmani, 2009; Chatterjee – Vartanian, 2016; Earnshaw, 2017).

3 RESULTS AND DISCUSSION

The central objective of the present study was to develop a synthesizing index—the Composite Material Resonance Index (CMRI)—designed to capture the multidimensional combination of experiences and psychological responses perceived during wood-based furniture consumption. The purpose of the CMRI is to integrate the key indices developed in the previous research, primarily Identity Resonance (IRQ), Aesthetic Cognitive Activation (ACAI), Emotional Sensory Load Index (ESLI), Perceived Quality and Authenticity (PISI), and Sustainability Value Integration Index (SVII)—into a single composite value. The following weighted formula calculated the CMRI:

$$\text{CMRI} = (\text{IRQ} \times 0.25) + (\text{ACAI} \times 0.20) + (|\text{ESLI}| \times 0.15) + (\text{SVII} \times 0.20) + ((1 - \text{PISI}) \times 0.20)$$

The absolute value of ESLI is used in the calculation because it indicates a more synchronized experiential state. The inverse form of PISI (1 – PISI) is applied to express a higher level of congruence between experienced and communicated quality. This equation considers:

1. the psychological depth of the alignment between self-image and material (IRQ),
2. the intensity of aesthetic engagement (ACAI),
3. the level of sensory–emotional coherence (ESLI),
4. the degree of ethical and value-based decision-making (SVII), and
5. the presence of perceptual coherence (PISI).

Following standardization, CMRI values were transformed to a 0–100 scale to ensure comparability across sub-indices with different weightings. The weights applied in the CMRI calculation equation were determined on normative and conceptual grounds, considering both theoretical validity and practical applicability. The weighting scheme is based on a structured set of considerations intended to proportionally reflect the complex psychological dimensions of wood-based material experience. The highest weight (0.25) was assigned to Identity Resonance (IRQ), as prior research has demonstrated that the degree of identification with material plays a central role in emotional attachment to premium furniture and in purchase intention (Grayson – Martinec, 2004; Kirmani, 2009). Aesthetic Cognitive Activation (ACAI) and Sustainability Value Integration (SVII) were each assigned a weight of 0.20, reflecting the high relevance of both aesthetic experience and ethical conviction in the perception of wood-based products—particularly in relation to neuroaesthetic preferences and sustainability-sensitive decision-making (Earnshaw, 2017; Al Darwish, 2023). The Emotional Sensory Load Index (ESLI) received a lower weighting of 0.15. Although it generates significant affective responses, its influence is often implicit and less consciously articulated in consumer decision-making. Finally, the PISI index, measuring the synchronicity between perceived and communicated quality and applied in inverse form, was also assigned a weight of 0.20, reflecting the decisive importance of perceptual integrity (Pine – Gilmore, 2007; Clark, 2013) in judgments of authenticity in premium products. The sum of the weights is exactly 1.00, ensuring the model’s scalability and interpretability while preserving the relative contribution of each dimension. Thus, the development of the weighting system did not aim at automatic,

data-driven weight generation, but rather at a consciously structured value-based decision, rendering the CMRI suitable for both academic research and industry application. However, future research could establish empirically calibrated weighting systems—using principal component analysis, regression modeling, or structural equation modeling—to further enhance the predictive and diagnostic validity of the CMRI.

3.1 Distribution and descriptive statistics of the CMRI

The CMRI values calculated for the sample of 145 respondents show a mean of 68.12 (SD = 9.41), indicating a moderate-to-high level of material resonance within the premium consumer segment. The values ranged from 40 to 95, suggesting substantial variability among participants in their affective and cognitive relationships with wood as a material.

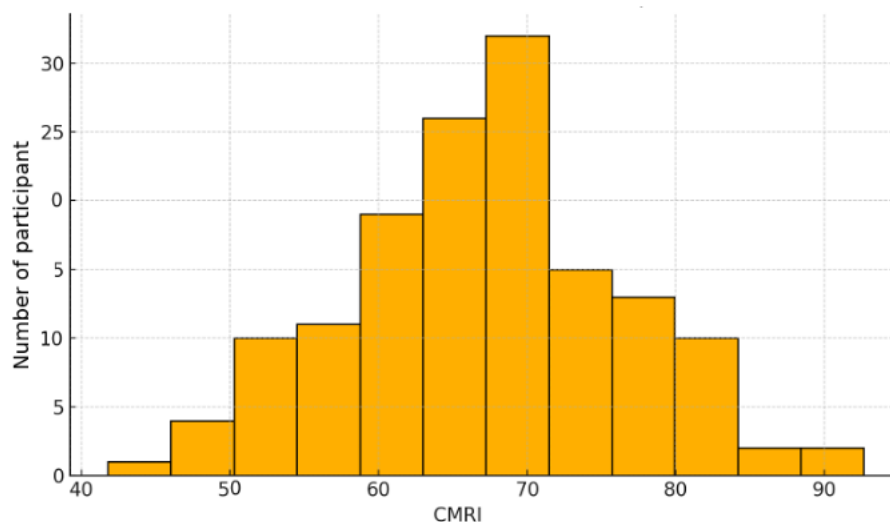


Figure 2. Distribution of CMRI values ($n = 145$)

Figure 2 illustrates the distribution of CMRI values across the full sample. The curve is right-skewed (positively skewed), indicating that the majority of respondents exhibited above-average identification with and resonance toward wood material. Three segments can be distinguished based on the distribution:

- Low CMRI (≤ 60) – 24 respondents (16.6%)
- Medium CMRI (61–75) – 79 respondents (54.5%)
- High CMRI (≥ 76) – 42 respondents (28.9%)

This segmentation enables further analysis of behavioral and perceptual patterns, particularly through comparisons between low and high CMRI groups. The mean values of the weighted sub-indices for each CMRI segment are presented in Table 3. *Note:* The ACAI was measured on a negative logarithmic scale; therefore, it was integrated into the CMRI only after normalization.

The following section explores the correlations between the CMRI, purchase intention (VPPI), and long-term material attachment (MASI). In addition, behavioral patterns are compared by examining groups with high and low CMRI values, with particular attention to differences in affective engagement, decision intensity, and attitudes toward wood as a material.

Table 3. Weight distribution and contribution of CMRI dimensions

Component	Mean value	Standard weight	Contribution to CMRI (%)
Identity Resonance Quotient (IRQ)	16.99	0.25	25.0%
Aesthetic Cognitive Activation Index	-0.79	0.20	18.5%
Emotional Sensory Load Index (abs.)	5.91	0.15	13.0%
Sustainability-Value Integration Index	18.38	0.20	22.3%
Perceptual Integrity Synchronization	0.31	0.20 (inverted)	21.2%

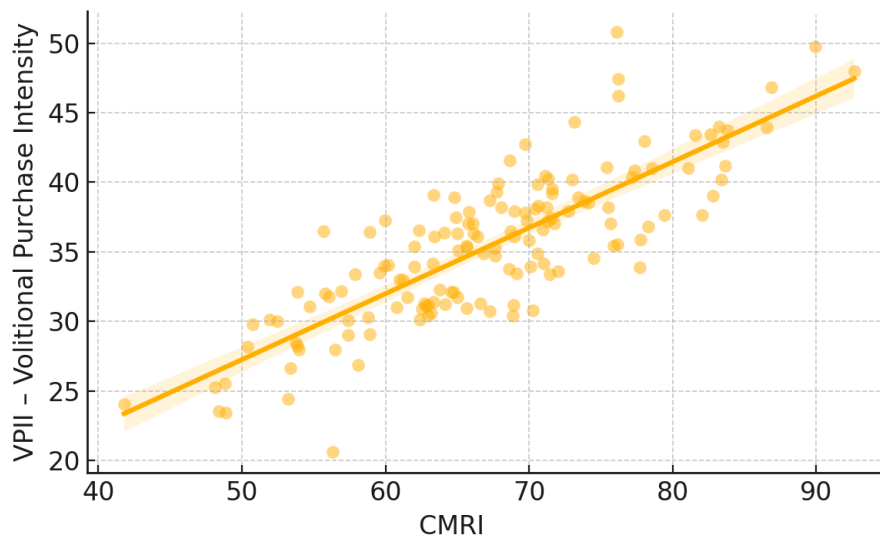


Figure 3. Correlation between CMRI and VPPI (Purchase Intensity)

Figure 3 illustrates that the correlation between the CMRI and the Volitional Purchase Intensity Index (VPPI) is $r = 0.81$, indicating a significant positive relationship. In other words, the higher the CMRI, the greater the likelihood that premium wood-based products elicit genuine commitment, not only at an aesthetic but also at the decision-making level. This finding reinforces the results of earlier models suggesting that emotional and identity-based congruence plays a key role in purchase motivation (Kirmani, 2009; Chatterjee – Vartanian, 2016). The empirical confirmation of the strong correlation between CMRI and VPPI demonstrates that material perception factors exert predictive influence not only by generating emotional responses but also by shaping concrete behavioral intentions. This relationship enables designers and brand strategists to exert a direct impact on consumer decision-making through targeted interventions aimed at product perception. From a scientific perspective, this result contributes to extending the modeling of purchase intention beyond classical rational–economic frameworks toward a multidimensional, identity– and experience–based interpretation.

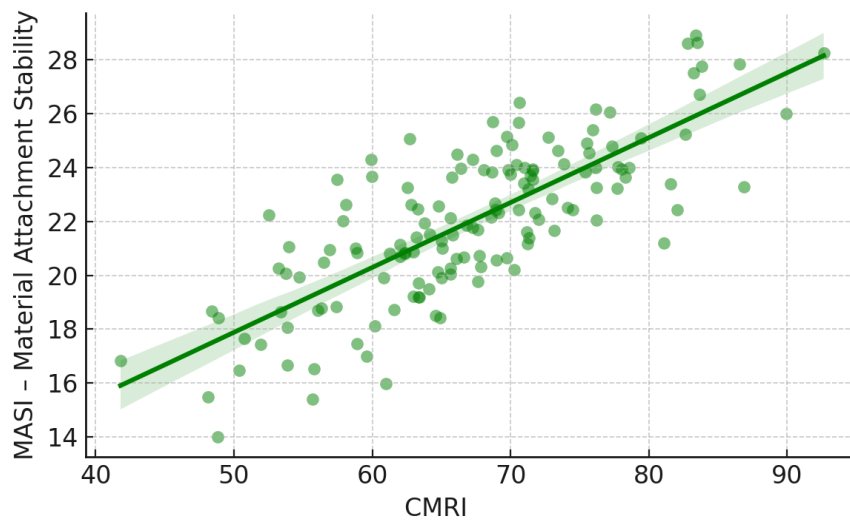


Figure 4. Relationship between CMRI and Material Attachment (MASI)

The correlation between the CMRI and the Material Attachment Stability Index (MASI) is $r = 0.67$, indicating a moderately strong relationship. This suggests that the CMRI effectively models longer-term material relationships as well. Wood as a material conveys temporal stability and memory-based attachment, which are nurtured by implicit memories and tactile impressions (Ko, 2017; Harju – Lähtinen, 2021). The relationship between CMRI and MASI highlights that perceptual and identity-related factors influence immediate decision-making and enduring material loyalty. In the evaluation of wood-based products, immediate aesthetic experience is fundamental; however, past experiences and affective representations consolidated over time also play decisive roles.

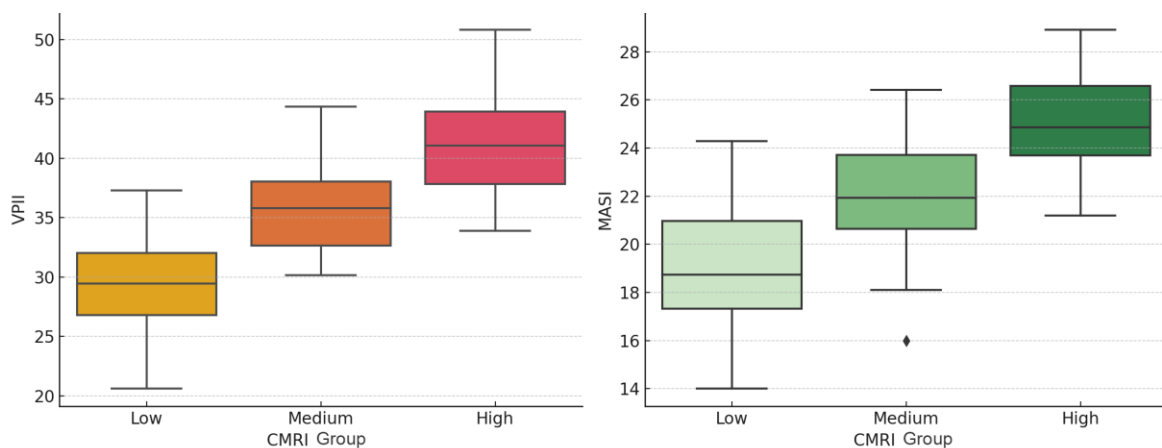


Figure 5. CMRI segments and consumer profiles: comparison of VPII and MASI across CMRI groups

The diagrams above show that members of the high-CMRI group achieve significantly higher scores on both the Volitional Purchase Intensity Index (VPII) and the Material Attachment Stability Index (MASI). Group-level analysis shows that the *High CMRI group* has an average of 41.55 VPII points and 25.15 MASI points, whereas the *Low CMRI group* reaches only 29.36 VPII points and 19.19 MASI points. These differences statistically support the applicability of the CMRI as a predictive tool. The differentiation presented in *Table 4* further

confirms the practical relevance of the CMRI, providing designers, brand strategists, and sales professionals with valuable insights into the extent to which wood as a material resonates with target groups at different levels: emotional, sensory, and identity-based.

Table 4. Differences in behavioral profiles

CMRI Group	Characteristics
Low (≤ 60)	A predominantly functional approach; purchasing decisions are primarily guided by price-value considerations. Lower emotional involvement and a limited connection to identity.
Medium (61–74)	A balanced orientation; certain aesthetic and value-based aspects are present. Moderate attachment and medium brand loyalty.
High (≥ 75)	Decision-making is characterized by aesthetic, symbolic, and identity-based considerations. High loyalty and a strong preference for natural, distinctive materials. Purchasing is perceived as a cultural and self-expressive act.

4 CONCLUSIONS

The introduction of the Composite Material Resonance Index (CMRI) represents a new milestone in the field of material perception and identity-based consumer modeling. The CMRI is an integrated and synthesized aggregation of previously developed psychometric indices (ESLI, IRQ, ACAI, PISI), capable of capturing affective, cognitive, and identity-forming mechanisms related to premium wood furniture in a single, unified metric. As such, it constitutes both a theoretical innovation and a significant practical tool for the wood furniture industry, particularly at the design strategy, brand communication, and product positioning levels.

The CMRI qualitatively interprets material perception and material-identity relationships, which were once considered largely subjective. The index expresses the interweaving of sensory experiences, aesthetic responses, sustainability-related attitudes, and self-representational factors. In doing so, it opens new avenues for the interdisciplinary integration of neuroaesthetics, identity psychology, and materials research (Karana et al., 2015; Plassmann et al., 2015; Chatterjee – Vartanian, 2016;). While the index may be applied to the study of other material types, it proves particularly robust in the case of wood, where material-specific emotional meaning is especially pronounced (Ko, 2017).

The practical implications of the CMRI can serve as a strategic compass for the furniture industry. As a measurement instrument, the CMRI can also function as a strategic decision-support system. Its relevance is particularly pronounced in three areas. First, in design communication. The visual and tactile attributes of wood should not be treated merely as secondary aesthetic elements but as active media of identity formation. Consumers exhibiting high CMRI values perceive these attributes not as superficial decorative details but as deeply personal, identity-supporting experiences. This insight raises a key strategic question for designers: How can material properties be transformed into symbolic dimensions? Closely related to this is the role of sensory emphasis and experiential retail design. The research indicates that users with high CMRI scores show heightened sensitivity to multisensory cues, particularly tactile textures and embodied experiences. Consequently, showroom design, furniture arrangement, and surface treatment techniques should prioritize raw wood effects, oiled or untreated structures, the use of natural light, and the avoidance of visual

overstimulation. Such atmospheric design not only provides sensory comfort but also enhances perceived authenticity and material congruence.

Finally, the symbolic positioning of wood possesses strategic significance. Solid wood is aesthetically appealing and bears deep cultural and emotional values, such as durability, rootedness, ecological lifestyles, and intergenerational usability (Schifferstein – Zwartkruis-Pelgrim, 2008). The identity resonance reflected in the CMRI engages directly with these values and enables brands to establish deeper, more affective relationships with their audiences through heritage-based storytelling techniques. The conscious communication of such symbolic meanings strengthens market positioning and contributes to the development of consumer loyalty and brand identity.

Several industry examples illustrate how experience-based and identity-oriented business models aligned with the foundations of the CMRI can be successfully applied in the premium wood furniture market. The Danish brand Carl Hansen & Søn, for instance, combines classic design with the symbolic power of craftsmanship: its product descriptions emphasize not only formal characteristics but also the story of the material, the origin of the wood, and traces of manual craftsmanship, thereby directly activating CMRI dimensions such as identity resonance, perceptual integrity, and emotional sensory experience. Similarly, the Italian brand Riva1920 works exclusively with solid wood, often using reclaimed historical materials—such as lagoon beams or centuries-old oak barrels—so that each piece carries a cultural narrative. This approach opens pathways toward sustainability and ethical dimensions (SVII) while simultaneously generating strong emotional attachment, particularly among consumers with high CMRI values.

In the context of furniture manufacturing companies, the relationship with material could be further deepened through a “forest to furniture” type of program, enabling consumers to become acquainted with the specific forest from which the furniture’s raw material originates. Such an approach could create localized material identity and cultural symbiosis, integrating sensory and identity-based experiences.

The study relied on quantitative psychometric instruments based on self-report scales. Although respondents were drawn from a thematically relevant sample, the research is not representative, and cultural embeddedness may have significantly influenced the results. Furthermore, the cross-sectional nature of the study did not allow for tracking temporal changes in attitudes related to perceived material quality and identity experience. The measurement model primarily focused on consciously articulated perceptions; therefore, non-conscious, implicit sensory and emotional responses, which may also be relevant in the context of premium materials, were only partially captured.

Future research may further enhance the theoretical and empirical applicability of the CMRI in several directions. Of particular importance is cross-cultural validation, which would allow for the examination of how symbolic meanings, sensory preferences, and identity constructions associated with material use differ across cultural and geographical contexts. In parallel, a deeper exploration of the model’s context-dependent functioning is warranted. Specifically, research should investigate how material resonance varies under identical material use across different design concepts, narrative framings, and brand communication strategies. Of particular relevance is the analysis of how communication surrounding material origin, processing, and temporality influences individual CMRI dimensions and contributes to strengthened perceptions of quality, emotional engagement, and identity formation in the premium segment.

An additional area of potential research lies in examining the impact of digital product experiences, particularly how virtual showrooms, augmented reality tools, or online configurators influence material perception and the evolution of the material resonance index in the absence of, or before, physical experience.

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Comparison of Noise-Filtering Ability of Vegetation – A Literature Review



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ABSTRACT

Vegetation belts may offer an effective and economical solution for reducing noise pollution as an environmental impact where sufficiently large areas are available. However, the complexity of the attenuation process makes choosing the right plant species or variety a complicated task. That studies have employed different methods to examine the noise-reducing properties of individual hedges and shrubby groups of trees only complicates matters further. The present study interprets and summarises the achieved results via an analysis of the relevant literature using statistical methods. We focused on the following areas: (1) commonness and value range to compare the general data of the selected studies, (2) location types and the measurement layouts, (3) the parameters used to describe the vegetation strips, and (4) the parameters used for noise measurement and attenuation calculation. In addition to the diversity of the examined environment and vegetation in the studies, the description of the implementation and physical characteristics of the measurements was, in many cases, incomplete in several aspects. At the same time, the differences between the employed parameters and their evaluation resulted in partially comparable noise attenuation data, thereby increasing the inhomogeneity in the literature.

TANULMÁNY INFÓ

Kulcsszavak:

Növényzsávok
Zajcsillapítás
Szakirodalmi áttekintés
Statisztikai módszerek

KIVONAT

Különböző növényzsávok zajvédelmének összehasonlítása – szakirodalmi áttekintés. A zajszennyezés, mint környezeti ártalom csökkentésére megfelelő méretű területeknél a növényzsávok hatékony és gazdaságos megoldást kínálhatnak. Figyelembe véve a csillapítási folyamat összetettségét, a megfelelő típus és növényfaj kiválasztása azonban bonyolult feladatot jelent. Ezt nehezíti továbbá, hogy a különböző tanulmányok eltérő módszerekkel vizsgálták az egyes sövények és bokros facsoportok zajcsillapító tulajdonságait is. Jelen cikk célja ezért az volt, hogy a vonatkozó szakirodalmak áttekintésével és elemzésével segítséget nyújtson az elért eredmények értelmezésében és összefoglalásában. Ennek érdekében statisztikai módszerekkel összehasonlításra kerültek a kiválasztott tanulmányok általános adatai (1), a helyszínek típusai és a mérési elrendezés (2), a növényzsávok leírására alkalmazott paraméterek (3) valamint a zajméréshez és a csillapítás kiszámításához felhasznált paraméterek (4) különösen gyakoriság és érték-terjedelem szempontjából. Összességében a vizsgált környezet és növényzet változatossága mellett a mérések kivitelezésének és fizikai jellemzőinek leírása sok esetben több szempontból hiányos volt. Ezzel párhuzamosan a felhasznált paraméterek és az azok kiértékelése közötti különbségek egymással részlegesen összehasonlítható zajcsillapítási adatokat eredményeztek, növelve ezzel a szakirodalmi inhomogenitást.

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1 INTRODUCTION

Noise and unwanted sound can be a disturbing environmental factor in urban and rural areas; however, reducing the effects by increasing the distance between the noise source and the affected area is often impossible. Erecting solid barriers to block the noise is not always feasible (Dobson – Ryan, 2000). Although vegetation can reduce noise over a wide frequency range, the potential of forests or narrow tree belts alongside surface transport corridors for reducing noise is often dismissed, particularly in studies involving conflicting experimental evidence (Attenborough – Taherzadeh, 2016). Nevertheless, planting vegetation of appropriate density can offer a cost-effective solution in high traffic areas (e.g. near motorways) where the construction of conventional noise abatement methodologies, primarily noise barrier walls, would be economically unfeasible (Harris – Cohn, 1985). Moreover, the ubiquitous green elements in many European cities can substantially mitigate air pollution through carbon dioxide sequestration during photosynthetic activity, depending on the leaf surface area (Gratani – Varone, 2013), while also reducing individual subjective noise annoyance by visually obscuring the noise sources (Bangjun et al., 2003).

The noise attenuation of vegetation depends on belt spacing, height, and depth as well as foliage density; nonetheless, meteorological conditions such as temperature, humidity, and wind make precisely quantifying such parameters difficult (Kerby, 1974). Nonlinear attenuation is mainly due to multiple scattering of sound energy in the canopy, which is affected by leaf density, leaf area per unit volume of the canopy, leaf width, and frequency (Aylor, 1972a). Leaf orientation and amount (on the order of two·10⁵ pieces in a mature tree) in the sound field (Martens – Michelsen, 1981) also contributes to sound scattering, as does the behaviour of the branches and the trunk as oscillators, adding to absorption due to transverse vibrations at lower frequencies (Embleton 1963).

The noise attenuation of vegetation strips is a complex process. In addition to extensive field measurements, noise prediction methods were also refined for sound propagation, vegetative barriers, and interactions with complex physical barriers (Borthwick et al., 1977). For example, in studies on traffic noise propagation, 3D finite-difference time-domain (FDTD) calculations proved that limited-depth (15 m) vegetation belts—tree spacing of less than 3 m and stem diameters of more than 0.11 m—can achieve significant noise reduction, despite the sound attenuation and reflection properties of the ground surface (Van Renterghem et al. 2012). Moreover, tall trees and dense underbrush with a planting depth of at least 30 m can provide reliable attenuation of 5–8 dB, with a line of sight of 15 m (i.e. visibility depth), depending on traffic density (Reethof, 1973). According to the Cadna/A simulation software results, the most effective green belt width range can be placed between 30–50 m, and the greatest noise attenuation intensity can be observed in vegetation strips 30–90 m in length (Su et al., 2023). As for tree height, among the factor indices created from LIDAR point cloud data, which provide the basis for the structural optimisation of urban green areas, 5 m was the most significant positive correlation with the attenuation, which was the percentage of point cloud grid (parameter defined by the authors). However, the coverage degree or the leaf area index as a function of the absolute height does not correlate with the actual reduction (Xu et al., 2022).

Based on the studies analysed, green belts can have a significant attenuation effect; however, inadequate consideration of spatial factors and the absence of urban planning processes necessitate mapping methods to identify optimal planting locations (Fletcher et al., 2022). Suitable plant species selection is also vital. For example, bamboo species that can be planted densely, grow quickly, and adapt to a short life cycle in sandy/clay soil layers are the most appropriate choice in the subtropical climate zone in Asia (Yasin et al., 2020). On the other hand, the triangular conifer species would be more efficient in continental climates in Europe or North America because most of the biomass is near the canopy base. Thus, the

microclimate changes due to a denser and lower canopy influence sound propagation and attenuation. Moreover, conifers do not shed their needles during winter (Van Renterghem et al., 2015).

Choosing the most suitable vegetation for the given conditions is a complicated and complex task requiring the evaluation of many parameters. The present study aims to clarify this task by different studies and categorising the systems of criteria used for research, noise measurement distances, and attenuation results.

2 MATERIALS AND METHODS

We selected 32 studies according to the following criteria:

1. The literature should cover a relatively wide interval of measurement methodology and data processing, starting from one of the earliest commonly cited works (e.g. Eyring, 1946) to the present day (Meng et al., 2025).
2. The geographical location and climate of the measurement sites by using the distribution of the Köppen climate zones (Kottek et al., 2006), as well as the type and character of the examined vegetation belts, should be different by presenting variant plant species, including forests (Huisman – Attenborough 1991), maintained and unmaintained hedges (Biocca et al., 2019), or agricultural plantations (Bashir et al., 2015).
3. Sound propagation differences entailed using point and line sources (e.g. Aylor, 1972b; Kragh, 1979) (not necessarily in the same study) either from a random/calibrated natural noise source or artificially induced effects with loudspeakers.
4. A detailed description of the measurement arrangement, including an available sketch, schematic diagram, or photograph documentation, to determine the typical distances between the plants and the tools or instruments used.
5. The authors should describe the characteristics of the examined belts with as many quantified parameters as possible (for which, as found in the studies, a correlation or functional relationship was established between the individual properties and the possible noise attenuation).
6. Finally, results related to octave-band (Pal et al., 2000), third-octave band (Fan et al., 2010), and discrete frequency values (Zhang et al., 2024) (regardless of the full or partial spectrum width covering the human hearing range), and the noise parameter used to calculate the attenuation should be clearly indicated.

Cases were not excluded from the comparison due to the absence of a criterion (which became evident during processing), provided that this did not adversely affect the conclusions drawn on other criteria.

Once the selected studies were processed, the data related to the individual aspects were summarised in the tables in the Appendix, displaying the results. Tables in some categories contain text-based parameters (e.g. when indicating the type of climate zone or the examined vegetation belt) or display a numerical value (e.g. for distances or the degree of attenuation). In addition, the presence or absence of the relevant parameter in the given article is marked with yes/no categories as a third grouping method. These are supplemented by the textual explanation of the data that cannot be determined clearly, helping to establish the basis for the comparison.

3 RESULTS AND DISCUSSION

3.1 General data of the selected studies

Based on the general data summarised in *Appendix Table 1*, the studies cover an interval of nearly eight decades, starting from the often-cited jungle acoustics published by Eyring in 1946 and extending to 2025. In addition, 18 of the sources (56.3%) examined the properties of green belts in different Asian countries. Nine, approximately a third (28.1%), examined European countries, while one study (de Oliveira et al. 2022) refers to South America.

Based on the locations indicated in the literature, *Figure 1/a* illustrates the distribution of the Köppen climate zones belonging to each study area. Concerning the distribution between the continents, the humid subtropical and subtropical monsoon climate typical in South Asian areas shows a particularly high number alongside the temperate continental and oceanic temperate zones of Europe and North America. However, the overlap in the 13 categories is low, as only four studies covered two climate zones simultaneously, partly due to measurements in several countries and the distance between locations within a country. Two studies are exceptions to the climate classification (Horoshenkov et al., 2013; Webb et al., 2023), in which the authors used laboratory measurements on small plant samples under artificial conditions instead of the open field.

Figure 1/b presents the vegetation belt types (based on the terminology used by the researchers) as objects. Of the vegetation types selected for the analysis, hedgerows, forest belts, and woody and shrubby vegetation strips of various shapes and layouts were the most numerous, while the other types show diversity in physical characteristics (for example, dimensions or density) from shrub belts (only densely planted shrubs in contrast to the vegetation strip) to jungle. In terms of overlap, six studies examined more than one category, which can be explained by the different measurement areas, as well as categorisation differences in the wording of textual descriptions and overlaps between the individual categories.

Based on the data aggregation, 27 studies named 226 plant species (an average of 8), of which 94 were coniferous (an average of 5 in 18 studies), and 130 were deciduous (also an average of 5 in 26 studies). As an exception, the difference between the total value (226) and deciduous/evergreen value (224) appeared in Bashir et al. (2015), in which the large-leaved corn and winter wheat examined in the agricultural area can be defined as annual crops. In two of the remaining five sources (Ow – Ghosh, 2017; de Oliveira et al., 2022), the semi-deciduous and evergreen vegetation could only be assumed based on the location and climate zone, while in another two (Liu et al., 2023; Zhang et al., 2024), the selected vegetation was only distinguished according to composition. The fifth, Huisman and Attenborough (1991), only provided the forest type where the measurements were taken. Overall, detailed information can be found in studies, including a list with the Latin species nomenclature (e.g. Tyagi et al., 2013) and a description without the vegetation composition, thereby reducing the homogeneity of the literature.

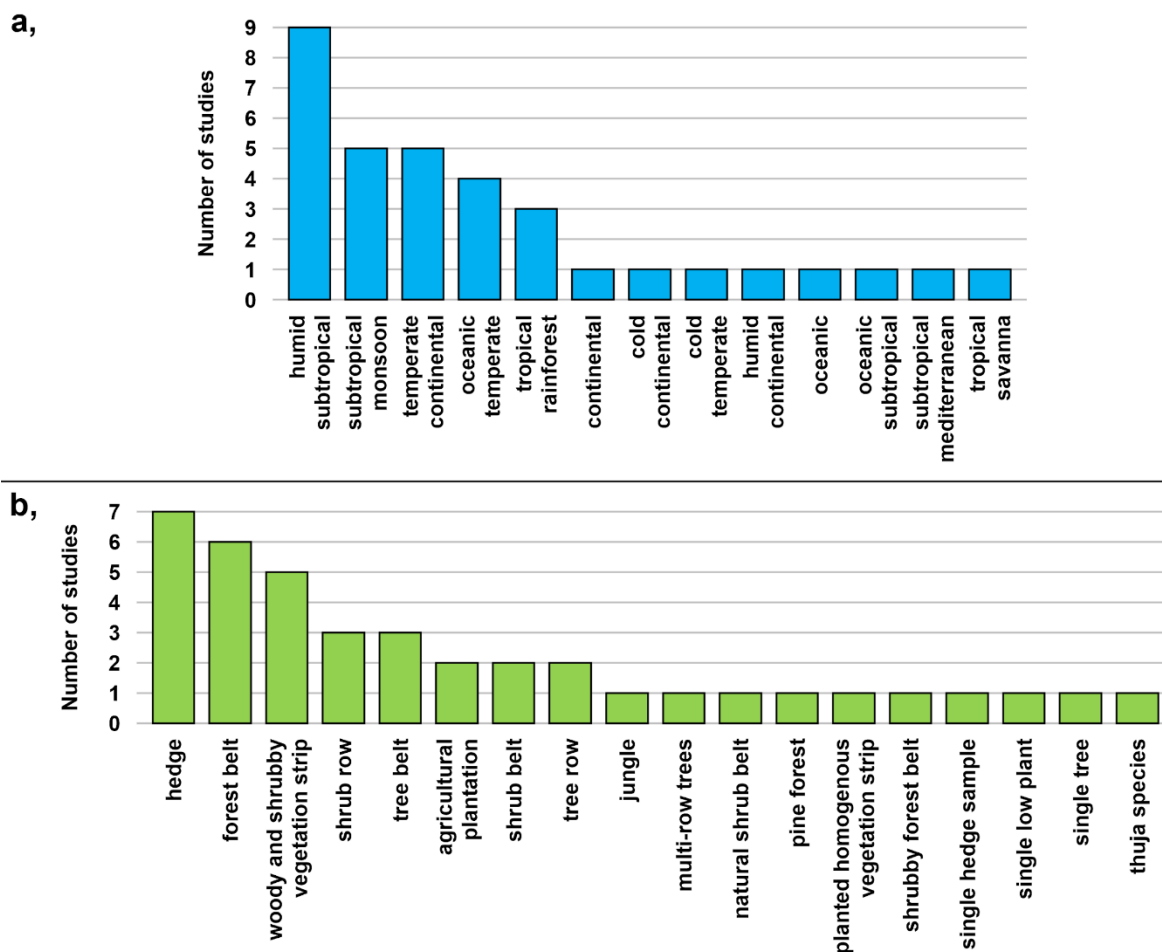


Figure 1. Köppen climatic zones belonging to the examined areas (a) and the distribution of the vegetation belt types (b)

3.2 Comparison of the location types and measurement layout

The next evaluation step involved classifying the measurement locations into five types: residential, industrial, agricultural, natural and laboratory (*Appendix Tables 2 and 3*). A total of 451 locations were distinguishable in the 32 studies; however, the average value of 7 per study doubled by the 217 city points indicated in Liu et al. (2023). The numerical composition of the location types in two studies (Fang – Ling, 2003; Fang, 2004) could not be clearly identified. Thus, measurements were taken in or near inhabited areas in almost 80% of cases, and the 40 natural and agricultural sites, presumably burdened with less environmental disturbance, appeared in only 11 studies.

The following differences between point and line sources (which are significantly different from the point of view of physical sound propagation) found in the selected studies should be highlighted regarding noise sources. For line sources, the authors used a real source in each case. These could be roads (e.g. Liu et al., 2024) or railway traffic noise (e.g. Kragh, 1979), but in the absence of data on vehicles passing in each lane during a given time, they were not quantified. On the contrary, the point sources used for attenuation calculation or control measurement, such as truck noise, could have been artificial, pre-recorded, and played back from loudspeakers, (e.g. Cook – Haverbeke, 1974), or they could have been noises from natural sources, such as vehicle engines (e.g. Oh et al., 2009), lawnmowers (e.g. Cook – Haverbeke, 1977), air conditioning units (e.g. Biocca et al., 2019) or motorised lawnmowers (e.g. Mohamed

– Krisantia, 2009). A double point source was used only by Eyring (1946) due to the technical limitations of producing the necessary frequency spectrum in that era.

The present study applied the following signs to compare the distance and height data of the measurement arrangements, as shown in *Figure 2*:

- L_1 : distance between the noise source and the microphone located in front of or at the border of the vegetation belt,
- L_2 : distance between the noise source and the border of the vegetation belt,
- L_3 : distance between the end of the vegetation belt and the first microphone placed behind the belt,
- L_4 : distance between the end of the vegetation belt and the last microphone placed behind the belt,
- $L_{\text{belt,max}}$: maximum vegetation belt width,
- L_{min} : distance between the noise source and the first microphone placed behind the vegetation belt,
- L_{max} : distance between the noise source and the last microphone placed behind the vegetation belt,
- H_s : height of noise source from ground level,
- H_{R1} , H_{R2} , H_{R3} : height of microphones from ground level.

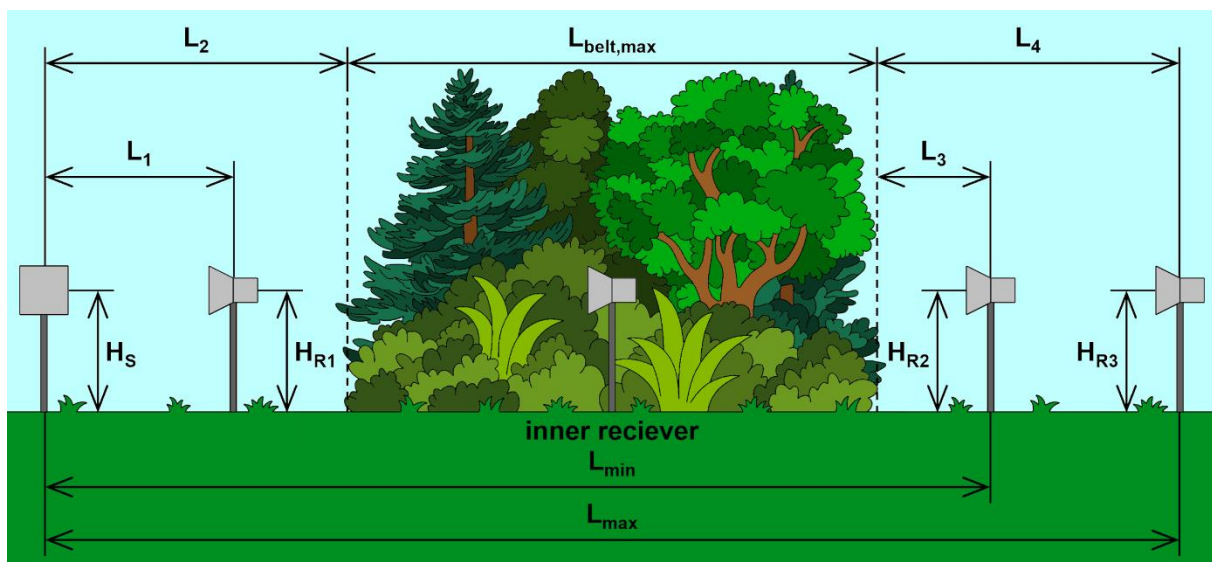


Figure 2. Applied distance and height signs for the measurement arrangement comparison

The largest distance values in *Appendix Tables 2 and 3* established the limits of the intervals. In cases involving more than one measurement location (due to differences between the devices and the layout of the vegetation belts), selection focused on where the most parameters could be clearly determined (e.g. Van Rentenghem et al., 2014). All values could at least be quantified at one measurement location in only a quarter of the studies (e.g. Lu et al., 2024); however, the sole exception where none of the data was available was the laboratory study by Horoshenkov et al. (2013), which investigated the noise reflectivity and absorption of plants placed in an impedance tube. For the remaining 23 studies containing partial information, some distances, such as L_3 and L_4 , were not interpretable when the required measurements were made within the vegetation belt (e.g. Price et al. 1988) or if one of the measuring microphones depicted in *Figure 2* was missing from the arrangement (Kim et al., 1989). For the most comprehensive processing, an approximate value was possible in four studies. In three of these, the distance between the road as a line source and the vegetation or one of the microphones

could be estimated based on the lane width that generally corresponds to three meters (Oh et al., 2009; de Oliveira et al., 2022; Liu et al., 2024), while in Eyring (1946), the values given in non-SI units could be converted by rounding.

Figure 3 summarises the differences between the intervals that can be specified for each applied distance, including the mean values. No significant difference was observed between the mean and range values of the source and microphone placed in front of the vegetation belt. Nevertheless, the differences in these same parameters were of magnitudes thirteen and seven times greater for the microphones placed behind the belt. Fang and Ling (2003) investigated the widest vegetation belt (within a substantially narrower measurement range), whereas the narrowest appears in Webb et al. (2023). The largest measurement range appears in Eyring (1946), resulting from internal measurements without specifying the width of the vegetation belt. The minimum of the L_1 and L_4 microphone distances and the width of the vegetation had a value greater than zero; however, for the interval of the L_2 and L_3 parameters, this zero value also occurred in several cases when the source or microphone was placed at the border of the belts.

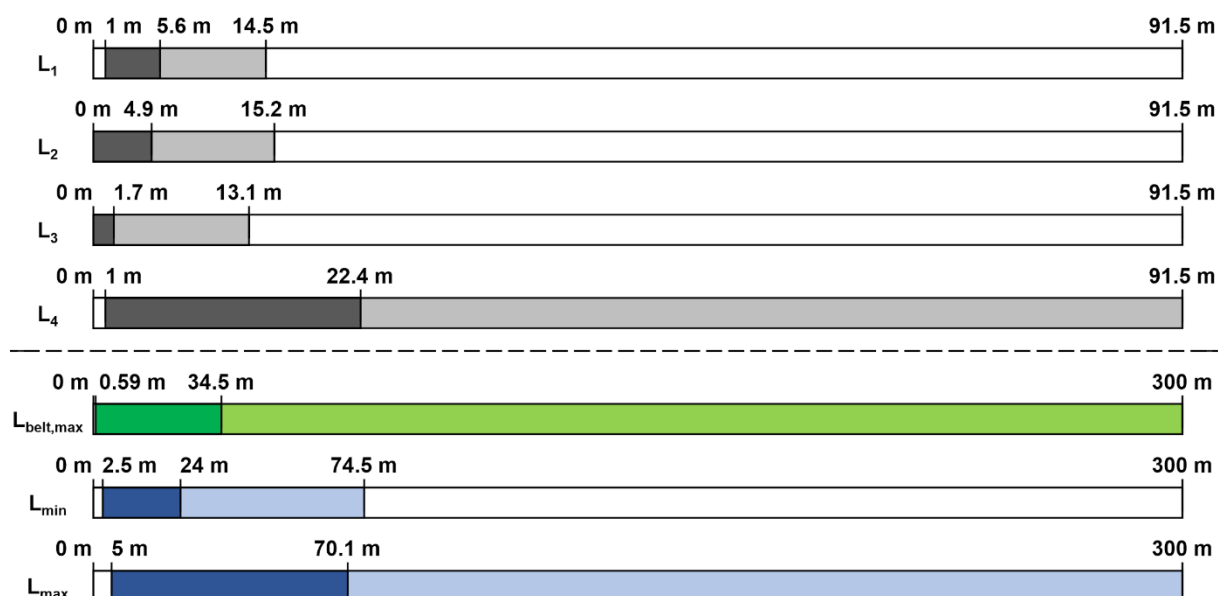


Figure 3. The interval and mean value of the applied distances

Numerically, the authors provided the number of microphones in 25 studies (nearly 80%), including the measurements made entirely within the vegetation. Internal microphones were also used in 13 studies (about 40%), and due to the multiple angles, height, direction, and attenuation in front of the belt, data were generally recorded using at least two microphones on average. From a practical perspective, the generally accepted measurement height of 1.5 meters above the ground level (which in Hungary is defined in the 27/2008. (XII. 3.) KvVM-EüM joint decree on environmental noise measurements) was used in half of the studies (e.g. Fang and Ling, 2005). In the remaining studies, the height ranged from 0.3 to 7.36 m, and in one research (Watts et al., 1999), microphone locations could not be determined from the description and the photographs. The source height varied between 0 and 1.5 meters depending on its type. In 13 studies (e.g. Pathak et al., 2008), the artificial point source and the microphones were positioned at the same height, while in the research of Tayagi et al. (2006), the engine height of the vehicles used as sources could be estimated at 0.5 m.

Information on ground cover, which is important in terms of sound reflection and attenuation, was unavailable in five studies (15.6%) (e.g. Karbalaei et al., 2015); however, in

18 cases, at least two types of soil could be distinguished. The detail and scope of the description also had an influence. For example, Aylor (1972b) explicitly provided numerical values for layer thickness. Watts et al. (1999) provided photographs that allowed the cover to be inferred near the source and the vegetation, whereas in Pathak et al. (2008), the public road and sidewalk referred only to the area surrounding the noise source.

3.3 Parameters used for describing the vegetation belts

For easier interpretation, the quantifiable parameters the authors used to characterise the vegetation belts were classified into parameter categories, considering the partially overlapping concepts and the same or similar measurement units. As a result, the 57 categories could be separated and were included in *Appendix Table 4/1, 4/2, 5/1 and 5/2*, along with their usage indicated on a yes/no basis and their corresponding measurement units. Parameters with similar meanings but different wording appeared across 14 categories; however, the measurement units used were identical within each category in six categories (as well as in all categories containing only a single parameter). Parallel to the above, by summarising the number of categories used in each study (*Figure 4*), we found that 21 studies (approximately 65%) specified five or fewer characteristic quantities. Two cases (Liu et al., 2023; Zhang et al., 2024) provided no numerical values. Horoshenkov et al. (2013) defined the highest number of categories (12) during laboratory measurements, while the average number per study was five (by rounding to the nearest whole number).

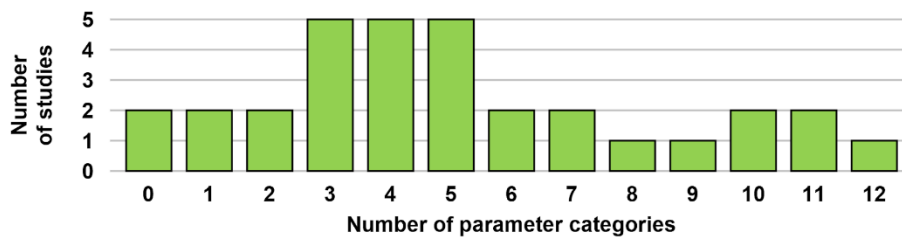


Figure 4. Distribution of the number of studies for the used parameter categories

Figure 5 illustrates the categories that appear in more than one research, together with their frequencies and measurement units. Among the 22 categories, the first three with the highest frequencies corresponded to the basic three spatial dimensions (height, depth, and length) of the vegetation belts; however, the simultaneous use of all three was observed only 11 times, barely a third (34.4%) of the compared studies. Another important finding is that the frequency of the visibility parameter was relatively low; however, its use for characterising the vegetations was already recommended by Eyring in 1946, one of the earliest pioneering studies. The visibility parameter is determined using the so-called white-glove method described by Fang (2004), in which one researcher wearing a raised white glove stops at several predetermined distances within the vegetation belt until the observer standing at the edge can no longer see the glove.

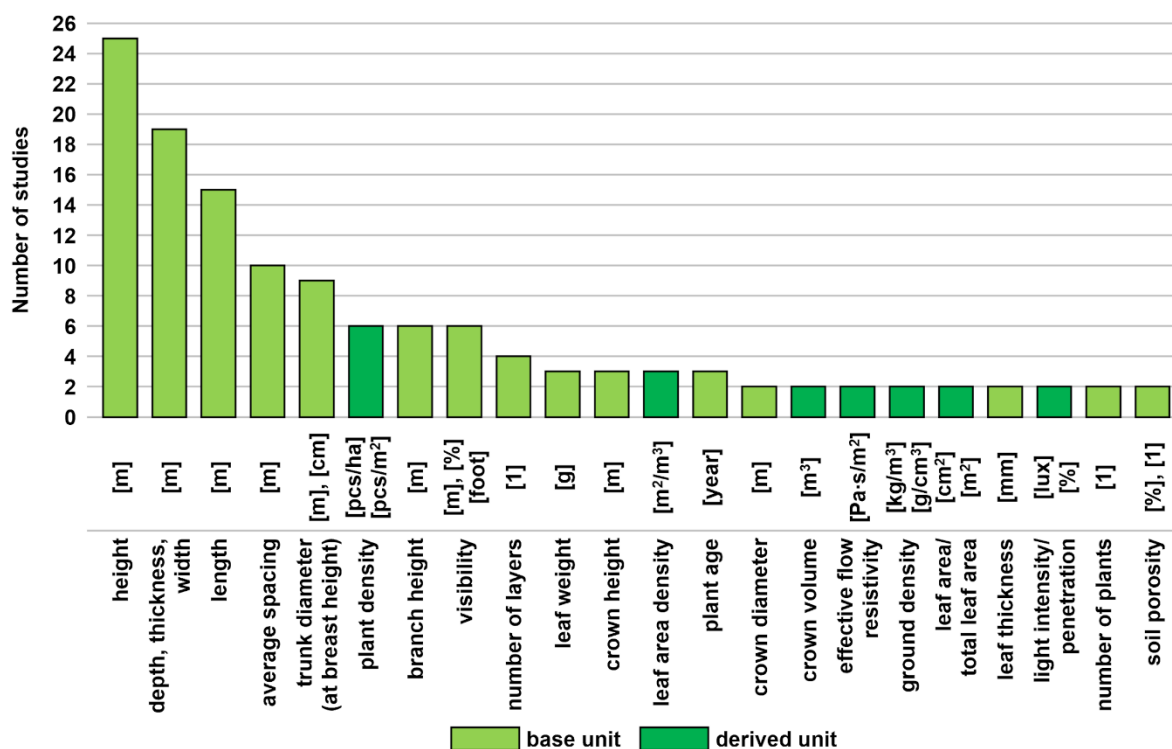


Figure 5. Frequency of parameter categories appearing in more than one study and their classification by measurement unit

In the grouping according to basic and derived units, 15 of the displayed categories (approximately 70%) were associated with base units or were dimensionless, of which ten referred to length, one each to mass and plant age, and three expressed characteristic values in the form of number of pieces or percentage. The exception to the only base unit/derived unit classification, also shown in the figure and classified in the derived group, was light intensity or penetration, where the value of the former is given in lux by Oh et al. (2009). The latter was expressed as a simple percentage form by Pal et al. (2000). Overall, the ratio of the categories was 44/13 (77/33%), showing a clear advantage for the basic units. In addition to the above, five studies also recorded physical obstacles located within or complementing the vegetation (e.g. garden beds, fences, walls), further increasing the complexity of the system of criteria and distorting the parallelisation of the given values for noise attenuation.

3.4 Parameters used for noise measurement and attenuation calculation

Appendix Tables 6 and 7, which have a structure similar to the categories of vegetation belts, summarise the 27 noise parameters used in the individual studies along with their symbols. These include both metrics commonly applied in acoustic measurement practice (such as SPL, L_{eq} , or L_{max}) and quantities defined by specific authors using functions (for example, NC, TNI, or L_{np} as described by Pathak et al. (2008)). In terms of counts, only one parameter was used in seven studies (approximately 20%). The seven parameters considered the highest number were distinguished by Pathak et al. (2008), and the average number of parameters reported per study, by rounding, was two.

The noise parameters used in at least two studies are illustrated in Figure 6 with their frequencies and symbols, which can be listed in descending order of frequency according to general acoustic terminology, with the following definition:

- **sound pressure level (SPL):** as a fundamental acoustic parameter, it expresses the sound pressure at a given point and moment compared to the reference sound pressure,
- **equivalent sound pressure level (L_{eq}):** the constant sound pressure level that contains the same amount of sound energy over the examined period as the actual, time-varying sound pressure level,
- **relative attenuation (–):** the difference in sound pressure level reduction between two different propagation conditions (e.g. two sound paths, vegetation types, or reference vs measurement sites),
- **insertion loss (IL):** the difference in sound pressure level reduction on the protected side before and after the installation of the noise protection solution (e.g. wall, embankment, vegetation) at the same measurement location,
- **maximum noise level (L_{max}):** specifies the highest instantaneous sound pressure level value measured during the given period,
- **sound value exceeding 10% of the time (L_{10}):** as a statistical characteristic of noise distribution, the sound pressure level that is exceeded by the measured sound pressure level during 10% of the time,
- **sound/noise level (L):** depending on the context, indicates the sound pressure level or noise level,
- **excess attenuation (A_e):** the reduction in sound pressure level that exceeds the value of the expected reduction in sound pressure level resulting from the geometric and atmospheric sound propagation in free space (in an unattenuated environment),
- **sound value exceeding 50% of the time (L_{50}):** as a statistical characteristic of noise distribution, the sound pressure level that is exceeded by the measured sound pressure level during 50% of the time.

An interesting observation in addition to the data was that the value of SPL was used more frequently than L_{eq} in some studies. One reason is that an artificial or natural source with a slightly varying noise level (e.g. Kim et al., 1989; Biocca et al., 2019), L_{eq} by expressing the energetic average, does not provide additional information compared to SPL. Both parameters were simultaneously included in only one research (Karbalaie et al., 2015). Nevertheless, the insertion loss or excess attenuation that can be used for site condition assessment and the maximum noise level (which shows magnitude differences) were used in a relatively small number of cases.

Another important aspect is that 11 literature sources (more than one third) did not apply the A-filter, which best represents the characteristics of human hearing, or its use could not be clearly determined. Moreover, only seven studies mentioned one of the six standards listed below, which greatly aid reproducibility:

- **ISO 10534-2:1998:** Acoustics – Determination of sound absorption coefficient and impedance in impedance tubes - Part 2: Transfer-function method,
- **ISO 9613-1:1993 and 2:1996:** Acoustics – Attenuation of sound during propagation outdoors – Part 1: Calculation of the absorption of sound by the atmosphere; Part 2: General method of calculation,
- **NBR 10151:2000:** Acoustics – Evaluation of noise in inhabited areas aiming at the comfort of the community – Procedure (Brazilian national standard),
- **GB 3096-2008:** Environmental Quality Standard for Noise (Chinese national standard),
- **ISO 1996-2:2007:** Acoustics – Description, measurement, and assessment of environmental noise – Part 2: Determination of environmental noise levels.

In connection with this, it is worth noting that in the examination of the frequency spectrum considered complete in practice and managed by most instruments (16–16,000 Hz), which was used in five studies (approximately 15%), the researchers consistently applied octave or third-octave band division. In contrast, among the 14 cases (more than 40%) analysing a partial spectrum, five did not apply such a division due to continuous spectrum measurement (e.g. Bashir et al., 2015), or the specification of the division was missing (e.g. Price et al., 1988). In addition to the documents containing five non-overlapping octave bands and nine third-octave band measurements, one study examined only discrete frequencies (Kim et al., 1989), while another (Zhang et al., 2024) used both the full spectrum and discrete values.

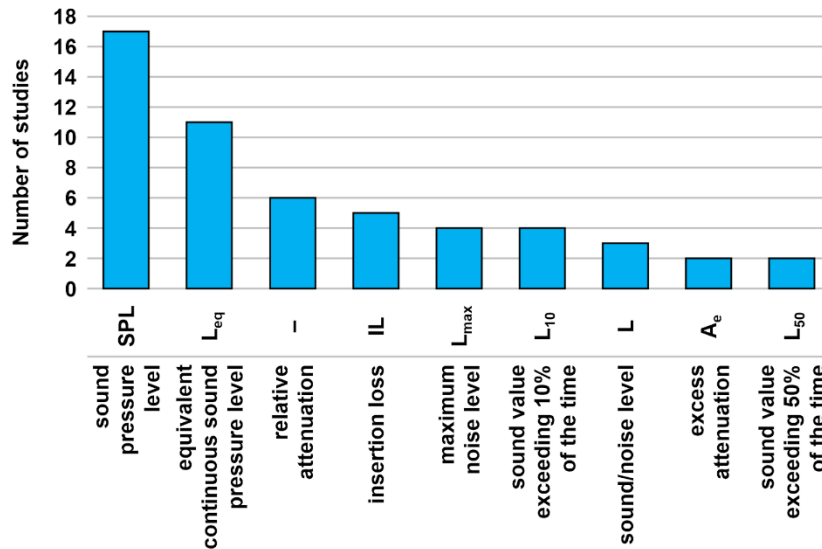


Figure 6. Frequency of noise parameters used more than once

As a final point of comparison, the following results show the maximum attenuation values given for each study, as noted in *Appendix Tables 6 and 7*. From a statistical perspective (based on the requirement of having at least two different maximum attenuation values to calculate the minimum, maximum, and range), the authors provided at least two different maximum attenuation values for four parameters (*Figure 7*), which in descending order according to interval range and data number, were L_{eq} (9 data), SPL (8 data), IL (3 data), and L (3 data). Based on the sound energy doubling per 3 dB derived from the basic acoustic equations and interval range, a full order of magnitude difference was detectable, even for the L noise parameter, which showed the smallest standard deviation. For the L_{eq} , the same difference exceeded a factor of twelve. Considering these findings, it can therefore be stated that, alongside the numerous described modifying conditions, the differences resulting from the measurement procedures have a significant impact, which calls into question the possibility of comparing the obtained results.

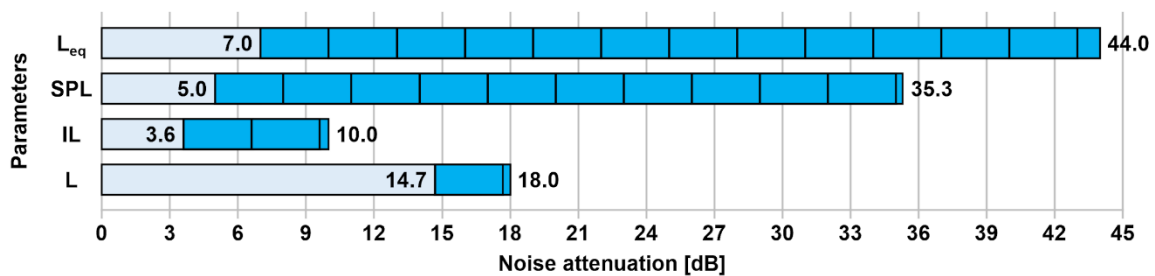


Figure 7. Range of noise attenuations with markings of energetic orders of magnitude

4 CONCLUSIONS

The 32 studies that the present paper analysed and included in the comparison have demonstrated that the selection of vegetation required to achieve effective noise attenuation is a complex task, as is the measurement of such attenuation. In addition to the diversity of noise sources and the significant differences observed in measurement configurations, the type of vegetation may substantially influence the actual attenuation achieved.

For example, Huisman and Attenborough (1991) reported that a maximum attenuation of 13.2 dB (SPL) could be achieved over a distance of 100 m in a coniferous forest, while Pal et al. (2000) demonstrated that a 20 dB reduction was achievable over nearly half that distance (60 m) in subtropical monsoon forests with dense understory vegetation. In contrast, properly designed hedges with adequate density can provide 3–14 dB attenuation (IL and L) over a much shorter distance of approximately 6 m (Van Rentenghem et al. 2014; Oh et al. 2009). Between these two categories, Ow and Ghosh (2017) measured an L_{eq} reduction of 11 dB within 30 m for woody and shrubby vegetation belts, while, depending on the measurement methodology, Tyagi et al. (2006) reported reductions that exceeded twice this value, reaching up to 24 dB (SPL) within 20 m.

Facilitating the harmonisation of future research necessitates standardising the measurement point selection process and introducing fundamental parameters for characterising vegetation belts. Together with the application of relevant international standards, this could substantially reduce inconsistencies among studies and facilitate the quantitative determination of the physical parameters required for noise propagation modelling, thereby also supporting evidence-based urban planning.

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APPENDIX

Table 1. General data of the selected studies

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	15.	16.
Author(s) and year	Eyring 1946	Aylor 1972b	Cook – Haverbeke 1974	Cook – Haverbeke 1977	Kragh 1979	Price et al. 1988	Kim et al. 1989	Huisman – Attenborough 1991	Watts et al. 1999	Pal et al. 2000	Fang and Ling 2003	Fang 2004	Fang and Ling 2005	Tyagi et al. 2006	Pathak et al. 2008	Mohamed – Krisantia 2009
Continent* Country**	N. A. PA	N. A. US	N. A. US	N. A. US	E. DK	E. UK	A. KR	E. NL	E. UK	A. IN	A. TW	A. TW	A. TW	A. IN	A. IN	A. MY
Climatic zone***	T. R.	H. C.	C.	T. C.	T. C.	T. C.	H. S.	O. T.	O. T.	T. S. S. M.	H. S.	H. S.	H. S.	S. M.	S. M.	T. R.
Type of objects****	J.	T. R. S. R. A. P.	M. T.	T. R. S. R.	F. B. S. F.	F. B.	H. T. S.	P. F.	F. B. S. B. W. S.	F. B.	P. S.	H.	F. B.	W. S.	S. R.	H.
Number of described species	3	10	7	8	8	3	2	–	4	16	20	5	6	16	4	6
Number of deciduous species	–	8	5	1	7	–	–	–	2	5	10	1	1	8	–	–
Number of evergreen species	3	2	2	7	1	3	2	–	2	11	10	4	5	8	4	6
	17.	18.	19.	20.	21.	22.	23.	24.	25.	26.	27.	28.	29.	30.	31.	32.
Author(s) and year	Oh et al. 2009	Fan et al. 2010	Horoshenkov et al. 2013	Tyagi et al. 2013	Van Renterghem et al. 2014	Bashir et al. 2015	Karbalaee et al. 2015	Ow and Ghosh 2017	Biocca et al. 2019	de Oliveira et al. 2022	Liu et al. 2023	Webb et al. 2023	Lu et al. 2024	Zhang et al. 2024	Liu et al. 2024	Meng et al. 2025
Continent* Country**	A. KR	A. CN	E. UK	A. IN	E. DE FR UK	E. UK	A. IR	A. SG	E. IT	S. A. BR	A. CN	E. UK	A. CN	A. CN	A. CN	A. CN RU
Climatic zone***	H. S.	H. S.	–	S. M.	O. T. T. C.	O. T.	H. S. O.	T. R.	S. D.	O. S.	S. M.	–	H. S.	C. T.	H. S.	C. C. T. C.
Type of objects****	H.	H.	S. L.	N. S.	H.	A. P.	T. B.	W. S.	H.	T. B.	W. S.	S. H.	S. T.	W. S.	F. B.	T. B. S. B.
Number of described species	9	6	4	46	7	2	12	–	2	–	–	2	7	–	5	6
Number of deciduous species	–	–	2	25	3	–	8	–	–	–	–	1	4	–	2	1
Number of evergreen species	9	6	2	21	4	–	4	–	2	–	–	1	3	–	3	5
* A. – Asia, E. – Europe, N. A. – North America, S. A. – South America																
** BR – Brazil, CN – China, DE – Germany, DK – Denmark, FR – France, IN – India, IR – Iran, IT – Italy, KR – South Korea, MY – Malaysia, NL – Netherlands, PA – Panama, RU – Russia, SG – Singapore, TW – Taiwan, UK – United Kingdom, US – United States																
*** C. – continental, C. C. – cold continental, C. T. – cold temperate, H. C. – humid continental, H. S. – humid subtropical, O. – oceanic, O. S. – oceanic subtropical, O. T. – oceanic temperate, S. D. – subtropical mediterranean, S. M. – subtropical monsoon, T. C. – temperate continental, T. R. – tropical rainforest, T. S. – tropical savanna																
**** A. P. – agricultural plantation, F. B. – forest belt, H. – hedge, J. – jungle, M. T. – multi-row trees, N. S. – natural shrub belt, P. F. – pine forest, P. S. – planted homogeneous vegetation strip, S. B. – shrub belt, S. R. – shrub row, S. F. – shrubby forest belt, S. H. – single hedge sample, S. L. – single low plant, S. T. – single tree, T. S. – thuja species, T. B. – tree belt, T. R. – tree row, W. S. – woody and shrubby vegetation strip																

Table 2. Data of the location types and measurement layout

		1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	15.	16.
Author(s) and year		Eyring 1946	Aylor 1972b	Cook – Haverbeke 1974	Cook – Haverbeke 1977	Kragh 1979	Price et al. 1988	Kim et al. 1989	Huisman – Attenborough 1991	Watts et al. 1999	Pal et al. 2000	Fang and Ling 2003	Fang 2004	Fang and Ling 2005	Tyagi et al. 2006	Pathak et al. 2008	Mohamed and Krisantia 2009
Number of locations		5	5	4	10	2	3	3	1	3	8	35	5	6	11	11	2
Location	Residential	–	–	–	10	–	–	–	–	3	–	✓	–	6	11	11	2
	Industrial	–	–	–	–	–	–	–	–	–	8	–	–	–	–	–	–
	Agricultural	–	3	1	–	–	–	–	–	–	–	–	–	–	–	–	–
	Natural	5	2	3	–	2	3	2	1	–	–	✓	–	–	–	–	–
	Laboratory	–	–	–	–	–	–	1	–	–	–	–	–	–	–	–	–
Noise source: point (P), line (L)		P	P	P, L	P	L	P	P	P	L	P	P	P	P	L	P	P
Noise source: real (R), artificial (A)		A	A	R, A	R	R	A	A	A	R	A	A	A	A	R	A	A
Number of sources		2	1	1	1	–	1	1	1	–	1	1	1	1	–	1	1
Distances [m]	L ₁	–	3	–	–	7.5	2	–	10	–	10	1	–	–	5	5	–
	L ₂	–	0	15.2	13.1	0	–	3	0	8	10	1	2	2	5	5	1
	L _{belt, max}	–	–	30.5	13.8	55	–	1	–	–	50	300	3	3	15	3	–
	L ₃	–	–	0	13.1	–	–	0	–	10	0	–	2	2	0	5	1
	L ₄	–	–	91.5	–	5.5	–	1	–	–	–	–	17	57	–	20	3
	L _{min}	≈30	65	45.7	40	55	12	4	10	18	60	16	7	7	20	13	–
L _{max}	≈300	–	137.2	–	68	96	5	100	–	–	–	62	62	–	28	–	
Number of microphones		4	2	1	1	4	3	–	–	–	2	–	–	2	2	2	1
Inner microphone		✓	✓	–	–	✓	✓	–	✓	–	✓	✓	–	–	–	–	–
Heights [m]	H _s	≈1.5	1.5	1.5	≈0.2	0	1.2	1	1	≈0.5	0.25	1.2	1.5	1.5	≈0.5	1.2	1.2
	H _{R1}	–	1.5	–	1.5	1.1	1.2	–	1	–	1.5	1.2	–	–	1.5	1.2	–
	H _{R2}	≈1.5	1.5	1.7	–	1.5	1.2	1	1	–	1.5	1.2	1.5	1.5	1.5	1.2	1.2
	H _{R3}	≈1.5	–	1.7	–	1.5	1.2	1	1	–	–	–	1.5	1.5	–	1.2	1.2
Ground cover*		J. V.	H. L. C.	Gs. U. A.	G. N.	P. S.	N. C.	–	B. N.	P. R. G.	V. C.	–	–	–	P. R. S. W.	P. R. S. W.	P. R. S. W.

* **B. N.** – soft ground thickly covered with branches and pine needles, **B. S.** – barren soil, **C. F.** – cultivated field, **C. S.** – clay-based soil, **E. S.** – exposed soil, **F. B.** – flower bed, **F. W.** – concrete floor covered with acoustic foam and natural wool, **G.** – grass, **G. A.** – grass-covered areas, **G. S.** – gravel surface, **Gd.** – grassed, **Gs.** – covered with grass species, **J. V.** – jungle-like undergrowth vegetation, **L.** – lawn, **L. C.** – leaf-covered ground, **H.** – 7-8 cm layer of humus, **N.** – natural, **N. C.** – needle-covered, **O. M.** – other soft materials, **P.** – paved, **P. R.** – public road, **P.S.** – peat soil covered with freshly cut grass, **S.** – soil, **S. S.** – substratum soil, **S. W.** – sidewalk, **U. A.** – uncovered agricultural land, **V. C.** – vegetation-covered, **V. H.** – covered with vegetation of varying heights

Table 3. Data of the location types and measurement layout (continued)

		17.	18.	19.	20.	21.	22.	23.	24.	25.	26.	27.	28.	29.	30.	31.	32.
Author(s) and year		Oh et al. 2009	Fan et al. 2010	Horoshenkov et al. 2013	Tyagi et al. 2013	Van Renterghem et al. 2014	Bashir et al. 2015	Karbalaei et al. 2015	Ow – Ghosh 2017	Biocca et al. 2019	de Oliveira et al. 2022	Liu et al. 2023	Webb et al. 2023	Lu et al. 2024	Zhang et al. 2024	Liu et al. 2024	Meng et al. 2025
Number of locations		9	6	1	11	3	1	9	3	2	3	217	1	6	27	2	36
Location	Residential	9	–	–	11	3	–	–	1	2	3	217	–	6	27	2	36
	Industrial	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	Agricultural	–	–	–	–	–	1	–	–	–	–	–	–	–	–	–	–
	Natural	–	6	–	–	–	–	9	2	–	–	–	–	–	–	–	–
	Laboratory	–	–	1	–	–	–	–	–	–	–	–	1	–	–	–	–
Noise source: point (P), line (L)		P	P	P	L	P, L	P	P	L	P	L	L	P	P	L	L	L
Noise source: real (R), artificial (A)		R	A	A	R	R, A	A	A	R	A	R	R	A	A	R	R	R
Number of sources		1	1	1	–	1	1	1	–	1	–	–	1	1	–	–	–
Distances [m]	L ₁	≈1.5	5	–	5	–	1	–	–	–	≈1.5	–	–	5.66	10	≈14.5	8
	L ₂	≈1.8	5	–	5	2.4	–	1	–	5	≈4.5	0	–	5.66	–	≈14.5	12
	L _{belt, max}	2.5	3.2	–	15	1.8	–	100	–	1.9	–	–	0.59	6.53	–	70	15
	L ₃	1	0	–	0	0.7	–	–	–	1	0	0	0.37	0	–	0	0
	L ₄	2	–	–	–	–	–	–	–	5	–	–	–	–	–	–	–
	L _{min}	≈5.3	8.2	–	20	4.9	2.5	26	27.5	7.9	60	–	4.1	12.19	≈13	≈74.5	27
	L _{max}	≈6.3	–	–	–	–	10	101	–	12.9	–	44.72	–	–	≈18	–	–
Number of microphones		3	2	2	2	2	4	1	–	1	2	8	4	2×2	2	7	–
Inner microphone		–	–	–	–	–	✓	✓	–	–	✓	✓	–	–	–	✓	✓
Heights [m]	H _s	≈0.5	1.5	–	≈0.5	≈0.5	0.3	–	≈0.5	0.8	≈0.5	≈0.5	1.16	1.5	≈0.5	≈0.5	≈0.5
	H _{R1}	1	1.5	–	1.5	≈1.5	0.3	–	–	–	≈1.5	1.5	1.16	7.36	1.5	1.2	1.5
	H _{R2}	1	1.5	–	1.5	≈1.5	0.3	1.2	1.5	0.8	≈1.5	1.5	1.16	7.36	1.5	1.2	1.5
	H _{R3}	1	–	–	–	–	0.3	1.2	–	0.8	–	–	–	–	–	–	–
Ground cover*		P. R. S. W.	S. L. O. M.	S. S. C. S.	P. R. S. W.	P. R. S. W.	C. F.	–	G.	P. R. G. S.	G. E. S.	P. R. S. W. G. A.	F. W.	V. H.	S. W. F. B. Gd. P.	P. R. L. C.	P. R. S. W. Gd.

* **B. N.** – soft ground thickly covered with branches and pine needles, **B. S.** – barren soil, **C. F.** – cultivated field, **C. S.** – clay-based soil, **E. S.** – exposed soil, **F. B.** – flower bed, **F. W.** – concrete floor covered with acoustic foam and natural wool, **G.** – grass, **G. A.** – grass-covered areas, **G. S.** – gravel surface, **Gd.** – grassed, **Gs.** – covered with grass species, **J. V.** – jungle-like undergrowth vegetation, **L.** – lawn, **L. C.** – leaf-covered ground, **H.** – 7-8 cm layer of humus, **N.** – natural, **N. C.** – needle-covered, **O. M.** – other soft materials, **P.** – paved, **P. R.** – public road, **P.S.** – peat soil covered with freshly cut grass, **S.** – soil, **S. S.** – substratum soil, **S. W.** – sidewalk, **U. A.** – uncovered agricultural land, **V. C.** – vegetation-covered, **V. H.** – covered with vegetation of varying heights

Table 4/1. Parameters used for describing the vegetation belts

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	15.	16.
Author(s) and year	Eyring 1946	Aylor 1972b	Cook – Haverbeke, 1974	Cook – Haverbeke 1977	Kragh 1979	Price et al. 1988	Kim et al. 1989	Huisman – Attenborough 1991	Watts et al. 1999	Pal et al. 2000	Fang – Ling 2003	Fang 2004	Fang – Ling 2005	Tyagi et al. 2006	Pathak et al. 2008	Mohamed – Krisantia 2009
Parameter categories and units	2	8	4	4	3	3	4	3	4	10	7	4	5	2	3	5
aggregation size of the soil [μm]	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-
average plant density [pcs/ha], density [pcs/m ²], plant/tree/trunk density [pcs/m ²]	-	✓	-	-	-	✓	-	✓	-	✓	-	-	-	-	-	✓
average canopy cover [m]	-	-	-	-	-	-	-	-	-	✓	-	-	-	-	-	-
average leaf inclination [°]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
average mass density of leaves [kg/m ³]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
average mass of leaves [g], fresh leaf weight [g], leaf weight [g]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
average spacing between consecutive plants) [m], average interval [m], horizontal distance [m], planting distance [m], tree spacing [m]	-	-	✓	✓	-	-	-	-	-	✓	✓	-	✓	-	-	✓
basal area [m ² /ha]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
branchless lower trunk [m], branch height [m], minimum height of branches [m]	-	-	-	-	-	-	-	-	-	✓	-	-	-	-	-	-
canopy branch cover [m]	-	-	-	-	-	-	-	-	-	✓	-	-	-	-	-	-
canopy leaf density [pcs/m ²]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
characteristic leaf dimension [m]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
crown diameter [m]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
crown height [m]	-	-	-	-	-	-	-	-	-	-	✓	-	-	-	-	-
crown volume [m ³]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
crown width [m]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
degree of vegetation screening [%]	-	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	-
depth, thickness, width [m]	-	-	✓	✓	✓	-	✓	-	-	✓	✓	✓	✓	✓	✓	-
diameter at breast height [m], effective scattering diameter [m], trunk diameter [cm]	-	✓	-	-	-	-	-	✓	-	✓	✓	-	-	-	-	-
dominant angle of leaf orientation [°]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
effective tortuosity [1]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
equivalent acoustical thickness [m]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
flow/effective flow resistivity [Pa·s/m ²]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
ground bulk density [g/cm ³], soil density [kg/m ³]	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-
ground cover [%]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
height [m]	-	✓	✓	✓	-	✓	✓	✓	✓	✓	✓	✓	✓	-	✓	✓
impervious area [%]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
layer thickness of needles [cm]	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-
leaf area [cm ²], determination of total leaf area by visual calculation [m ²]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Table 4/2. Parameters used for describing the vegetation belts (continued)

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	15.	16.
Author(s) and year	Eyring 1946	Aylor 1972b	Cook – Haverbeke 1974	Cook – Haverbeke 1977	Kragh 1979	Price et al. 1988	Kim et al. 1989	Huisman – Attenborough 1991	Watts et al. 1999	Pal et al. 2000	Fang – Ling 2003	Fang 2004	Fang – Ling 2005	Tyagi et al. 2006	Pathak et al. 2008	Mohamed – Krisantia 2009
Parameter categories and units	2	8	4	4	3	3	4	3	4	10	7	4	5	2	3	5
leaf area density [m ² /m ³], foliage area per unit volume [m ² /m ³]	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-
leaf area index of crown [1]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
leaf area index of low-growing plants [1]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
leaf shape by length/width [1]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
leaf facility [g/cm ²]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
leaf/average leaf thickness [mm]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
length [m]	-	-	✓	-	✓	-	✓	-	✓	-	✓	✓	✓	-	✓	✓
light intensity [lux], horizontal/vertical light penetration [%]	-	-	-	-	-	-	-	-	-	✓	-	-	-	-	-	-
lines of trees [1], number of layers [1]	-	-	-	✓	-	-	-	-	-	-	-	-	-	-	-	✓
living vegetation volume of low-growing plants [m ³]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
mean leaf width [cm]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
mean/measured leaf size [mm]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
moisture level of the soil [%]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
number of plants/trees [1]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
one sees a distance of approximately [foot], visibility [m, %]	✓	-	-	-	-	-	-	-	-	-	✓	✓	✓	✓	-	-
optical porosity [%]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
percentage of vegetation cover [%]	-	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	-
plant absorption coefficient [1]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
plant age [year]	-	-	-	-	✓	✓	✓	-	-	-	-	-	-	-	-	-
plant porosity [1]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
planting width [m]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
propagation path length through vegetation [m]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
ratio of species [%]	-	-	-	-	-	-	-	-	-	✓	-	-	-	-	-	-
rows of plants/trees [1]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
soil porosity [%, 1]	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-
terrain loss coefficient [dB/foot]	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
terrain slope [%]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
vertical distance [m]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Obstacles in the belt (raised garden bed, wall, fence, etc.)	-	-	✓	✓	-	-	-	-	-	-	-	-	-	-	-	-

Table 5/1. Parameters used for describing the vegetation belts (continued)

	17.	18.	19.	20.	21.	22.	23.	24.	25.	26.	27.	28.	29.	30.	31.	32.
Author(s) and year	Oh et al. 2009	Fan et al. 2010	Horoshenkov et al. 2013	Tyagi et al. 2013	Van Renterghem et al. 2014	Bashir et al. 2015	Karbalaei et al. 2015	Ow – Ghosh 2017	Biocca et al. 2019	de Oliveira et al. 2022	Liu et al. 2023	Webb et al. 2023	Lu et al. 2024	Zhang et al. 2024	Liu et al. 2024	Meng et al. 2025
Parameter categories and units	5	9	12	3	6	5	1	1	5	11	0	6	10	0	11	7
aggregation size of the soil [μm]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
average plant density [pcs/ha], density [pcs/m ²], plant/tree/trunk density [pcs/m ²]	-	-	-	-	-	-	-	-	-	✓	-	-	-	-	-	-
average canopy cover [m]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
average leaf inclination [°]	-	-	-	-	-	-	-	-	-	-	-	-	✓	-	-	-
average mass density of leaves [kg/m ³]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	✓	-
average mass of leaves [g], fresh leaf weight [g], leaf weight [g]	-	✓	✓	-	-	-	-	-	-	-	-	-	-	-	✓	-
average spacing between consecutive plants) [m], average interval [m], horizontal distance [m], planting distance [m], tree spacing [m]	-	✓	-	-	-	-	-	-	-	✓	-	-	-	-	✓	✓
basal area [m ² /ha]	-	-	-	-	-	-	-	-	-	✓	-	-	-	-	-	-
branchless lower trunk [m], branch height [m], minimum height of branches [m]	-	✓	-	-	-	-	-	-	-	✓	-	-	✓	-	✓	✓
canopy branch cover [m]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
canopy leaf density [pcs/m ²]	-	-	-	-	-	-	-	-	-	-	-	✓	-	-	-	-
characteristic leaf dimension [m]	-	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-
crown diameter [m]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	✓	✓
crown height [m]	-	-	-	-	-	-	-	-	-	✓	-	-	✓	-	-	-
crown volume [m ³]	-	-	-	-	-	-	-	-	-	-	-	-	✓	-	✓	-
crown width [m]	-	-	-	-	-	-	-	-	-	-	-	-	✓	-	-	-
degree of vegetation screening [%]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
depth, thickness, width [m]	✓	✓	-	✓	✓	-	-	-	✓	-	-	✓	-	-	✓	-
diameter at breast height [m], effective scattering diameter [m], trunk diameter [cm]	-	-	-	-	-	-	-	✓	-	✓	-	-	✓	-	✓	✓
dominant angle of leaf orientation [°]	-	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-
effective tortuosity [1]	-	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-
equivalent acoustical thickness [m]	-	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-
flow/effective flow resistivity [Pa·s/m ²]	-	-	✓	-	-	✓	-	-	-	-	-	-	-	-	-	-
ground bulk density [g/cm ³], soil density [kg/m ³]	-	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-
ground cover [%]	-	-	-	-	-	-	-	-	-	✓	-	-	-	-	-	-
height [m]	✓	✓	✓	✓	✓	✓	-	-	✓	✓	-	✓	✓	-	✓	✓
impervious area [%]	-	-	-	-	-	-	-	-	-	✓	-	-	-	-	-	-
layer thickness of needles [cm]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
leaf area [cm ²], determination of total leaf area by visual calculation [m ²]	-	✓	✓	-	-	-	-	-	-	-	-	-	-	-	-	-

Table 5/2. Parameters used for describing the vegetation belts (continued)

	17.	18.	19.	20.	21.	22.	23.	24.	25.	26.	27.	28.	29.	30.	31.	32.
Author(s) and year	Oh et al. 2009	Fan et al. 2010	Horoshenkov et al. 2013	Tyagi et al. 2013	Van Renterghem et al. 2014	Bashir et al. 2015	Karbalaei et al. 2015	Ow – Ghosh 2017	Biocca et al. 2019	de Oliveira et al. 2022	Liu et al. 2023	Webb et al. 2023	Lu et al. 2024	Zhang et al. 2024	Liu et al. 2024	Meng et al. 2025
Parameter categories and units	5	9	12	3	6	5	1	1	5	11	0	6	10	0	11	7
leaf area density [m ² /m ³], foliage area per unit volume [m ² /m ³]	-	-	-	-	✓	✓	-	-	-	-	-	-	-	-	-	-
leaf area index of crown [1]	-	-	-	-	-	-	-	-	-	-	-	-	✓	-	-	-
leaf area index of low-growing plants [1]	-	-	-	-	-	-	-	-	-	-	-	-	✓	-	-	-
leaf shape by length/width [1]	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-
leaf facility [g/cm ²]	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-
leaf/average leaf thickness [mm]	✓	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-
length [m]	✓	✓	-	-	✓	-	✓	-	✓	-	-	✓	-	-	-	-
light intensity [lux], horizontal/vertical light penetration [%]	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
lines of trees [1], number of layers [1]	-	-	-	-	-	-	-	-	✓	-	-	-	-	-	✓	-
living vegetation volume of low-growing plants [m ³]	-	-	-	-	-	-	-	-	-	-	-	-	✓	-	-	-
mean leaf width [cm]	-	-	-	-	✓	-	-	-	-	-	-	-	-	-	-	-
mean/measured leaf size [mm]	-	-	-	-	-	✓	-	-	-	-	-	-	-	-	-	-
moisture level of the soil [%]	-	-	-	-	-	-	-	-	-	-	-	✓	-	-	-	-
number of plants/trees [1]	-	-	-	-	-	-	-	-	-	✓	-	✓	-	-	-	-
one sees a distance of approximately [foot], visibility [m, %]	-	-	-	✓	-	-	-	-	-	-	-	-	-	-	-	-
optical porosity [%]	-	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	-
percentage of vegetation cover [%]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
plant absorption coefficient [1]	-	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-
plant age [year]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
plant porosity [1]	-	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-
planting width [m]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	✓
propagation path length through vegetation [m]	-	-	-	-	✓	-	-	-	-	-	-	-	-	-	-	-
ratio of species [%]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
rows of plants/trees [1]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	✓	-
soil porosity [%, 1]	-	-	-	-	-	✓	-	-	-	-	-	-	-	-	-	-
terrain loss coefficient [dB/foot]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
terrain slope [%]	-	-	-	-	-	-	-	-	-	✓	-	-	-	-	-	-
vertical distance [m]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	✓
Obstacles in the belt (raised garden bed, wall, fence, etc.)	✓	-	-	-	✓	-	-	-	-	-	-	-	-	✓	-	-

Table 6. Parameters used for noise measurement and attenuation calculation

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	15.	16.
Author(s) and year	Eyring 1946	Aylor 1972b	Cook – Haverbeke 1974	Cook – Haverbeke 1977	Kragh 1979	Price et al. 1988	Kim et al. 1989	Huisman – Attenborough, 1991	Watts et al. 1999	Pal et al. 2000	Fang – Ling 2003	Fang 2004	Fang – Ling 2005	Tyagi et al. 2006	Pathak et al. 2008	Mohamed – Krisantia 2009
Parameter and symbol	2	1	3	2	2	1	2	1	4	2	3	2	2	2	7	1
absorption coefficient	α	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
background noise	B. N.	-	-	-	-	-	✓	-	-	-	-	-	-	-	-	-
corrected level difference attenuation spectrum ⁽³⁾	-	-	-	-	-	✓	-	-	-	-	-	-	-	-	-	-
equivalent continuous sound pressure level	L _{eq}	-	-	-	✓	-	-	-	✓	✓	-	-	-	-	✓	-
equivalent noise level	dB _{eq}	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
excess attenuation	A _e	-	✓	-	-	-	-	-	-	-	✓	-	-	-	-	-
fast A-weighted maximum noise level	L _{AF,max}	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
insertion loss	IL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
intensity level ⁽¹⁾	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-
level difference between microphones	LD	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
loudness level	-	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	-
masking level ⁽²⁾	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-
maximum noise level	L _{max}	-	-	-	✓	-	-	-	✓	✓	-	-	-	-	-	-
noise average	ΔL _{Aep}	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
relative attenuation	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
noise climate	NC	-	-	-	-	-	-	-	-	-	-	-	-	-	✓	-
noise decrement	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
noise difference	R _{noise}	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
noise pollution level	L _{np}	-	-	-	-	-	-	-	-	-	-	-	-	-	✓	-
noise/sound level	L	-	-	✓	✓	-	-	-	-	-	-	-	-	-	-	-
relative attenuation ⁽⁴⁾	-	-	✓	✓	-	-	-	-	-	-	✓	✓	✓	✓	-	-
sound pressure level	SPL	-	-	✓	-	-	✓	✓	-	-	✓	✓	✓	✓	-	✓
sound value exceeding 1% of the time	L ₁	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
sound value exceeding 10% of the time	L ₁₀	-	-	-	-	-	-	-	✓	-	-	-	-	-	✓	-
sound value exceeding 50% of the time	L ₅₀	-	-	-	-	-	-	-	-	-	-	-	-	-	✓	-
sound value exceeding 90% of the time	L ₉₀	-	-	-	-	-	-	-	-	-	-	-	-	-	✓	-
traffic noise index	TNI	-	-	-	-	-	-	-	-	-	-	-	-	-	✓	-
transfer function for the sound wave	H	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Filter type	-	-	A	A	A	-	-	-	A	A	A	A	A	A	-	-
Measurement standard	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Interval – full spectrum (16-16,000 Hz)	-	-	-	-	-	-	-	-	-	✓	-	-	-	-	-	-
Interval – partial spectrum	✓	✓	✓	-	-	✓	-	✓	✓	-	✓	-	-	✓	✓	-
Discrete frequency values	-	-	-	-	-	-	✓	-	-	-	-	-	-	-	-	-
Octave band measurement	-	-	✓	-	-	-	-	-	-	✓	-	-	-	-	-	-
Third-octave band measurement	-	-	-	-	-	-	-	✓	✓	-	✓	-	-	✓	✓	-
Parameter used to determine noise attenuation	(1) (2)	A _e	L	L	L _{eq}	(3)	SPL	SPL	L _{eq}	L _{eq} L _{max}	(4)	SPL	SPL	SPL	L _{eq}	SPL
Maximum attenuation [dB]	0.02*	27.0	15.0	18.0	9.0	20.0	35.3	13.2	7.0	21.1	10**	5.0	5.0	24.0	26.0	7.9

* in dB/foot; ** in dB(A)/20 m

Table 7. Parameters used for noise measurement and attenuation calculation (continued)

	17.	18.	19.	20.	21.	22.	23.	24.	25.	26.	27.	28.	29.	30.	31.	32.
Author(s) and year	Oh et al. 2009	Fan et al. 2010	Horoshenkov et al. 2013	Tyagi et al. 2013	Van Renterghem et al. 2014	Bashir et al. 2015	Karbalaei et al. 2015	Ow – Ghosh 2017	Biocca et al. 2019	de Oliveira et al. 2022	Liu et al. 2023	Webb et al. 2023	Lu et al. 2024	Zhang et al. 2024	Liu et al. 2024	Meng et al. 2025
Parameter and symbol	2	2	2	4	3	3	2	4	2	1	1	1	2	1	3	2
absorption coefficient α	-	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-
background noise B. N.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
corrected level difference	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
attenuation spectrum	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
equivalent continuous sound pressure level L_{eq}	-	✓	-	-	-	-	✓	✓	✓	-	✓	-	-	-	✓	✓
equivalent noise level dB_{eq}	-	-	-	-	-	-	-	-	-	✓	-	-	-	-	-	-
excess attenuation A_e	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
fast A-weighted maximum noise level $L_{AF,max}$	-	-	-	-	✓	-	-	-	-	-	-	-	-	-	-	-
insertion loss IL	-	-	-	-	✓	✓	-	✓	-	-	-	✓	✓	-	-	-
intensity level	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
level difference between microphones LD	-	-	-	-	-	✓	-	-	-	-	-	-	-	-	-	-
loudness level	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
masking level	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
maximum noise level L_{max}	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	-	-
noise average relative attenuation ΔL_{Aep}	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-
noise climate NC	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
noise decrement	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
noise difference R_{noise}	-	-	-	-	-	-	-	-	-	-	-	-	-	-	✓	-
noise pollution level L_{np}	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
noise/sound level L	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
relative attenuation	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
sound pressure level SPL	-	-	-	✓	✓	✓	✓	-	✓	-	-	-	✓	✓	✓	✓
sound value exceeding 1% of the time L_1	-	-	-	✓	-	-	-	-	-	-	-	-	-	-	-	-
sound value exceeding 10% of the time L_{10}	-	-	-	✓	-	-	-	✓	-	-	-	-	-	-	-	-
sound value exceeding 50% of the time L_{50}	-	-	-	✓	-	-	-	-	-	-	-	-	-	-	-	-
sound value exceeding 90% of the time L_{90}	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
traffic noise index TNI	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
transfer function for the sound wave H	-	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-
Filter type	-	A	-	A	A	A	A	A	A	-	A	-	A	A	A	A
Measurement standard***	-	-	(I)	(II) (III)	(III)	-	-	-	-	(IV)	-	-	(II)	-	(V)	(VI)
Interval – full spectrum (16-16,000 Hz)	-	✓	-	-	-	-	-	-	✓	-	-	-	✓	✓	-	-
Interval – partial spectrum	-	-	-	✓	✓	✓	-	-	-	-	-	✓	-	-	✓	-
Discrete frequency values	-	-	-	-	-	-	-	-	-	-	-	-	-	✓	-	-
Octave band measurement	-	-	-	-	-	-	-	-	-	-	-	-	✓	✓	✓	-
Third-octave band measurement	-	✓	-	✓	✓	-	-	-	✓	-	-	-	-	-	-	-
Parameter used to determine noise attenuation	L	ΔL_{Aep}	H	$L_{1,10}$ L_{50}	IL	SPL	L_{eq}	L_{eq}	L_{eq}	dB_{eq}	L_{eq}	IL	IL	SPL	R_{noise}	L_{eq}
Maximum attenuation [dB]	14.7	≈7.0	75*	20.0	3.6	14.7	44.0	11.0	7.0	14.8	1**	≈10	10.0	5.2	6.6	8.0

* in %; ** in dB/1%; *** (I) ISO 10534-2:1998, (II) ISO 9613-1:1993, (III) ISO 9613-2:1996, (IV) NBR 10151:2000, (V) GB 3096-2008, (VI) ISO 1996-2:2007

Guide for Authors

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