

CONTENTS

Syamsuddin Millang, Budi Arty, Eny Yuniati, Ahmad R. Makkasau, Dicky, and Devi Asriani. Plant species selection and contribution of agroforestry systems to the income of local and transmigrant famers in East Luwu Regency, Indonesia	3
Svetoslav Anev, Zornitsa Karcheva, Miroslava Zhiponova, and Ganka Chaneva. Biochemical acclimation of European beech (<i>Fagus sylvatica</i> L.) saplings to canopy opening.....	22
Todor Petrov and Hristo Lukanov. Grown characteristics and effectiveness of common quail (<i>Coturnix coturnix</i> , Linnaeus 1758) raising for game restocking.....	37
Rym Barhoumi, Leila Kadik, Ettayib Bensaci, and Rabah Bounar. Effect of invasion by <i>Robinia pseudoacacia</i> on floristic diversity of <i>Quercus suber</i> forests in Chrea, Algeria	49
Svetoslav Anev. Assessment of ice-storm damage in forests using remote sensing	61
Bi Tra Aimé Vroh, Kouassi Bruno Kpangui, and Abdoulaye Cissé. Floristic diversity, composition and biomass of neglected riparian forests in Southern Côte d'Ivoire	74
Taras Bondarenko, Andrii Sasyuk, Volodymyr Zaika, Vasyl Pavlyuk, Yurii Olifir, and Marek Trenčiansky. The influence of undergrowth species on the formation of forest litter and agrochemical soil properties in pine forest stands of Minor Polissya region in Ukraine	91
Bakayoko Hillihase, N'Gouan Emmanuel-Joël Abrou, Venance-Pâques Gniayou Kouadio, Adjo Estelle Genevieve Adiko, and Constant Yves Adou Yao. Diversity and distribution of mega-trees in the vegetation of Azagny National Park, Southern Côte d'Ivoire	103
Nexhat Balaj, Vezir Januzi, and Hyzer Rizani. A study of adaptive potential and aesthetic impact of Floribunda and Grandiflora rose cultivars in urban landscape in Suhareka, Kosovo: An investigation of vegetative growth and remontant flowering ..	117
Vasil Kolev and Gradimir Gruychev. Population dynamics and conservation status of <i>Salmo labrax</i> in the Strugarnitsa River, North-Western Bulgaria.....	129
Hasniar Ulang Dari, Mukrimin Mukrimin, and Yusran. Assessing the impact of green open spaces on urban microclimate in Pinrang Regency, South Sulawesi, Indonesia	137
Zainal Abidin, Muhammad Irfan Affandi, Hari Kaskoyo, Dewi Lengkana, and Eny Puspasari. Community and forest linkages in food, water, fuelwood of community residing nearby Wan Abdul Rachman Forest Park, Indonesia	159

Plant species selection and contribution of agroforestry systems to the income of local and transmigrant famers in East Luwu Regency, Indonesia

Syamsuddin Millang^{1*}, Budi Arty¹, Eny Yuniati², Ahmad R. Makkasau¹, Dicky¹, and Devi Asriani¹

¹Faculty of Forestry, University of Hasanuddin, Makassar, Indonesia.

*E-mail: smillang60@yahoo.com

²Department of Biology, Faculty of Mathematics and Natural Sciences, University of Tadulako, Palu, Indonesia

Received: 02 November 2024 / Accepted: 31 January 2025 / Available online: 11 February 2025



Open Access: This work is distributed under the Creative Commons Attribution 4.0 License.

Abstract

Each tribe has unique experiences and knowledge regarding plant utilization and cultivation. This knowledge and experience are passed down from generation to generation until they become a habit. The habit of selecting and cultivating plants is reflected in the agroforestry system that is developed. Differences in the composition of plant species within the agroforestry system affect farmers' income of local tribe and transmigrant. This study aims to determine the considerations for selecting plant species, analysing the composition of plant species, farmers' income, and the contribution of agroforestry systems to farmer household income. A vegetation survey and structured interviews using questionnaires were conducted. Respondents were determined using the purposive sampling method with the criteria of farmers who implement an agroforestry system and a minimum managed land area of 0.5 ha. Data were analysed descriptively and quantitatively. The results showed that the composition of plant species differed between local and transmigrant farmers. Transmigrant farmers tend to cultivate vegetable crops, such as tomatoes and chilies, while local tribes tend to develop high-value commodity crops, such as pepper and cocoa. Both tribes tend to consider economic rather than socio-cultural factors when selecting plant species. The average agroforestry income of local tribe is greater than that of transmigrant, but the contribution of the agroforestry system to the household income of local tribe is smaller than that of transmigrant, as a consequence of local tribes having other sources of income besides the agroforestry system. It is recommended to maintain the composition of plant species in the local tribe's agroforestry system by optimizing the arrangement of plant growth spaces.

Key words: economic factor, farmer household income, high-value commodity, species composition.

Introduction

Each tribe has a set of life values that are different from other tribes in cultivating,

utilizing, and preserving plants. Differences in cultivating, utilizing, and preserving plants were caused by variations in environmental, social, and cultural conditions

(Millang et al. 2024). Local communities, such as the Luwu tribe, utilize plants in their environment according to their cultural level. The local wisdom of an ethnic group in cultivating, utilizing, and preserving plants reflects their cultural practices in managing biological resources. The socio-cultural background of the ethnic group contains local knowledge and wisdom that is unique and different from other ethnic groups (Permana et al. 2011). They have close relationship with these plants, because they have experienced the process of getting to know, cultivating, and utilizing these plants over a long period of time (Ogwu et al. 2017).

Agroforestry systems are a collective term for all land-use management practices that intentionally cultivate woody perennial plants on the same land management unit as agricultural crops and/or livestock, either in a spatial mixture or in a temporal sequence (Lundgren 1987, Craswell et al. 1998, Tiwari 2022) and there are ecological and economic interactions between woody and non-woody components (Zhang et al. 2023). Agroforestry systems are natural resource management systems that integrate trees on agricultural land and agricultural landscapes to diversify, maintain production and maintain environmental sustainability (Molla 2019, Dhakal and Rai 2020, Purba et al. 2020, Nagar et al. 2021). Agroforestry systems are land management systems that combine the production of agricultural crops, woody plants, shrubs, livestock and/or aquatic resources that can provide many benefits, increase agricultural resilience and environmental sustainability, and improve people's livelihoods (Qurniati 2023). Farmers, who implement agroforestry patterns, will maximize the use of available land by planting various types of plants in suc-

cession, so that the diversity produced on a land includes not only the diversity of plant types and ages but also the diversity of products (Markum et al. 2021), including providing ecological services, maintaining biodiversity, and increasing community resilience in terms of food security (Kumar 2006, Gonçalves et al. 2021, Tirkey et al. 2024). With the diversity of plant species and products, farmers can harvest and utilize the production of their agroforestry system sustainably to meet their economic needs (Nurjanah et al. 2020). The combination of forestry and agricultural components applied to the agroforestry system creates strong interactions between each component based on the composition of the types of plants developed, so that the application of the agroforestry system can provide economic value for farmers' income (Olivi et al. 2015, Wanderi et al. 2019, Notaro et al. 2022). Nair (1993) classified agroforestry systems based on structural, functional, socio-economic, and ecological distribution. Structural basis refers to the nature and arrangement of agroforestry components, forming agroforestry systems such as agrisilviculture, silvopastural, and agrosilvopastural.

The success of an agroforestry system is determined by many factors (Millang 2021, Widiyanto and Hani 2021, Zhang et al. 2023), one of which is the selection of agroforestry component types. The factors and process of selecting the right and appropriate agroforestry component types (forestry, agriculture and/or livestock) are one of the crucial stages in agroforestry development. Consideration of the ease of these species to be combined with various cultures and the concept of multipurpose tree species are the most important characteristics (Tiwari 2022). The main criteria for selecting tree species are that they are

preferred by farmers, well known by farmers (famous), and provide high income and low costs (Tengnas 1994). Other important factors are the economy (Hartoyo et al. 2024) and the socio-culture of the community. Wulandari et al. (2014) stated that the involvement of communities around forests can optimize forest land by implementing agroforestry based on the socio-economic conditions of the community, such as community preferences and adoption of agroforestry patterns. The selection of plant species composition and management methods is very important and determines the success of the agroforestry system (Millang 2021). Not only in Indonesia (Cahyono et al. 2020), but several countries have adopted the agroforestry system in managing their land, such as Pakistan (Ahmad et al. 2023), Ethiopia (Amare and Darr 2023) and Uganda (Buyinza et al. 2020).

In each different region, farmers' habits in implementing and managing agroforestry systems are also different, as well as differences in tribe affecting the amount of income of agroforestry farmers (Olivi et al. 2015). Transmigration is a development equalization program carried out by the Central Government of Indonesia. The program is carried out by moving very densely populated areas such as Java, Bali, and Madura to an island or region with a small population such as Sulawesi (Manay 2016, Anggraini and Hamid 2024). Wasuponda District, East Luwu Regency is one of the areas where transmigrants from several regions were placed in 1984 (Hamzah and Cangara 2018). Transmigrant farmers certainly bring their habits, customs, and culture, including in terms of selecting cultivated plant species. The two tribes have long interacted and lived in harmony and peace. The two tribes ap-

ply an agrisilviculture system in managing their agricultural land. For this reason, research was conducted on considerations in selecting plant species. Research on considerations and reasons for selecting plant species and the contribution of the agrisilviculture systems to farmer household income in relation to tribe differences has never been revealed. Therefore, this research is very important to be conducted to reveal considerations in selecting plant species, the composition of plant types developed, the income of local and Javanese transmigrant farmers, and the contribution of the agroforestry system to farmer household income.

Material and Methods

Time and research location

This research was conducted from June to October 2023 in four villages, namely Tabarano, Balambano, Ledu-Ledu, and Perumpanai Villages, Wasuponda District, East Luwu Regency, South Sulawesi. The area of Wasuponda District is 1244 km². The research area is classified as a lowland tropical rainforest with an altitude of 391–950 m a.s.l. According to data from the Makassar Class I Meteorological Station, the research area's climate falls under Type A based on the Schmidt and Ferguson classification. The average air temperature is 22.68 °C with a minimum air temperature of 14.60 °C and a maximum of 31.8 °C. The average area of land owned by local farmers is 1.5 ha with a range of 0.5 – 4.0 ha, while transmigrants own 1.2 ha with a range of 0.5 – 2.0 ha (Central Statistics Agency of East Luwu Regency 2022). The research location is illustrated in Figure 1.

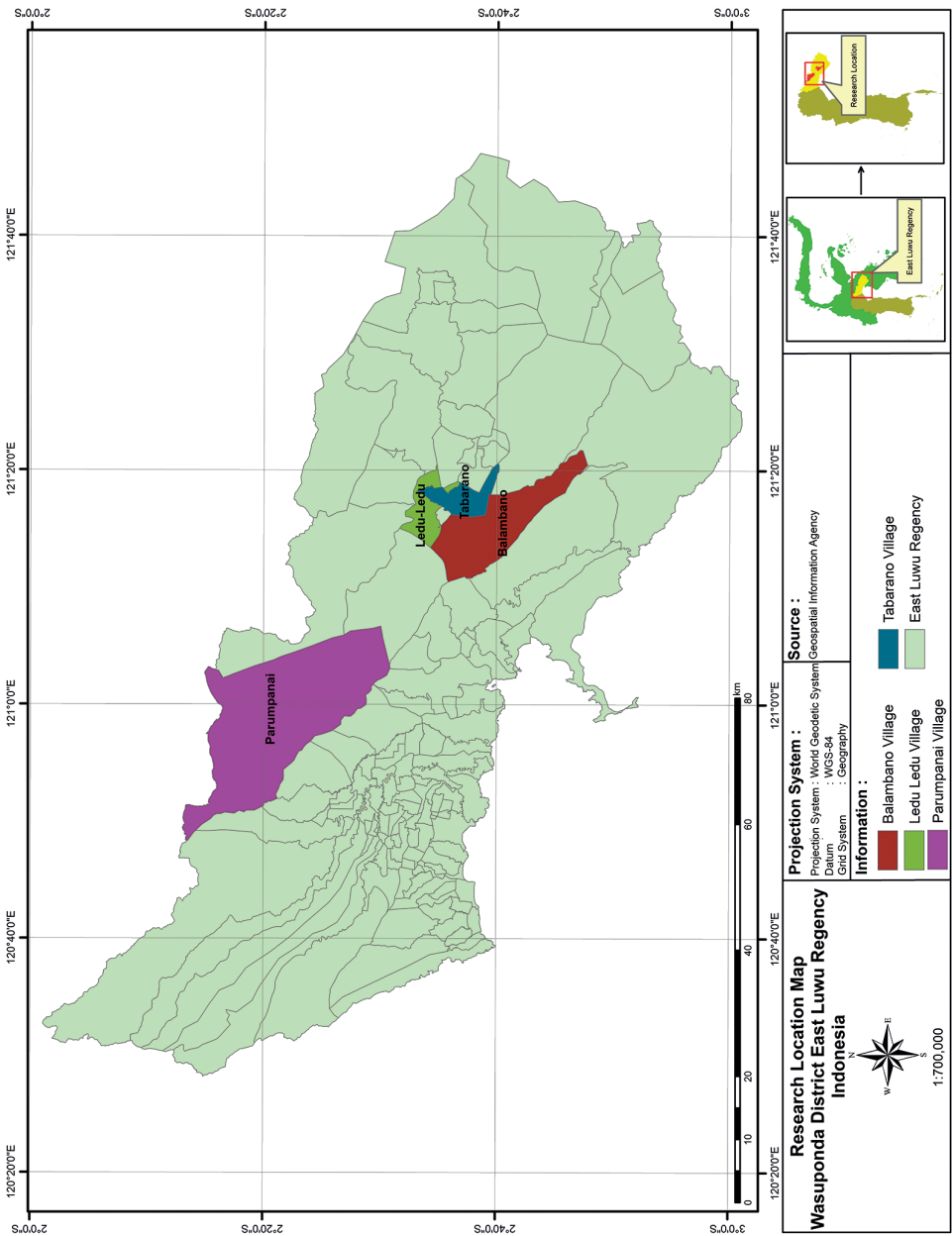


Fig. 1. Research location map.

Data collection

The research method used was survey and structured interview. Determination of respondents and sampling plots were carried out using the Purposive Sampling method with the criteria that respondents had a minimum land area of 0.5 ha and implemented an agroforestry system. The number of interviewed respondents were 45 people consisting of 25 local tribe farmers (Luwu) and 20 Javanese transmigrant farmers. Socio-economic data were obtained by conducting interviews based on a previously created questionnaire. Vegetation surveys were conducted on 20 sampling plots to obtain data on plant types, plant height and diameter.

Data analysis

The obtained data and information were tabulated and analysed using formulas. The stem volume of the trees was determined using formula (1).

$$V = G \cdot H \cdot q, \quad (1)$$

where: V is stem volume of trees, m^3 ; G is tree base area ($\pi \cdot d^2 \cdot 4^{-1}$), m^2 ; H is total height, m ; q is bar form number (0.8).

Mean annual increment by volume per year that occurs up to a certain period. It was determined using formula (2).

$$Z_v = V_t \cdot t^{-1}, \quad (2)$$

where: Z_v is mean annual increment, $m^3 \cdot yr^{-1}$; V_t is tree stem volume at age t , m^3 ; t is age, years.

The cost analysis was done using formula (3).

$$TC = FC + VC, \quad (3)$$

where: TC is total cost, $IDR \cdot ha^{-1} \cdot yr^{-1}$; FC is fixed cost, $IDR \cdot ha^{-1} \cdot yr^{-1}$; VC is variable cost, $IDR \cdot ha^{-1} \cdot yr^{-1}$ (1 $IDR = 58 \cdot 10^{-6}$ € and 1 € = 91.41 IDR – at the rate as of November 02, 2024).

The revenue analysis was done using formula (4).

$$TR = P \cdot Q, \quad (4)$$

where: TR is total revenue, $IDR \cdot ha^{-1} \cdot yr^{-1}$; P is price of product, IDR ; Q is production obtained in an agroforestry system business (wood's product, m^3 ; or commodity, food and vegetables, kg).

The income analysis was done using formula (5).

$$I = TR - TC, \quad (5)$$

where: I is income, $IDR \cdot ha^{-1} \cdot yr^{-1}$; TR is total revenue, $IDR \cdot ha^{-1} \cdot yr^{-1}$; TC is total cost of production, $IDR \cdot ha^{-1} \cdot yr^{-1}$.

The contribution of agroforestry systems to farmer household income was done using formula (6).

$$I_{af} = I_{hr} \cdot 100 \cdot I_{tot}^{-1}, \quad (6)$$

where: I_{af} is the percentage of income from the agroforestry system, %; I_{hr} is total income from the agroforestry system, $IDR \cdot ha^{-1} \cdot yr^{-1}$; I_{tot} is total household income of farmers, $IDR \cdot yr^{-1}$.

Results and Discussion

Considerations for selecting plant species

The most important thing to consider in designing an agroforestry system is what products are produced, how to choose the right type of components, determine how the components are arranged and how to fully support environmental factors. The results of the study showed that the selection of plant types in the agroforestry system by farmers was mostly based on economic factors, both by local tribes and Javanese transmigrants.

A total of 22 plant species were developed in the agroforestry system by local tribes, there were 19 plant species among

them based on economic considerations and only 3 types of plants were chosen based on ecological considerations. Likewise, with Javanese transmigrants, there were 17 plant species chosen based on economic considerations and only 2 plant species chosen based on ecological considerations. The factors considered by farmers in choosing plant species in the agroforestry system are presented in Figure 2.

Figure 2 explains that the main factor that farmers consider in choosing plant species is the economic factor. This is different from that stated by Murthy et al. 2016, Mukhlis et al. 2022 that the purpose of developing agroforestry is not only the economic aspect but also various aspects, such as ecology and environment, aesthetics and culture, social status of farmers and mitigation and adaptation to climate change. However, in line with the research results of Prabawani et al. (2024) that farmers prioritize meeting the basic needs of their households while still considering land sustainability as a secondary matter. Subsistence farmers

always prioritize family needs over the interests of natural resource sustainability, for example maintaining land fertility, preventing erosion. Also, in line with Wolle et al. (2021), Fahad et al. (2022), Jinger et al. (2022), and Salceda-Gonzalez et al. (2024), agroforestry can overcome various environmental problems, such as land degradation, climate change, and loss of biodiversity.

Although both tribes have introduced several plant species from the Fabaceae family that can fertilize the soil (El Sabagh et al. 2020), such as gamal (*Gliricidia sepium* (Jacq.) Steud.) (Beedy et al. 2010, Aroonluk 2021, Camelo et al. 2021, Alamu et al. 2023, Kisaka et al. 2023, Maier et al. 2023) and sengon (*Paraserianthes falcataria* (L.) Greuter & R. Rankin) (Elfis et al. 2023, Ristanu et al. 2023), farmers of both tribes do not understand and do not mention ecological considerations (increasing soil fertility). Gamal plants are chosen and planted only to replace the function of tajar (poles for climbing pepper plants) (Prasmatiwi et al. 2024). Tajar is very expensive because it is made of

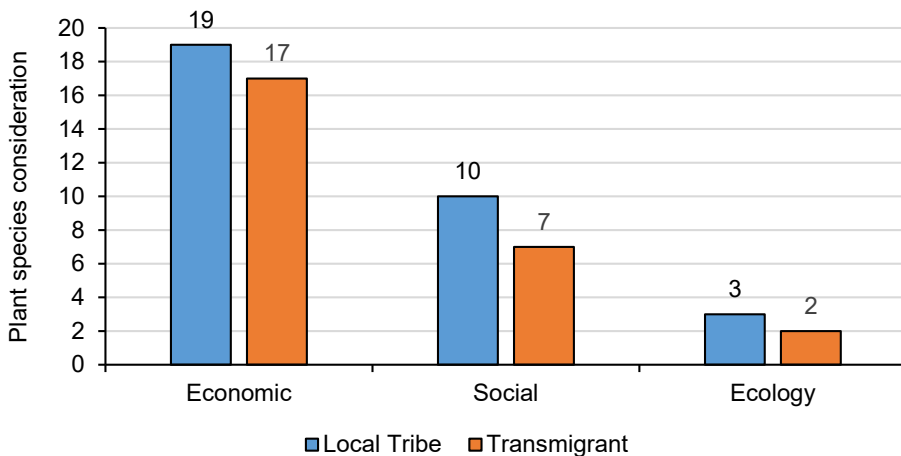


Fig. 2. Considerations for selecting plant species in agroforestry systems by local tribes and Javanese transmigrants.

strong and durable wooden poles (not easily attacked by insects). This indicates that ecological factors have not been widely considered in the selection of plant species for agroforestry systems, both among local tribes and Javanese transmigrants. This is in contrast to Zada et al. (2022) in Shangla and Swat districts, Khyber Pakhtunkhwa Province (KPK), Pakistan, that small-scale agroforestry provides non-financial benefits, such as environmental sustainability, higher living standards, less soil erosion, and shade.

Socio-cultural factors, farmers have not been the main consideration in selecting plant types, unlike the Toraja tribe, who make socio-culture the main factor in selecting agroforestry component types (Millang et al. 2024). It seems that farmers have not planted plant species related to customs and socio-culture, such as petai (*Parkia speciosa* Hassk.) and jengkol (*Archidendron pauciflorum* (Benth.) I.C. Nielsen) among Javanese transmigrants. This is different from Javanese farmers in Temanggung and Magelang Regencies, who like petai and jengkol vegetables as traditional food ingredients, so that both plant species are developed and combined with woody plants, fruits, and food crops, such as suren, durian, and rice in their agroforestry system (Pralawani et al. 2024). The same thing was found in plant species that are often used for traditional food 'Bugalu/kapurung' by local tribes, such as 'patikala' (*Etilingera elatior* (Jack) R.M.Sm.) and 'kadundung' (*Spondias pinnata* (L.f.) Kurz) were not found in the study. Factors that are more often conveyed by farmers as socio-cultural considerations, such as easy to plant, easy to harvest and short harvest time, and can be used by themselves. This gives an illustration that cultural factors are less considered in the selection of plant species.

Plant species composition

The results of the study showed that the agroforestry system applied by farmers of both tribes is simple agroforestry characterized by the presence of one or two species of main plants, such as pepper in local tribes and tomatoes in transmigrants. The number of plant species planted by each farmer, both local and transmigrants, is very limited. Timber and fruit crops as tree components and high-value commodity crops and vegetables as agricultural components. The number of plant species found was 27, classified into 4 groups, namely timber crops, fruit crops, commodity crops, food and vegetables. The number of plant species is relatively the same between local tribes and Javanese transmigrants, namely 22 and 18 species respectively. The composition of plant species found in the agroforestry system of local and Javanese transmigrant farmers is presented in Table 1 and Figure 3.

Table 1 shows that the composition of plant species in the agroforestry system consists of 27 species spread across 20 families with a sample plot area of 2.0 ha. The limited number of plant species cultivated by both tribes is due to the simple agrisilviculture system applied. Simple agrisilviculture systems generally have a limited species structure and composition due to the presence of one or two plant species that are prioritized. The number of plant species found is less when compared to several research results on agroforestry systems in tropical and subtropical areas, namely Eyasu et al. (2020) found 32 species and 20 families; Negash (2021) found 59 species and 36 families; Vibhuti et al. (2019) found 70 plant species; Afentina et al. (2020) found 101 species and 34 families; and Millang (2009)

Table 1. Composition of plant species in the agroforestry system of local tribes and Javanese transmigrant farmers.

No	Plant species			Number of respondents		
	Name in Indonesia	Scientific	Family	Local tribe	Javanese transmigrant	Both tribes
1	Merica	<i>Piper nigrum</i> L.	Piperaceae	17	0	17
2	Durian	<i>Durio zibethinus</i> L.	Bombacaceae	16	5	21
3	Gamal	<i>Gliricidia sepium</i> Jacq.	Fabaceae	14	5	19
4	Rambutan	<i>Nephelium lappaceum</i> L.	Sapindaceae	11	8	19
5	Langsat	<i>Lansium domesticum</i> Corr	Meliaceae	10	5	15
6	Kakao	<i>Theobroma cacao</i> L.	Malvaceae	9	5	14
7	Alpukat	<i>Persea americana</i> Mill.	Lauraceae	9	13	22
8	Mangga	<i>Mangifera indica</i> L.	Anacardiaceae	8	11	19
9	Cengkeh	<i>Syzygium aromaticum</i> L.	Myrtaceae	7	5	12
10	Kapuk	<i>Ceiba pentandra</i> L.	Malvaceae	6	4	10
11	Jati putih	<i>Gmelina arborea</i> Roxb.	Verbenaceae	4	4	8
12	Jabon	<i>Neolamarckia cadamba</i> Roxb.	Rubiaceae	4	5	9
13	Sukun	<i>Artocarpus altilis</i> (Parkinson ex F.A.Zorn) Fosberg	Moraceae	3	0	3
14	Jagung	<i>Zea mays</i> L.	Foaceae	2	0	2
15	Nangka	<i>A. heterophyllus</i> J.	Moraceae	2	9	11
16	Kemiri	<i>Aleurites moluccanus</i> L.	Euphorbiaceae	2	0	2
17	Aren	<i>Arenga pinnata</i> Merr.	Arecaceae	2	0	2
18	Vanili	<i>Vanilla planifolia</i> A.	Orchidaceae	2	0	2
19	Sengon	<i>Paraserinthes falcataria</i> L.	Fabaceae	2	0	2
20	Sawit	<i>Elaeis guineensis</i> Jacq.	Arecaceae	2	0	2
21	Lombok	<i>Capsicum annum</i> L.	Solanaceae	1	14	15
22	Buah naga	<i>Hylocereus polyrhizus</i> Rose	Cactaceae	1	0	1
23	Kacang panjang	<i>Vigna unguiculata</i> L.	Fabaceae	0	5	5
24	Buncis	<i>Phaseolus vulgaris</i> L.	Fabaceae	0	5	5
25	Tomat	<i>Solanum lycopersicum</i> L.	Solanaceae	0	14	14
26	Kangkung	<i>Ipomea aquatica</i> (Parkinson ex F.A.Zorn) Fosberg.	Convolvulaceae	0	4	4
27	Sawi	<i>Brassica chinensis</i> L.	Brassicaceae	0	4	4

found 32 species in a 4.0 ha sample plot in a house yard in Pattalikang Village, Gowa Regency, South Sulawesi. Likewise, when compared to the results of a study of the yard agroforestry system in Southwest Bangladesh, which found 419

species (Kabir et al. 2010); yards in South and Southwest Ethiopia were found to have 206 species (Kassa et al. 2022). The number of plant species developed by farmers is relatively small because each tribe develops certain types of plants that

are considered main crop and other plants are only complementary. Local tribes prioritize commodity crops, such as pepper and cocoa, while Javanese transmigrants prioritize food crops and vegetables, such as tomatoes and chilies. With both tribes, each having one or two main/superior plants that are given more growing space, other plants have less opportunity to get space. Especially transmigrants, who plant more tomato and chili species that require full light, so other plants that can provide shade will be cut or pruned. Thus, the number of species developed by both tribes is limited.

Figure 3 shows that plant species planted by local tribes and Javanese transmigrants are divided into 5 categories. There are differences between the two tribes, namely that Javanese transmigrants tend to develop and cultivate food crops and vegetables, while local tribes tend to plant commodity crops, such as pepper, cacao, and cloves. Local tribes plant cash crops because local people have relatively larger land than Javanese transmigrants. In

addition, Javanese transmigrants generally do not have additional income outside the agroforestry system, so Javanese transmigrants prioritize daily needs, such as food and vegetables to fulfil their lives. This is by what was stated by Wanderi et al. (2019), who stated that the composition of various plant species will have different impacts on the income that will be received by farmers. In addition to the main types of plants, farmers also plant various secondary crops, which serve as shade plants and additional income sources (Prasmatiwati et al. 2020, Novasari 2022).

Revenue

The study results revealed that income sources for local and transmigrant Javanese agroforestry farmers originated from four categories, namely timber crops, fruit crops, food and vegetables, and commodity crops. The amount of farmer income in each category varies. The amount of income for local and transmigrant Javanese tribes is presented in Figure 4.

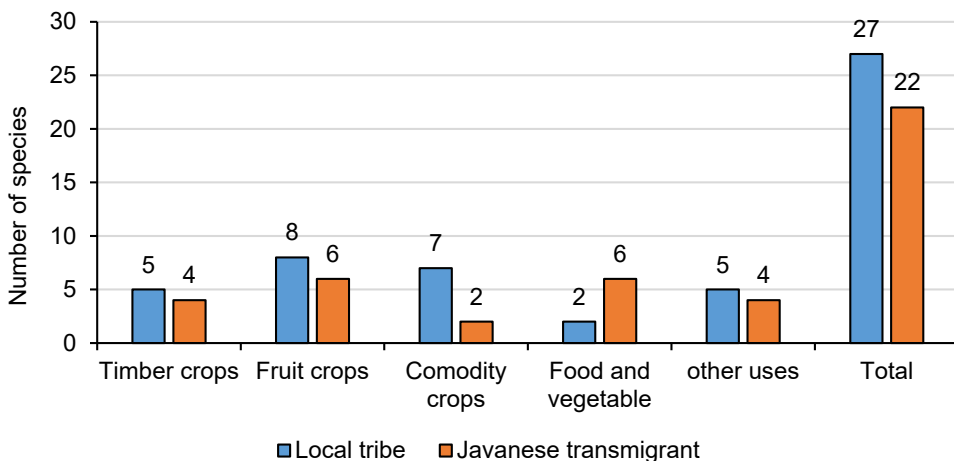


Fig. 3. Composition of agroforestry plant species categorized by local tribes and Javanese transmigrants.

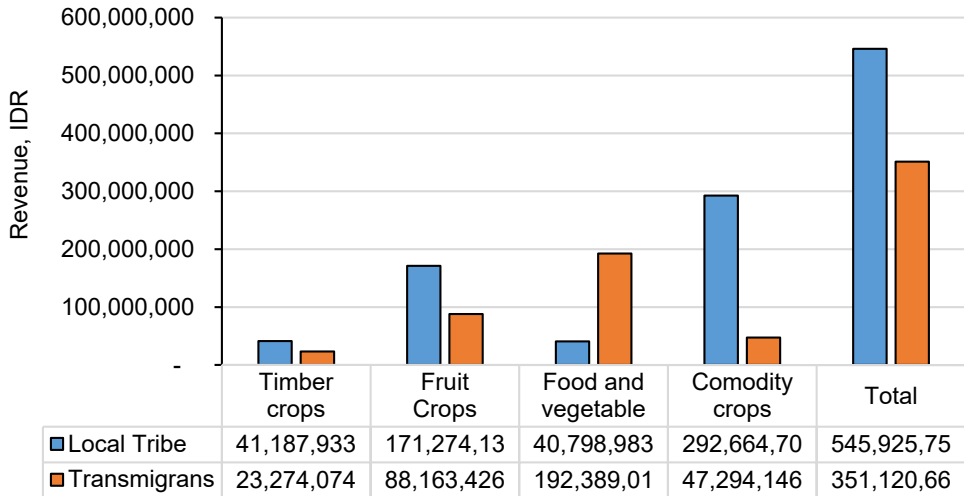


Fig. 4. Category of sources and amount of income of agroforestry farmers in local tribes and Javanese transmigrants.

Figure 4 shows that the largest revenue of local tribes comes from commodity crops of IDR 292,664,704 and fruit crops of IDR 171,274,130, while for Javanese transmigrant farmers from food crops and vegetables of IDR 192,389,015. The difference in the amount and group of revenue between local tribes and Javanese transmigrants is due to differences in the focus of management and selection of plant species. Local tribes focus on the management and selection of commodity crops and fruits (Hendri et al. 2023), while Javanese transmigrants focus more on the management and selection of food crops and vegetables. This is in line with the statement of Duffy et al. (2021) that agroforestry systems contribute to food access, income, health, environmental stability and climate change resilience. If the management of the agroforestry system is commercial and focuses on one type of commodity crop, such as coffee, the income that can be obtained from that one type is 54 %, while traditional agro-

forestry systems allow greater access to plants that have medical benefits. In addition to differences in plant species, differences in revenue can also be influenced by the knowledge, experience, and culture of each tribe. Fruits, animal feed, wood, logs, and cash generation are the main productive roles of this tree species. In addition, these trees also have agroecological services through increasing soil fertility, controlling erosion, mitigating climate change, and conserving biodiversity (Lelamo 2021).

Figure 4 shows that the income from the tree component producing sawnwood and firewood is the lowest, this is because the number of trees planted by each farmer is very limited, the price of wood at the research location is very cheap (ranging from IDR 200,000 – 3,500,000 m⁻³) and the harvest period is long. This is in line with the results from the study by Lehmann et al. (2020) that the gross margin received from the tree component for wood chips is relatively small, even 3 times smaller than

the establishment cost, while the revenue from the agricultural component, namely winter wheat, is very large, even 6 times greater than the production cost. Thus, farmers are generally reluctant to plant trees unless there is a subsidy due to the longer payback period.

Income

The results of the study showed that the average income obtained by local and transmigrant farmers was different and that local farmers were higher than transmigrants. The average income of local and transmigrant farmers is presented in Figure 5.

Figure 5 shows that the income of local farmers is greater than that of transmigrant, local farmers earn an average income of IDR 19,992,447 $\text{ha}^{-1}\cdot\text{yr}^{-1}$, while transmigrant Javanese farmers only earn IDR 15,994,783 $\text{ha}^{-1}\cdot\text{yr}^{-1}$. This is because local farmers tend to develop commodity crops and fruits that are more expensive and stable in the market, such as pepper, cloves, and cocoa, while transmigrant farmers tend to develop food crops and vegetables, such as tomatoes and chilies that are unstable and cheaper. Local

tribes plant and develop more high-value fruit and cash crops, while they develop less food crops and vegetables because local food sources (staple foods) already exist or are available, either in the form of paddy fields or sago. Meanwhile, transmigrants plant and develop more vegetables that have a short life span, so that they can earn income in a short time to meet their families' daily needs. The same thing was stated by Molla (2019) that the main reason farmers implement the agroforestry system is to earn income and meet their family's food needs.

The average income of agroforestry farmers of the two tribes (local/Luwu and transmigrants/Java) of IDR 18,215,707 $\text{ha}^{-1}\cdot\text{yr}^{-1}$ is greater when compared to the income of agroforestry farmers in Parungpanjang Bogor of IDR 16,780,000 (Desmiwati et al. 2021). Likewise, the average income of agroforestry farmers in the Kendeng Mountains Area, Java, Indonesia, was IDR 14,390,771 $\text{ha}^{-1}\cdot\text{yr}^{-1}$ (57.43 % of the total household income of IDR 25,071,029 yr^{-1}) Santosa et al. (2023). However, it is smaller when compared to the income of agroforestry farmers in Sukoharjo 1 Village, Pringsewu Regency, Lampung, Sumatra of IDR 50,142,696 $\text{ha}^{-1}\cdot\text{yr}^{-1}$ (Olivi et

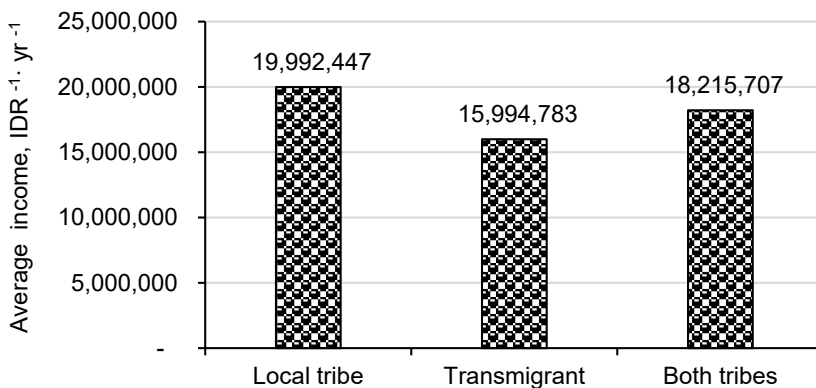


Fig. 5. Average income of local and transmigrant Javanese agroforestry farmers.

al. 2015) and agroforestry productivity in Marena, Enrekang Regency, South Sulawesi of IDR 20,512,208 $\text{ha}^{-1}\cdot\text{yr}^{-1}$ (Samrin et al. 2024).

The results of the study showed that there was a difference in income between local tribes and transmigrants, local tribes generated higher incomes. This could be due to differences in the area of cultivated land owned and the types of crops planted. The average area of land owned by local tribes and transmigrants was 1.5 and 1.2 ha, respectively. There is a tendency that the wider cultivated land owned, the higher income received. Likewise, the suitability of plant species selected and planted also plays a major role in increasing income. If expensive commodity plant species (cloves, pepper, cocoa) are widely planted, farmers' income tends to be higher and vice versa, if the agroforestry system is dominated by sawn wood trees, the income tends to be lower (Duffy et al. 2021, Millang et al. 2024).

The average income received by farmers from the agroforestry system in both tribes was 18,215,707 $\text{ha}^{-1}\cdot\text{yr}^{-1}$, with a range of IDR 8,753,000 to IDR 37,312,778

$\text{ha}^{-1}\cdot\text{yr}^{-1}$. District minimum wage (DMW) of East Luwu Regency in 2024 were IDR 3,434,298 per month (Central Statistics Agency of East Luwu Regency 2024). The income obtained by farmers from the agroforestry system when compared to the DMW of East Luwu Regency is equivalent to 44.20 % of the DMW. This shows that the agroforestry system is an important source of income for farmers (Achmad et al. 2022) and makes a major contribution to the income of farmers in local tribes and transmigrants (Duffy et al. 2021). Therefore, it is necessary to encourage the implementation of an agroforestry system so that farmers' land is more productive and sustainable.

Contribution of agroforestry

The results of the study show that the contribution of agroforestry systems to the average income of local farmers and Javanese transmigrants varies greatly. The contribution of agroforestry systems to the household income of local farmers and Javanese transmigrants is presented in Figure 6.

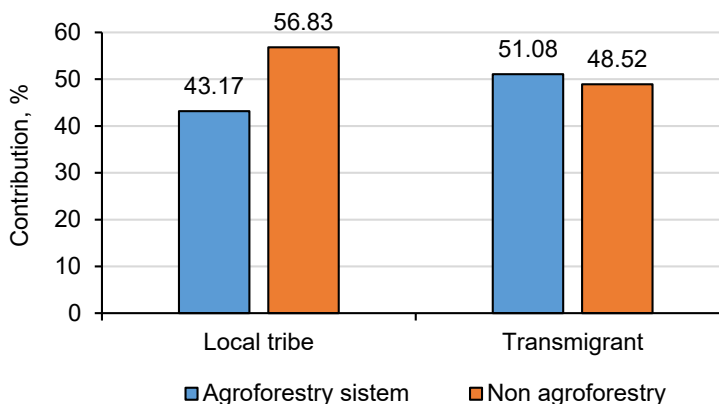


Fig. 6. Contribution of agroforestry systems to household income of local and transmigrant farmers.

Figure 6 shows that the contribution of the agroforestry system to the household income of local tribal farmers is small, and vice versa, for transmigrant farmers the contribution is large, namely 43.17 % and 51.08 %, respectively. The difference in the contribution of the agroforestry system is because local tribal farmers have other jobs besides being farmers. In local tribes, some work as employees of mining companies and sales businesses, in addition to farming agroforestry. Thus, income outside the agroforestry system is greater. This is in line with what was stated by Salatalohy et al. (2019) and Diniyati and Achmad (2020), that farmers do not only have one type of job that they rely on but have other jobs to meet their family's needs. On the other hand, for transmigrants, the contribution is greater because their main job is generally as agroforestry system farmers, so their income outside the agroforestry sector is small.

The contribution of the agroforestry system, especially for transmigrants, is quite high when compared to the results of Zerihun's research (Zerihun 2021), which reported that the contribution of the agroforestry system in the Eastern Cape Province of South Africa was <10 %. However, it is in the same range when compared to the report by Sudomo et al. (2023), that the agroforestry system of smallholder farmers contributes to farmers' income by 51–54 % and if semi-commercial can support 57 %. Likewise, the research results of Santosa et al. (2023) reported that the contribution of the agroforestry system to the household income of farmers in the Kendeng Mountains Area, Indonesia, was 57.43 %. But in contrast to the research results of Murniati et al. (2022) on the cocoa-based agroforestry system as an alternative to resolving land use conflicts in conservation forest areas contributed to

the total income of farmers by 75.63 %.

Conclusions

The selection of appropriate plant species and the proper management of agroforestry systems are influenced by tribe and also have significant implications for farmers' income. The agroforestry systems developed by both tribes tend to be simple agroforestry systems, namely prioritizing one type of plant, especially high-value commodity crops. Local tribe farmers and transmigrants cultivate a relatively limited variety of crops, 27 species from 20 families. Local tribe tend to focus on high-value commodity crops, such as pepper and cocoa, while transmigrants primarily cultivate vegetables, such as chilies and tomatoes. The primary factors influencing the selection of plant species by both local tribes and transmigrants are economic considerations, while ecological and socio-cultural factors are given less priority. The average income of local farmers from agroforestry systems (IDR 19,992,447 ha⁻¹·yr⁻¹) is higher than that of transmigrants (IDR 15,994,783 ha⁻¹·yr⁻¹), as local tribes generally grow high-value, stable-price crops. However, the contribution of agroforestry to the household income of local farmers (43.17 %) is lower than that of transmigrants (51.08 %), since transmigrants predominantly rely on agroforestry, whereas local tribal farmers engage in additional occupations outside agroforestry. To enhance agroforestry systems of both tribes, it is recommended to introduce plant species from the Fabaceae family and improve the spatial arrangement of crops to minimize interspecies competition. These improvements could increase farmers' incomes and help maintain soil fertility.

References

- ACHMAD B., SANUDIN, SIARUDIN M., WIDIYANTO A., DINIYATI D. SUDOMO A., HANI A., FAUZIYAH E., SUHAENDAH E., WIDYANINGSIH T. S., HANDAYANI WURI., MAHARANI D., SUHARTONO, PALMOLINA M., SWESTIANI D., SULISTIADI H. B. S., WINARA A., NUR Y. H., DIANA M., GARTIKA D., RUSWANDI A. 2022. Traditional Subsistence Farming of Smallholder Agroforestry Systems in Indonesia: A Review. *Sustainability* 14(14), 8631. 33 p. <https://doi.org/10.3390/su14148631>
- AFENTINA, McSHANE P., WRIGHT W. 2020. Ethnobotany, rattan agroforestry, and conservation of ecosystem services in Central Kalimantan, Indonesia. *Agroforestry Systems* 94(2): 639–650. <https://doi.org/10.1007/s10457-019-00428-x>
- AHMAD S., XU H., EKANAYAKE E.M.B.P. 2023. Socioeconomic Determinants and Perceptions of Smallholder Farmers towards Agroforestry Adoption in Northern Irrigated Plain, Pakistan. *Land* 12(4), 813. 25 p. <https://doi.org/10.3390/land12040813>
- ALAMU E.O., ADESOKAN M., FAWOLE S., FAWOLE S., MAZIYA-DIXON B., MEHRETEAB T., CHIKOYE D. 2023. *Gliricidia sepium* (Jacq.) Walp Applications for Enhancing Soil Fertility and Crop Nutritional Qualities: A Review. *Forests* 14(3), 635. 13 p. <https://doi.org/10.3390/f14030635>
- AMARE D., DARR D. 2023. Farmers' Intentions Toward Sustained Agroforestry Adoption: An Application of the Theory of Planned Behavior. *Journal of Sustainable Forestry* 42(9): 869–886. <https://doi.org/10.1080/10549811.2022.2123358>
- ANGGRAINI O., HAMID A. 2024. Economic Development of the Transmigration Community of Air Terang Village, Tilolan District, Buol Regency [Perkembangan Ekonomi Masyarakat Transmigrasi Desa Air Terang Kecamatan Tilolan Kabupaten Buol]. *Jurpis: Jurnal Pendidikan Ilmu Sosial* 21(1): 46–61 (in Indonesian). <https://www.jurnalikipuntad.com/index.php/jurpis/article/view/3708/2033>
- AROONLUK S. 2021. Diversity of Leguminous *Gliricidia* sp. in Thailand and Utilization of *Gliricidia sepium* as a Compost Fertilizer for Soil Improvement. *Journal of Sustainability Science and Management* 16(6): 138–147. doi: 10.46754/jssm.2021.08.012
- BEEDY T.L., SNAPP S.S., AKINNIFESI F.K., SILESHI G.W. 2010. Impact of *Gliricidia sepium* intercropping on soil organic matter fractions in a maize-based cropping system. *Agric Ecosyst Environ* 138(3–4): 139–146. <https://doi.org/10.1016/j.agee.2010.04.008>
- BUYINZA J., NUBERG I.K., MUTHURI C.W., DENTON M.D. 2020. Assessing smallholder farmers' motivation to adopt agroforestry using a multi-group structural equation modeling approach. *Agroforestry Systems* 94(6): 2199–2211. <https://doi.org/10.1007/s10457-020-00541-2>
- CAHYONO E.D., FAIRUZZANA S., WILLIANTO D. 2020. Agroforestry innovation through planned farmer behavior: Trimming in pine – coffee systems. *Land* 9(10), 363. 20 p. <https://doi.org/10.3390/land9100363>
- CAMELO D., DUBEUX J.C.B., DOS SANTOS M.V.F. 2021. Soil microbial activity and biomass in semiarid agroforestry systems integrating forage cactus and tree legumes. *Agronomy* 11(8), 1558. 13 p. <https://doi.org/10.3390/agronomy11081558>
- CENTRAL STATISTICS AGENCY OF EAST LUWU REGENCY 2022. East Luwu Regency in Numbers 2022 [Kabupaten Luwu Timur Dalam Angka 2022]. Central Bureau of Statistics. 411 p. (in Indonesian). <https://luwutimurkab.bps.go.id/id/publication/2022/02/25/7452a8d-0f92579822148dd22/kabupaten-luwu-timur-dalam-angka-2022.html> (Accessed on October 25, 2024)
- CENTRAL STATISTICS AGENCY OF EAST LUWU REGENCY 2024. Luwu Timur Regency in Figures 2024 [Kabupaten Luwu Timur Dalam Angka 2024] Central Bureau of Statistics. 431 p. (in Indonesian). <https://luwutimurkab.bps.go.id/en/publication/2024/02/28/789405eef2f-71466554b25f8/kabupaten-luwu-timur-dalam-angka-2024>
- CRASWELL E.T., SAJJAPONGSE A., HOWLETT D.J.B., DOWLING A.J. 1998. Agro-

- forestry in the management of sloping lands in Asia and the Pacific. *Agroforestry Systems* 38: 121–137. <https://doi.org/10.1023/A:1005960612386>
- DESMIYATI D., VERIASA T.O., AMINAH A., SAFITRI A.D., HENDARTO K.A. et al. 2021. Contribution of Agroforestry Systems to Farmer Income in State Forest Areas: A Case Study of Parungpanjang, Indonesia. *Forest and Society* 5(1): 109–119. <http://dx.doi.org/10.24259/fs.v5i1.11223>
- DHAKAL A., RAI R.K. 2020. Who adopts agroforestry in a subsistence economy? – Lessons from the Terai of Nepal. *Forests* 11(5), 565. 15 p. <https://doi.org/10.3390/f11050565>
- DINIYATI D., ACHMAD B. 2020. Livelihoods survival strategy of sharecropper household in Sumbawa District, West Nusa Tenggara and Tasikmalaya Districts, West Java. *IOP Conference Series: Earth and Environmental Science* 533, 012022. 9 p. doi: 10.1088/1755-1315/533/1/012022
- DUFFY C., TOTH G.G., HAGAN R.P.O., McKEOWN P.C., RAHMAN S.A., WIDYANINGSIH Y., SUNDERLAND T.C.H., SPILLANE C. 2021. Agroforestry contributions to smallholder farmer food security in Indonesia. *Agroforestry Systems* 95: 1109–1124. <https://doi.org/10.1007/s10457-021-00632-8>
- EL SABAGH A., HOSSAIN A., ISLAM M. S., FAHAD S., RATNASEKERA D., MEENA R.S., WASAYA A., YASIR T.A., IKRAM M., MUBEEN M., FATIMA M., NASIM W., ÇİĞ A., ÇİĞ F., ERMAN M., HASANUZZAMAN M. 2020. Nitrogen Fixation of Legumes Under the Family Fabaceae: Adverse Effect of Abiotic Stresses and Mitigation Strategies. In: Hasanuzzaman M., Araújo S., Gill S. (Eds), *The Plant Family Fabaceae*. Springer, Singapore: 75–111. https://doi.org/10.1007/978-981-15-4752-2_4
- ELFIS E., TITISARI P.W., FERAZONA S., FARRADINNA S. 2023. Enrichment Smallholder Oil Palm Plantations Through the Application Local Plant Agroforestry on Peatlands in Siak Regency, Riau [Pengayaan Kebun Sawit Rakyat Melalui Penerapan Agroforestri Tumbuhan Lokal pada Lahan Gambut di Kabupaten Siak, Riau]. *Jurnal Pengabdian Pada Masyarakat* 8(3): 674–682 (in Indonesian). <https://doi.org/10.30653/jppm.v8i3.430>
- EYASU G., TOLERA M., NEGASH M. 2020. Woody species composition, structure, and diversity of homegarden agroforestry systems in southern Tigray, Northern Ethiopia. *Heliyon* 6(12), e05500. 9 p. <https://doi.org/10.1016/j.heliyon.2020.e05500>
- FAHAD S., CHAVAN S.B., CHICHAGHARE A.R. 2022. Agroforestry Systems for Soil Health Improvement and Maintenance. *Sustainability (Switzerland)* 14 (22), 14877. 25 p. <https://doi.org/10.3390/su142214877>
- GONÇALVES C.Q., SCHLINDWEIN M.M., MARTINELLI G. 2021. Agroforestry Systems: A Systematic Review Focusing on Traditional Indigenous Practices, Food and Nutrition Security, Economic Viability, and the Role of Women. *Sustainability* 13(20), 11397. <https://doi.org/10.3390/su132011397>
- HAMZAH H., CANGARA H. 2018. Integration of Bali and Local Ethnic Transmigrant in Wotu District East Luwu District: An Approach from the Perspective of Cultural Communication [Integrasi Transmigran Etnik Bali Dan Lokal Di Kecamatan Wotu Kabupaten Luwu Timur: Suatu Pendekatan Dari Perspektif Komunikasi Antarbudaya]. *Jurnal Komunikasi KAREBA* 7(2): 202–211 (in Indonesian). <https://api.semanticscholar.org/CorpusID:198648010>
- HARTOYO A.P.P., SUNDAWATI L., SETIAJIATI F., AMANULLAH F.R. 2024. Plant Species Composition and Local Farmers' Perceptions of Agroforestry Practices: Initial Findings from Aceh and Java, Indonesia. *BIO Web of Conferences* 123, 01035. 12 p. <https://doi.org/10.1051/bioconf/202412301035>
- HENDRI, RAHMADANIARTI A., MAHATMANDIRA G.A. 2023. Optimization agroforestry to address green economy and climate change in Manokwari Regency, West Papua. In: *IOP Conference Series: Earth and Environmental Science* 1192(1), 012038. doi: 10.1088/1755-1315/1192/1/012038
- JINGER D., KUMAR R., KAKADE V. 2022. Agroforestry for controlling soil erosion and enhancing system productivity in ravine

- lands of Western India under climate change scenario. *Environmental Monitoring and Assessment* 194, 267. <https://doi.org/10.1007/s10661-022-09910-z>
- KABIR MD.E., WEBB E.L., DHAR T.K. 2010. Are Home-gardens Managed Properly in Rural Bangladesh? *Asia-Pacific Journal of Rural Development* 20(2): 47–68. <https://doi.org/10.1177/101852912010>
- KASSA G., BEKELE T., DEMISSEW S., ABEBE T. 2022. Above- and belowground biomass and biomass carbon stocks in home-garden agroforestry systems of different age groups at three sites of southern and southwestern Ethiopia. *Carbon Management* 13(1): 531–549. <https://doi.org/10.1080/17583004.2022.2133743>
- KISAKA O.M., SHISANYA C., COUNAC L. 2023. Integrating no-tillage with agroforestry augments soil quality indicators in Kenya's dry-land agroecosystems. *Soil and Tillage Research* 227, 105586. <https://doi.org/10.1016/j.still.2022.105586>
- KUMAR B.M. 2006. Agroforestry: the new old paradigm for Asian food security. *Journal of Tropical Agriculture* 44(1–2): 1–14. <https://jtropag.kau.in/index.php/ojs2/article/view/144>
- LEHMANN L.M., SMITH J., WESTAWAY S., PISANELLI A., RUSSO G., BOREK R., SANDOR M., GLIGA A., SMITH L., GHALEY B.B. 2020. Productivity and Economic Evaluation of Agroforestry Systems for Sustainable Production of Food and Non-Food Products. *Sustainability*, 12(13), 5429 <https://doi.org/10.3390/su12135429>
- LELAMO L.L. 2021. A review on the indigenous multipurpose agroforestry tree species in Ethiopia: management, their productive and service roles and constraints. *Helion* 7(9), e07874. 9 p. <https://doi.org/10.1016/j.heliyon.2021.e07874>
- LUNDGREN B.O. 1987. Institutional aspects of agroforestry research and development. In: Steppeler H.A., Nair P.K.R. (Eds), *Agroforestry a decade of development*. International Council for Research in Agroforestry (ICRAF), Nairobi, Kenya: 43–51.
- MAIER R., SCHACK-KIRCHNER H., NYOKA B.I., LANG F. 2023. Gliricidia intercropping supports soil organic matter stabilization at Makoka Research Station, Malawi. *Geoderma Regional* 35, e00730. <https://doi.org/10.1016/j.geodrs.2023.e00730>
- MANAY H. 2016. Demographic projects in the shadow of national disintegration: a study of transmigration in Gorontalo, 1950–1960 [Proyek demografi dalam bayang-bayang disintegrasi nasional: studi tentang transmigrasi di Gorontalo, 1950–1960]. *Jurnal Sejarah Citra Lekha* 1(2): 93–106 (in Indonesian). <https://doi.org/10.14710/jscl.v1i2.12766>
- MARKUM, ICHSAN A.C., SAPUTRA M., LESTARI A.T., ANUGRAH G. 2021. The patterns of agroforestry: the implementation and its impact on local community income and carbon stock in Sesat Forest, Lombok, Indonesia. In: *IOP Conference Series: Earth and Environmental Science* 917, 012043. 11 p. doi: 10.1088/1755-1315/917/1/012043
- MILLANG S. 2009. Structure and Composition of Mixed Garden Agroforestry Types in Various Sizes of Land Ownership in Pattalikalang Village, Manuju District, Gowa Regency. [Struktur dan Komposisi Jenis Agroforestry Kebun-Campuran pada Berbagai Luas Pemilikan Lahan di Desa Pattalikalang Kecamatan Manuju Kabupaten Gowa]. *Biocelebes* 3(2): 64–73 (in Indonesian).
- MILLANG S. 2021. Productivity of Pangi (*Pangium edule* Reinw.) and biodiversity of agroforestry systems at various altitudes in Toraja Regency, South Sulawesi. *IOP Conference Series: Earth and Environmental Science* 886, 012062. 12 p. doi: 10.1088/1755-1315/886/1/012062
- MILLANG S., YUNIATI E., PAEMBONAN S.A., ARTY B., MAKKAU A.R. 2024. Ethnobotany of the Kombong Agroforestry System and Tongkonan Conservation in the Toraja Tribe, South Sulawesi, Indonesia. *Forest and Society* 8(1): 271–295. <https://orcid.org/0009-0001-1225-5225>
- MOLLA B. 2019. The role of agroforestry on house hold income of rural communities the case Soddo Zuria Woreda; South Ethiopia. *Global Journal of Human-Social Science* 19(B3): 39–48. <https://socialscienceresearch.org/index.php/GJHSS/article/>

view/2960

- MUKHLIS I., RIZALUDIN M.S., HIDAYAH I. 2022. Understanding Socio-Economic and Environmental Impacts of Agroforestry on Rural Communities. *Forests* 13(4), 556. 13 p. <https://doi.org/10.3390/f13040556>
- MURNIATI M., SUHARTI S., YENY I., MINARNINGSIH M. 2022. Cacao-based agroforestry in conservation forest area: farmer participation, main commodities and its contribution to the local production and economy. *Forest and Society* 6(1): 243–274. doi: 10.24259/fs.v6i1.13991
- MURTHY I.K., DUTTA S., VARGHESE V., JOSHI P.P., KUMAR P. 2016. Impact of Agroforestry Systems on Ecological and Socio-Economic Systems: A Review. *Global Journal of Science Frontier Research: Environment & Earth Science* 16(5): 15–27. <https://api.semanticscholar.org/CorpusID:134583196>
- NAGAR B., RAWAT S., PANDEY R., KUMAR M. 2021. Variation in specific gravity and carbon proportion of agroforestry tree species of Himalaya. *Environmental Challenges* 4, 100156. <https://doi.org/10.1016/j.envc.2021.100156>
- NAIR P.K.R. 1993. Classification of agroforestry systems. Chapter 3: 21–37. In: *An introduction to agroforestry*. Dordrecht, Netherlands, Kluwer Academic Publishers. 499 p.
- NEGASH L. 2021. A Selection of Africa's Native Trees: Biology, Uses, Propagation and Restoration Techniques. Addis Ababa, Ethiopia. 621 p.
- NOTARO M., GARY C., LE COQ J.-F., METAY A., RAPIDEL B. 2022. How to increase the joint provision of ecosystem services by agricultural systems. Evidence from coffee-based agroforestry systems. *Agricultural Systems* 196, 103332. 12 p. <https://doi.org/10.1016/j.agsy.2021.103332>
- NOVASARI D. 2022. Potential for Carbon Stored in Simple and Complex Agroforestry Planting Patterns in the Batutegei Forest Management Unit [Potensi Karbon Tersimpan Pada Pola Tanam Agroforestri Sederhana Dan Kompleks di Kesatuan Pengelolaan Hutan Batutegei]. Ms thesis. Universitas Lampung. 95 p. (in Indonesian). <http://digilib.unila.ac.id/63910/3/TESIS%20TANPA%20PEMBAHASAN.pdf>
- NURJANAH A.W., WULANDARI C., QURNIATI R., BAKRI S. 2020. The role of children in agroforestry farming in the Bina Wana Community Forest, West Lampung [Peranan Anak Pada Usaha Tani Agroforestri di Hutan Kemasyarakatan Bina Wana, Lampung Barat]. *Journal of Tropical Upland Resources* 2(2): 173–180. (in Indonesian). <https://doi.org/10.23960/jtur.vol2no2.2020.101>
- OGWU M.C., OSAWARU M.E., OBAHIAGBON G.E. 2017. Ethnobotanical survey of medicinal plants used for traditional reproductive care by Usen people of Edo State, Nigeria. *Malaya Journal of Biosciences* 4(1): 17–29.
- OLIVI R., QURNIATI R., FIRDASARI F. 2015. Contribution of Agroforestry to Farmers' Income in Sukoharjo Village 1, Sukoharjo District, Pringsewu Regency [Kontribusi Agroforestri Terhadap Pendapatan Petani di Desa Sukoharjo 1 Kecamatan Sukoharjo Kabupaten Pringsewu]. *Jurnal Sylva Lestari* 3(2): 1–12. doi: 10.23960/jsl231-12
- PERMANA R.C.E., NASUTION I.P., GUNAWIJAYA J. 2011. Local Wisdom Regarding Disaster Mitigation in the Baduy Community [Kearifan Lokal Tentang Mitigasi Bencana Pada Masyarakat Baduy]. *Makara Human Behavior Studies in Asia* 15(1): 67–76 (in Indonesian). <https://doi.org/10.7454/mssh.v15i1.954>
- PRABAWANI B., HADI S.P., FISHER M.R., WARSONO H., DEWI R.S., AINUDDIN I. 2024. Socioeconomic perspective of agroforestry development in Central Java. *Environmental and Sustainability Indicators* 22, 100354. 10 p. <https://doi.org/10.1016/j.inindic.2024.100354>
- PRASMATIWI F.E., EVIZAL R., ASTUTI T.N., ZAHARA A.R. 2024. Agroforestry coffee reduces household vulnerability to climate change. *Forestry Ideas* 30(2): 244–280.
- PRASMATIWI F.E., LESTARI D.A.H., ISMONO R.H., NURMAYASARI I., EVIZAL R. 2020. Determining the cost of production and income from coffee farming in Bulok District, Tanggamus Regency [Penentuan harga pokok produksi dan pendapatan usaha tani kopi di Kecamatan Bulok Ka-

- bupaten Tanggamus]. *Journal of Tropical Upland Resources* 2(1): 140–149 (in Indonesian). <https://doi.org/10.23960/jtur.vol-2no1.2020.89>
- PURBA M., MARSELA A., MUSTIKA R., SUBAKTI R., KHAIRANI S., SUWARDI A.B. 2020. Potential for Agroforestry Development Based on Local Fruit Plants [Potensi Potensi Pengembangan Agroforestri Berbasis Tumbuhan Buah Lokal]. *Jurnal Ilmiah Pertanian* 17(1): 27–34 (in Indonesian). <https://doi.org/10.31849/jip.v17i1.4113>
- QURNIATI R. 2023. Agroforestry: Potential and Implementation in River Basin Landscapes [Agroforestri: Potensi dan Implementasi dalam Lanskap Daerah Aliran Sungai]. Pusaka Media. Lampung. 143 p. (in Indonesian).
- RISTANU N., KARYANINGSIH I., NURLAILA A. 2023. Revegetation Efforts for Ex-Sand Mining Land in Cipancur Village, Kalimanggis District, Kuningan Regency, West Java [Upaya Revegetasi Lahan Bekas Tambang Pasir di Desa Cipancur Kecamatan Kalimanggis Kabupaten Kuningan Jawa Barat]. *Journal of Forestry and Environment* 5(1): 29–43 (in Indonesian). doi: 10.25134/jfe.v5i1.9046
- SALATALOBY A., DASSIR M., MILLANG S. 2019. Strategy and Structure of Household Livelihoods of Agroforestry Farmers in Gowa Regency, South Sulawesi Province. [Strategi dan Struktur Nafkah Rumah Tangga Petani Agroforestri Di Kabupaten Gowa Provinsi Sulawesi Selatan]. *Jurnal Hutan dan Masyarakat* 11(2): 127–138 (in Indonesian). <http://dx.doi.org/10.24259/jhm.v11i2.8297>
- SALCEDA-GONZALEZ M., UDAWATTA R.P., ANDERSON S.H. 2024. Agroforestry on runoff nitrogen and phosphorus losses from three paired watersheds after 25 years of implementation. *Agroforestry Systems* 98: 603–617. <https://doi.org/10.1007/s10457-023-00932-1>
- SAMRIN S., MILLANG S., RIDWAN, DAUD M. 2024. Land Productivity and Land Equivalent Ratio of Agroforestry System in Marena Customary Forest, Enrekang Regency, South Sulawesi Province, Indonesia. *Jurnal Sylva Lestari* 12(2): 532–548. <https://doi.org/10.23960/jsl.v12i2.877>
- SANTOSA F.J., PADMANINGRUM W., WIDIYANTO, RUBIYANTO C., PURWANTO D., WARDANI R.R.I.K. 2023. Structure of Agroforestry Farmers' Household Income: Findings from the Kendeng Mountains Area, Indonesia. *IOP Conference Series: Earth and Environmental Science* 1364, 012019. doi: 10.1088/1755-1315/1364/1/012019
- SUDOMO A., LEKSONO B., TATA H.L., RAHAYU A.A.D., UMRONI A. et al. 2023. Can Agroforestry Contribute to Food and Livelihood Security for Indonesia's Smallholders in the Climate Change Era? *Agriculture* 13(10), 1896. 25 p. <https://doi.org/10.3390/agriculture13101896>
- TENGNAS B. 1994. Agroforestry extension manual for Kenya. International Centre for Research in Agroforestry. Nairobi. 177 p. https://apps.worldagroforestry.org/Units/Library/Books/PDFs/06_Agroforestry_extension_manual_for_kenya.pdf?n=141 (Accessed on October 20, 2024).
- TIRKEY A.I.P., KUMAR R., SINGH A.K., RAM R.K., MISHRA N.K., PRASAD R.S. 2024. Agroforestry for rural economic empowerment and food security: A review. *International Journal of Research in Agronomy* 7(10): 713–716. <https://doi.org/10.33545/2618060X.2024.v7.i10j.1880>
- TIWARI P. 2022. Selection of Forest Tree Species in Agroforestry System. In Book: AGROFORESTRY – Prospective, Strategies and Future Aspect publisher: Taran Publication: 138–146. https://www.researchgate.net/publication/360180093_Selection_of_Forest_Tree_Species_in_Agroforestry_System (Accessed on October 20, 2024).
- VIBHUTI, BARGALI K., BARGALI S.S. 2019. Species composition, diversity and traditional uses of homegarden in Kumaun Himalaya, India. *Indian Journal of Agricultural Sciences* 89(9): 1415–1418. <https://doi.org/10.56093/ijas.v89i9.93479>
- WANDERI W., QURNIATI R., KASKOYO H. 2019. Contribution of Agroforestry Crops to Farmers' Income and Welfare [Kontribusi Tanaman Agroforestri terhadap Pendapatan dan Kesejahteraan Petani]. *Jurnal Sylva*

- Lestari 7(1): 118–127 (in Indonesian).
- WIDIYANTO A., HANI A. 2021. The Role and Key Success of Agroforestry (A Review). *Jurnal Agroforestry Indonesia* 4 (2): 69–80. <https://media.neliti.com/media/publications/491804-none-96ca3bda.pdf>
- WOLLE H.S., BARBERI P., CARLESI S. 2021. Effect of Homegarden and Parkland Agroforestry Practices in Ethiopia on Selected Soil Properties. *African Journal of Food, Agriculture, Nutrition and Development* 21(5): 18115–18130. <https://doi.org/10.18697/aj-fand.100.19220>
- WULANDARI C., BUDIONO P., YUWONO S.B., HERWANTI S. 2014. Adoption of Agroforestry Patterns and Crop Systems Around Register 19 Forest Park, Lampung Province, Indonesia. *Jurnal Manajemen Hutan Tropika* 20(2): 86–93. doi: 10.7226/jtfm.20.2.86
- ZADA M., ZADA S., ALI M., ZHANG Y., BEGUM A., HAN H., ARIZA-MONTES A., ARAYA-CASTILLO L. 2022. Contribution of Small-Scale Agroforestry to Local Economic Development and Livelihood Resilience: Evidence from Khyber Pakhtunkhwa Province (KPK), Pakistan. *Land* (Basel) 11(1), 71. 21 p. <https://doi.org/10.3390/land11010071>
- ZHANG W., SU K., WANG Q., YANG L., SUN W., RANJITKAR S., SHEN L., KINDT R., JI Y., MARSHALL P., PISEY P.S., EL-KASSABY Y.A. 2023. Agroforestry species selection for forest rehabilitation in the asia-pacific region: a meta-analysis on high-level taxonomy. *Forests* 14(10), 2045. 14 p. <https://doi.org/10.3390/f14102045>
- ZERIHUN M.F. 2021. Agroforestry practices in livelihood improvement in the Eastern Cape Province of South Africa. *Sustainability* 13(15), 8477. 13 p. <https://doi.org/10.3390/su13158477>

Biochemical acclimation of European beech (*Fagus sylvatica* L.) saplings to canopy opening

Svetoslav Anev^{1*}, Zornitsa Karcheva^{1,2}, Miroslava Zhiponova²,
and Ganka Chaneva²

¹Department of Dendrology, Faculty of Forestry, University of Forestry, 10 Kliment Ohridski Blvd., 1797 Sofia, Bulgaria. *E-mail: svetoslav.anev@ltu.bg

²Department of Plant Physiology, Faculty of Biology, Sofia University, 8 Dragan Tsankov Blvd., 1164 Sofia, Bulgaria.

Received: 18 December 2024 / Accepted: 05 February 2025 / Available online: 11 February 2025



Open Access: This work is distributed under the Creative Commons Attribution 4.0 License.

Abstract

The biochemical acclimation of European beech (*Fagus sylvatica* L.) saplings to canopy openings caused by various forest cuttings or natural disturbances was assessed in the 'Petrohan' training and experimental forest range in the Western Stara Planina Mountains. We examined changes in the activity of key enzymatic antioxidants, the accumulation of reducing sugars, the synthesis of phenols and flavonoids, and the content of photosynthetic pigments. Our findings indicated that among the antioxidant enzymes studied, catalase showed the most significant increase in activity in response to the canopy openings. The increase in superoxide dismutase activity was less pronounced, while guaiacol peroxidase was only activated when the saplings were fully exposed to sunlight after the removal of shade from older trees. More pronounced defensive response was observed in the accumulation of reducing sugars and synthesis of phenolics, particularly at higher altitudes and in areas with larger canopy openings. Illumination emerged as primary factor influencing flavonoid accumulation. Following canopy openings, European beech leaves often exhibited reduced chlorophyll content, particularly chlorophyll *b*, in favour of synthesizing more carotenoids. Cutting all mature trees during the group selection harvest practice induced stress on saplings similar to that observed after a large disturbance. Further studies on the influence of orography on patch location could enhance understanding of the mechanistic control of illumination and the stress experienced by saplings of shade-tolerant species like European beech.

Key words: catalase, guaiacol peroxidase, flavonoids, phenols, photosynthetic pigments, superoxide dismutase.

Introduction

European beech (*Fagus sylvatica* L.) is one of the most widely spread tree species in European forests, and it reaches its southeastern natural spread limit in the

Bulgarian mountains. In these borderline areas, populations of European beech are often subjected to stress due to the variation of one or more environmental factors that approach the species' biological tolerance limit. Forest cuttings or distur-

bances can substantially alter the light environment experienced by forest saplings (Kozłowski 2002, Dietze and Clark 2008). The extent of this change is influenced by factors, such as type and intensity of cutting or disturbance, spatial distribution of canopy openings, and initial forest structure. Different cutting practices can create spatial heterogeneity in resource availability, such as light, water, and CO₂. For example, forest cuttings often produce edges between cleared areas and the remaining forest. These edge effects can increase light penetration under the canopy, creating transitional zones with higher light levels compared to the forest interior (Matlack and Litvaitis 1999, Zheng and Chen 2000). In selective logging or partial cutting scenarios, some trees remain in the stand, providing partial shade and creating a dappled light environment with varying shade and sun flecks, which can stimulate regeneration, sapling physiology, and growth (Wagner et al. 2010, 2011). On the other hand, significant canopy openings after clear-cutting or windthrow lead to a drastically altered environment that can be particularly stressful for saplings (Oliver 1980), especially for late-successional species like European beech. Large canopy openings expose beech saplings to heightened environmental stresses, including elevated temperatures and greater fluctuations in soil moisture. This altered environment poses a potential threat to sapling growth and survival.

Few studies have explored the influence of different silvicultural systems or natural disturbances on biochemical acclimation in forests, which is the earliest and most critical stage of sapling adjustment to changing environmental factors. Canopy openings, whether caused by natural disturbances or silvicultural practices, further increase stress, especially on under-

storey saplings. The stress resulting from the stand's opening affects individual saplings unevenly, giving a haphazard character to the litter during this early stage of beech forest development. Acclimation of shade-developed leaves or saplings to increased light may depend on their ability to minimize the magnitude or duration of photoinhibition while enhancing photosynthetic capacity (Naidu and DeLucia 1998). The reactions of individual saplings are initially expressed at the biochemical and physiological levels—manifesting in changes in fundamental indicators, such as antioxidant defence activity, photosynthesis, respiration, and transpiration. These modifications lead to changes in the carbon and water balance of the saplings, potentially triggering gradual exhaustion (Lamloom et al. 2016). Schulze et al. (2019) note that plants rarely experience optimal levels of all essential abiotic factors. Stress responses, in turn, can have adverse effects on growth and other plant processes due to compromises in carbon balance. Under environmental pressure, plants allocate resources to their defence systems, which involve various biochemical, physiological, anatomical, and morphological mechanisms to adapt to their conditions. According to Naidu and DeLucia (1998), the ability to acclimate existing leaves to changing environmental conditions may enable forest tree saplings to exploit canopy gaps when conditions are unfavourable for new leaf production.

Antioxidant systems have been frequently studied in tree species with respect to drought or temperature compensation (Polle and Rennenberg 1994, Rennenberg et al. 2006). As Foyer et al. (1994) pointed out, high levels of incident sunlight combined with extreme temperatures can lead to photoinhibition and oxidative stress in photosynthetically

active tissues due to imbalance between light capture and light utilization for assimilation. Several authors have noted that heat and drought stress increase the production of reactive oxygen species (ROS) (Todorova et al. 2022, 2023, 2024; Carvalho and Helena 2008; Lee et al. 2009; Impa et al. 2012). Biochemical acclimation begins with the plant's need to neutralize these oxygen radicals, which are produced under conditions that deviate significantly from the species' optimal environment. Even during the storage of beech seeds, accumulation of free ROS, such as superoxide radical ($O_2^{\cdot-}$) and hydrogen peroxide (H_2O_2), is observed, and their levels correlate with a loss of seed viability (Pukacka and Ratajczak 2005). However, the most significant challenges occur in the survival of seedlings and saplings. Polle et al. (2001) observed increased oxidative stress as European beech saplings' leaves aged.

Different enzymatic mechanisms for antioxidant protection under stressed conditions are well known. Kraj (2016) pointed out that, except for catalase (CAT), the activity of antioxidative enzymes, such as superoxide dismutase (SOD), ascorbate peroxidase, monodehydroascorbate reductase, dehydroascorbate reductase, and glutathione reductase is highest during the pre-senescence stage of leaves. Popović et al. (2015) noted that the combined analysis of the specific activities and isoform profiles of peroxidases, SOD, and glutathione peroxidases, along with variations in phenolic compound levels, enabled the discrimination between stressed and control seedlings of European beech. Due to higher ascorbic acid and glutathione content and slower activity loss of antioxidative enzymes involved in the decomposition of superoxide anions and hydrogen peroxide, sun-exposed leaves

showed better control over redox balance, oxidative stress, and senescence induction (Kraj and Ślepaczuk 2022). Polle et al. (1997) established that CAT activity is higher in European beech saplings with limited mineral and CO_2 supply. However, high irradiance provokes conditions of instability in the photosynthetic machinery, possibly through reactive oxygen species production at both PSII and PSI (Desotgiu et al. 2012). Lee et al. (2009) showed that activation of SOD and CAT by drought treatment continued when leaf water potential reached -1.65 MPa. After that, their activity remained stable. At the same time, guaiacol peroxidase (GPX) increased primarily under progressive drought stress and correlated with an increase in lipid peroxidation and growth restriction (Lee et al. 2009).

The role of non-enzymatic antioxidants includes reducing sugars and secondary metabolites, such as ascorbic acid, glutathione, tocopherols, carotenoids, flavonoids, phenolic compounds, proline, and anthocyanins (Ashraf et al. 2019, Rudenko et al. 2023). Specific polyphenol concentrations may serve as chemical indicators of a population's acclimation potential and could contribute to forecasting the effects of climate change (Visiné-Rajczki et al. 2023). Anthocyanins, pigments found in the vacuoles of plant cells, help absorb UV light and neutralize free radicals, particularly under light-stress conditions. Phenolic compounds, including tannins and phenolic acids, act as potent antioxidants by neutralizing reactive oxygen species (ROS) and chelating metal ions that promote oxidative stress. Flavonoids, a diverse group of polyphenolic compounds, can neutralize a wide range of ROS and protect cells from UV-induced oxidative damage (Panche et al. 2016).

Some authors (Cadahía et al. 2015)

conducted quantitative analyses that showed cinnamic acids and flavanols were the dominant components of the non-enzymatic antioxidant system in European beech leaves. The metabolomic profiling of European beech leaves identified 56 compounds, including hydroxycinnamic acid derivatives, flavan-3-ols, proanthocyanidins, and flavanols, 38 of which are cited for the first time in this species (Cadahía et al. 2015). According to Visiné-Rajczi et al. (2023), in the polyphenolic antioxidant system of beech leaves, flavonoid (quercetin, kaempferol) glycosides and flavan-3-ol compounds were shown to be potent antioxidants with a strong relation to stem growth.

One of the most vital acclimation traits of European beech to changes in illumination is its ability to develop leaves with different morphological characteristics – sun and shade ecotype leaves. This adaptation enhances light capture and maximizes photosynthetic rates in high-light environments (Wagner et al. 2010). Sun leaves in beech typically have smaller surface areas but are thicker and contain fewer chloroplasts than shade leaves (Closa et al. 2010). In addition, shaded leaves have more equal concentrations of chlorophyll *a* and chlorophyll *b*, whereas in sun leaves, this ratio favours chlorophyll *a* (Lichtenthaler et al. 2007). Fully sun-grown leaves exhibit lower and earlier maximum leaf pigment levels, faster degradation of pigments during senescence, and a higher chlorophyll *a* / chlorophyll *b* ratio compared to leaves growing deeper in the canopy (Kraj and Ślepaczuk 2022). This acclimation enables sun leaves to maximize light absorption and photosynthetic efficiency in high-light environments (Vogelmann and Gorton 2014). Eschrich et al. (1989) noted that the determination of sun and shade leaves in the winter

buds of European beech begins towards the end of July in the previous year. Sun leaves of European beech generally have higher rates of saturated photosynthesis than shade leaves. This acclimation is due to higher content and activity of Rubisco, which allows for efficient light capture and maximum carbon assimilation. On the other hand, shade leaves typically have higher light-use efficiency under low light conditions than sun leaves, thanks to thinner leaves and more chloroplasts in the mesophyll cells (Anev 2024).

This study aimed to evaluate the biochemical responses of European beech saplings to changes in light regimes following different types of forest cutting or large canopy openings caused by wind-throw.

Materials and Methods

Experimental sites and plots

The biochemical responses of European beech (*Fagus sylvatica* L.) saplings to canopy openings were studied in the ‘Petrohan’ training and experimental forest range, located in the Western Stara Planina Mountains. The region has a mountainous climate with moderate continental influence, characterized by mean annual temperature of 4.8 °C at 1450 m a.s.l. and average annual precipitation of approximately 1080 mm, with higher rainfall in spring months (Kutchukova 1983, Koleva and Peneva 1990). According to Marinova and Bocheva (2023), the average temperature anomaly in Bulgaria for the reference period 1991–2020, compared to 1961–1990, is 0.8 °C. Unlike the average annual air temperature, no significant change in the annual precipitation amount was observed during this period. Marino-

va and Bocheva (2023) noted that in the Petrohan region, temperature anomalies vary between 0.5 °C in autumn and 1.5 °C in summer. At the same time, precipitation rates have decreased by an average of 10–20 mm per year, particularly in winter and spring. Soils in the area are predominantly brown acidic (district eutric cambisol), formed on granite bedrock, with average depth exceeding 80 cm (Malinova and Petrova 2019).

The experimental sites (ES) were selected along an altitude gradient in mono-dominated European beech stands with different silvicultural or disturbance histories. Each ES consisted of two plots: one with an open canopy (O) and the other with a closed canopy, which served as control (C). In 2011, the canopy of the ES1-O plot was opened through group selection harvest, where all mature 120-year-old trees (100%) were cut down, simulating a micro-disturbance in a gap of approximately 0.1 ha, which was not expanded thereafter. In 2013, the canopy of the ES2-O plot, composed of 120-year-old trees, was thinned through a progressive shelterwood

harvest over an area with a 50 m diameter, removing 40 % of the mature trees. In 2018, additional 25 % of the mature trees were removed, and the initial cutting area was expanded to 0.5 ha (Fig. 1).

In the winter of 2013/2014, an extreme wind event disturbed the 80-year-old European beech stand (ES3-O), affecting approximately 2.5 ha. All mature trees (100 %) were uprooted and subsequently removed from the windthrow area over a two-year period. In 2011, the canopy of the ES4-O plot was thinned by shelterwood harvest, with eight mature 160-year-old trees (~15 %) evenly removed across a total area of 0.1 ha. No additional trees were cut in this plot thereafter. The control C-plots were placed near the O-plots in stands that had not been subject to logging or natural disturbance for at least the last twenty years (Table 1).

Biometric indicators of the studied saplings were examined in another of our studies (Marinova and Anev 2024). Different types of forest harvesting and disturbances, combined with the altitude, slope, and aspect of the ES, result in variations

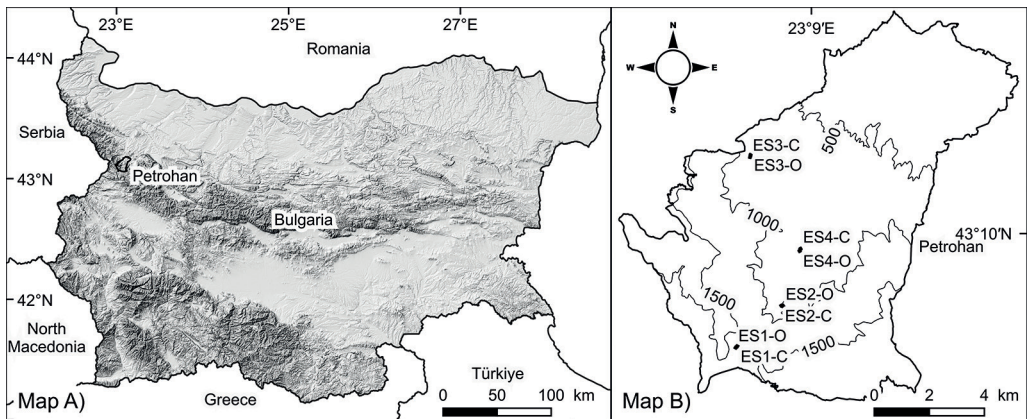


Fig. 1. Location of the experimental sites.

Note: Map A) a general view of Petrohan's position on a relief map of Bulgaria; Map B) experimental sites (ES) on a Petrohan map with elevation contour lines. CRS: WGS 84 / UTM zone 35N.

Table 1. Characteristic of the open (O) and closed (C) canopy plots in experimental sites (ES).

Plots	Latitude	Longitude	Elevation, m	Slope $\pm$ SE, °	Aspect	PPFD $\pm$ SE, $\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$
ES1-C	43°7'32"	23°7'25"	1439	15.0 $\pm$ 0.8	E	47.7 $\pm$ 5.8
ES1-O	43°7'30"	23°7'23"	1450	10.9 $\pm$ 0.8	E	912.7 $\pm$ 197.3
ES2-C	43°8'22"	23°8'33"	970	24.4 $\pm$ 1.7	W	39.0 $\pm$ 12.2
ES2-O	43°8'23"	23°8'37"	1015	28.8 $\pm$ 0.4	W	773.2 $\pm$ 244.2
ES3-C	43°11'15"	23°7'32"	870	22.2 $\pm$ 2.8	E	163.1 $\pm$ 95.2
ES3-O	43°11'18"	23°7'33"	862	21.3 $\pm$ 3.0	E	1125.5 $\pm$ 186.5
ES4-C	43°9'29"	23°9'00"	713	8.4 $\pm$ 0.7	NW	171.5 $\pm$ 10.7
ES4-O	43°9'27"	23°8'59"	718	6.2 $\pm$ 1.4	NW	385.2 $\pm$ 42.2

in understory illumination. Photosynthetic photon flux density (PPFD) was measured above the crowns of saplings with a Li-190 SA portable quantum sensor (LI-COR Inc., Lincoln, NE, USA) at noon on a typical cloudless July day in the centre of the experimental sites.

Plant material and analyses

In July 2019, fifteen randomly selected leaves per plot were collected from beech saplings for biochemical analysis. Immediately after detachment, leaves were frozen in liquid nitrogen for further analysis. The activity of superoxide dismutase (SOD) was assessed following the method of Beauchamp and Fridovich (1971), which is based on the inhibition of photochemically generated superoxide anion ($\text{O}_2^{\cdot -}$) that reduces nitroblue tetrazolium to a blue-coloured formazan. Catalase (CAT) activity was determined following Aebi's method (Aebi 1984), by monitoring the decrease in absorbance of hydrogen peroxide (H_2O_2) at 240 nm, reflecting its enzymatic degradation. Guaiacol peroxidase activity was determined using the method of Hart et al. (1971), by recording the increase in absorbance at 470 nm due to the oxidation of guaiacol in the presence of H_2O_2 . The quantification of phe-

nols and flavonoids was carried out using a Shimadzu UV 1800 spectrophotometer (Kyoto, Japan), following methods described by Zhiponova et al. (2020). Total phenols were assessed using the method of Singleton et al. (1999), involving reaction with Folin-Ciocalteu reagent and sodium carbonate (Na_2CO_3), followed by absorbance measurement at 765 nm and calculation against a standard curve with gallic acid. Total flavonoids were analysed according to the method of Chang et al. (2020), involving reaction with aluminium chloride (AlCl_3) and potassium chloride (KCl), followed by absorbance measurement at 415 nm and calculation against a standard curve with quercetin. All measurements were performed in three technical replicates. The data are presented as mean $\pm$ SE. One-way analysis of variance (ANOVA) followed by Fisher's LSD test with a significance level of 0.05 was performed to estimate the differences between all variants.

Results and Discussion

Enzymatic antioxidants activity

The enzymatic antioxidant activity in the leaves of European beech saplings in-

creased in response to canopy openings and heightened light exposure. Catalase (CAT) activity was 5.18 times higher in the leaves from the windthrow ES3-O plot compared to the ES3-C plot. In ES1, this difference was 3.26 times; in ES2, it was 2.52 times; and the smallest difference, 2.39 times, was observed in ES4. This gradation closely corresponded to the size of the canopy openings and the resulting changes in the light regime. The increased CAT activity in the O-plots can be explained by higher rates of photorespiration, which produces one of the main reactive oxygen species (ROS), hydrogen peroxide (H_2O_2). Although the differences were less pronounced than those for CAT, superoxide dismutase (SOD) activity was also higher in most O-plots compared to their corresponding C-plots, except for the windthrow ES3-C plot (Fig. 2).

Although Peltzer et al. (2002) established that high temperatures can harm protective enzymes such as SOD, ascorbate peroxidase, and glutathione reductase, Polle and Rennenberg (1994) highlighted that beech leaves acclimate to high light, drought, and heat by increasing

SOD levels and activity. In our study, an increase in GPX activity in the O-plots relative to the C-plots was observed in ES1 (2.05 times higher) and especially in ES3 (3.69 times higher). In contrast, GPX levels in the C-plots of ES2 and ES4 were similarly high compared to their respective O-plots. Lee et al. (2009) noted that SOD, CAT, and GPX activity typically increases under progressive drought stress, which is likely experienced by saplings in ES1-O and ES3-O due to the complete canopy removal in these plots. However, in our experiment, such increases were not consistently observed for SOD in ES3-O. This discrepancy may be attributed to sapling exhaustion in the large windthrow area. Alternatively, it could be explained by increased SOD activity in saplings from the ES3-C plot.

Scartazza et al. (2016) observed that the total pool of ascorbate and phenols was higher in European beech leaves from the top and middle canopy layers compared to those from the bottom layer, where peroxidase activity was more prominent. Furthermore, GPX plays a critical role in phenolic synthesis (Burguieres et

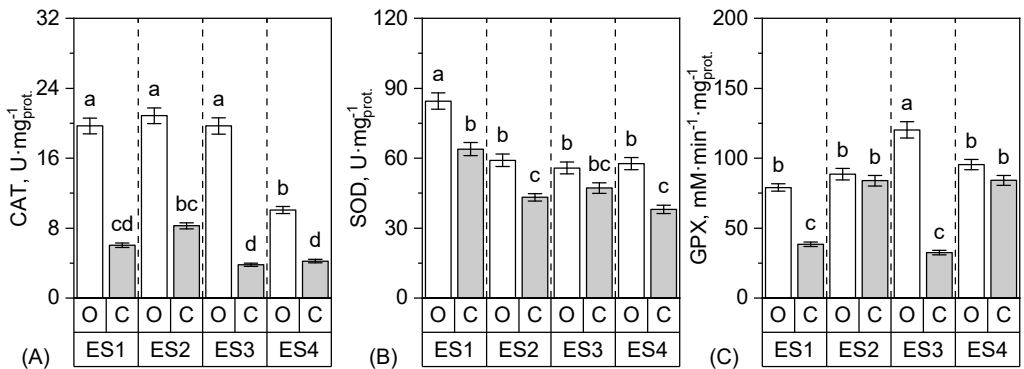


Fig. 2. Changes in the activity of enzymatic antioxidants: (A) catalase (CAT), (B) superoxide dismutase (SOD), and (C) guaiacol peroxidase (GPX) in *F. sylvatica* leaves as affected by canopy opening in the experimental sites.

Note: The data are presented as mean ± SE. Means that do not share a letter are significantly different (One-way ANOVA with Fisher's LSD test, P -value < 0.05).

al. 2007), cell wall lignification (Marjamaa et al. 2003), and the protection of auxins from oxidation and rapid degradation (Kervers et al. 1981). According to Kraj and Ślepaczuk (2022), sun leaves exhibit better control over redox balance, oxidative stress, and senescence induction. This is attributed to their higher ascorbic acid and glutathione content, as well as slower activity loss of antioxidative enzymes involved in the decomposition of superoxide anion and hydrogen peroxide (H_2O_2).

Non-enzymatic antioxidants

The content of reducing sugars was higher in all O-plots compared to their corresponding C-plots. In the O-plots, a clear trend of increasing reducing sugar accumulation with altitude was observed, except in the windthrow ES3 plot. Despite being at a lower altitude, reducing sugar levels in ES3 were equal to those in ES2. Nautiyal (1983) reported that at higher altitudes, soluble sugar content tends to be higher during the active growth phase but decreases during senescence, which may have been accelerated in ES3-O due to critically severe conditions (Anev and Marinova 2021).

Canopy opening had a lower influence on reducing sugar levels compared to altitude. The most significant differences between O- and C-plots were observed in PP2 and PP3 (1.84 times higher in O-plots), while the smallest difference was found in PP4 (1.24 times higher). In plots closer to the optimum altitude for European beech in Bulgaria (ES2 and ES3) the most substantial increases in reducing sugars after canopy opening were observed, both around 1.84 times. Conversely, at the highest (ES1) and lowest (ES4) plots, the increases were weaker: 1.35 times and 1.24 times, respectively.

Abobatta (2020) emphasized that these carbohydrates play a major role in stress mitigation, serving as carbon storage and aiding in the scavenging of reactive oxygen species under drought conditions. The similar levels of reducing sugars in ES3 and ES2, despite ES3 being 150 m lower in altitude, may indicate difficulties in assimilate transportation from the leaves or an intensified effort to enhance defence mechanisms under the drastically altered conditions of the windthrow area (Anev and Marinova 2021) (Fig. 3).

In all plots, canopy opening, whether caused by cutting or natural disturbance, increased phenol synthesis. In some plots (ES2 and ES3), flavonoid levels also increased. The differences in phenol content between O-plots and C-plots were more pronounced with larger canopy openings. For instance, phenol content in the windthrow ES3-O plot was 2.31 times higher than in ES3-C, whereas in ES4-O, where gradual short-term cutting was implemented, the increase was only 1.2 times.

A similar trend was observed for flavonoids. Significant differences between O- and C-plots were detected in ES2 and ES3, but no such differences were observed in ES1 and ES4. Visiné-Rajczi et al. (2023) noted strong correlations between proanthocyanidins, such as Procyanidin B dimer 5, and average stem diameter in European beech, suggesting that these compounds may act as growth indicators. While the low flavonoid content in ES4-O may be explained by less intense canopy thinning, another factor likely influences ES1-O. At higher altitudes, where UV exposure is greatest due to the combination of altitude and canopy opening, saplings require more UV protection.

Despite the significant synthesis of phenols at high altitudes, their transforma-

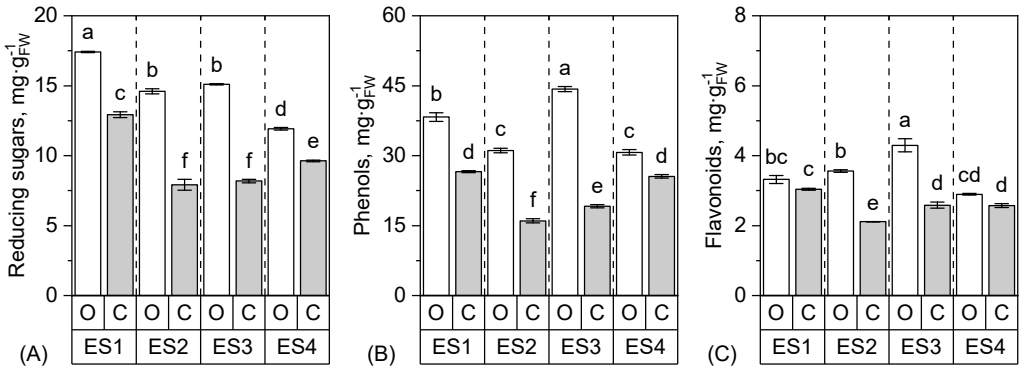


Fig. 3. Changes in the content of non-enzymatic antioxidants (A) reducing sugars; (B) phenols; and (C) flavonoids in *F. sylvatica* leaves as affected by canopy opening in experimental sites.

Note: The data are presented as mean $\pm$ SE. Means that do not share a letter are significantly different (One-way ANOVA with Fisher's LSD test, P -value < 0.05).

tion into flavonoids may be limited by an unknown factor. This suggests that different phenolic compounds might play a role in the light adaptation of European beech saplings at higher altitudes.

Photosynthetic pigments content

Site-specific variations in the amount of plastid pigments were observed. For leaves in ES1 and ES3, which were exposed to high-intensity light (Table 1), higher levels of chlorophyll *a* was measured in the C-plots than in the O-plots. The chlorophyll *a* concentration in the less illuminated ES2-O was similar to that in ES2-C. In ES4-O, which received the least change in illumination, the chlorophyll *a* concentration was even higher than in its corresponding control (ES4-C). The differences in chlorophyll *b* concentrations between the C- and O-plots were directly proportional to the degree of canopy opening. The most significant decrease in chlorophyll *b* concentration was observed in the windthrow plot ES3-O, while in the least affected plot, ES4-O, no significant

reduction in chlorophyll *b* was observed compared to the control plot. According to Vogelmann and Gorton (2014), chlorophyll *b* is the pigment that absorbs diffuse light more efficiently, and its high concentration serves as a marker of acclimation to shading. From this perspective, the lowest levels observed in the windthrow plot ES3-O could indicate a reverse acclimation process in saplings to extremely high light levels. However, these low levels may also signify exhaustion caused by the altered environment, as both chlorophyll concentrations in ES3-O were the lowest compared to all other plots. (Fig. 4).

The second O-plot, where the difference in total chlorophyll content was significant compared to the C-plot, is ES1-O, where the open gap (~ 0.1 ha) was large enough to induce similar stress. Lichtenthaler et al. (1981) indicated that high light-adapted leaves in European beech contained more chlorophyll per unit leaf area than shaded leaves, possibly due to thicker leaf laminae and more chlorophyll-bearing cells in the thicker mesophyll, especially in the palisade zone, which was

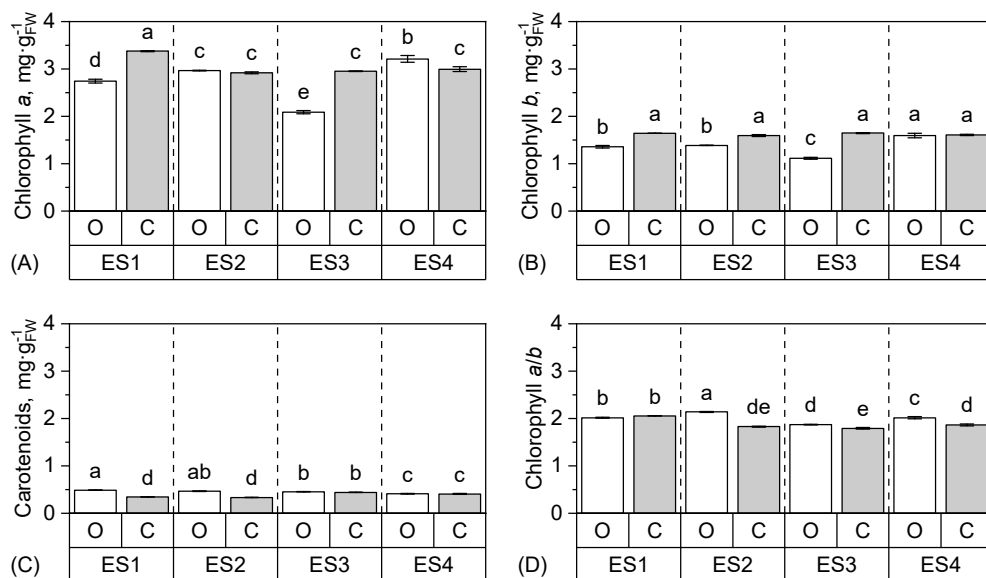


Fig. 4. Changes in the content of plastid pigments (A) chlorophyll *a*; (B) chlorophyll *b*; (C) carotenoids and (D) chlorophyll *a* / *b* ratio in *F. sylvatica* leaves as affected by canopy opening in experimental sites.

Note: The data are presented as mean $\pm$ SE. Means that do not share a letter are significantly different (One-way ANOVA with Fisher's LSD test, P -value < 0.05).

two-rowed in sunny leaves and only one-rowed in shaded leaves. However, when measured per unit leaf mass, the method used in the present experiment, shaded leaves contained more chlorophyll than sunny ones. Scartazza et al. (2016) pointed out that the chlorophyll *a* to chlorophyll *b* ratio and the pool of xanthophyll-cycle pigments in European beech leaves increased at the highest irradiance, along with lutein and β -carotene. This strategy was likely related to the need for shaded saplings to capture the scarce photons more efficiently below the canopy (Anev 2024). Our results partially confirmed this hypothesis. In ES1, ES2, and ES3, the total chlorophyll content (chlorophyll *a* + chlorophyll *b*) was significantly higher in C-plots compared to O-plots. However, in ES2, the differences were not significant (1.04 times), as in ES1 (1.22 times), with

the highest difference observed in ES3 (1.44 times). This trend was attributed to both the higher chlorophyll *a* content (1.23 and 1.41 times higher in ES1 and ES3, respectively) and the higher chlorophyll *b* content (1.21, 1.15, and 1.48 times higher in ES1, ES2, and ES3, respectively). ES4-O was the only plot where the total chlorophyll content was higher than in the corresponding C-plots.

Differences in carotenoid biosynthesis between C and O plots were observed only in ES1 and ES2, likely related to the protective function of carotenoids in neutralizing photooxidative radicals. Since carotenoids protect chlorophyll from photooxidation and photosynthesis from photoinhibition (Maoka 2020), the observed differences in ES1 and ES2 may be attributed to increased solar radiation with shorter wavelengths at higher altitudes

(Ahrens and Henson 2015). The equalized concentrations in the O and C plots in ES3 and ES4 may result from the lower UV and blue light at lower altitudes. However, in ES4, and especially in ES3, carotenoid contents might also reflect their role as signalling compounds for the synthesis of the stress hormone abscisic acid (ABA). Furthermore, Scartazza et al. (2016) concluded that non-photochemical quenching was strongly and positively related to the carotenoid / (chlorophyll $a + b$) ratio.

Conclusions

The acclimation of European beech forests to natural disturbances and human activities involved adjustments at the biochemical level, which provided a basis for physiological, anatomical, and morphological changes. Canopy openings and altered microclimates caused shifts in the saplings' metabolism and defence systems. Catalase activity increased the most after the canopy opened, helping the plant detoxify harmful hydrogen peroxide. Superoxide dismutase also increased, but to a lesser extent. Guaiacol peroxidase was significantly activated only when the saplings were fully exposed to sunlight, following the removal of shading by older trees. An increased accumulation of reducing sugars and phenolic compounds in the leaves was observed, particularly in saplings at higher altitudes or in areas with more significant canopy openings. Flavonoids also accumulated more in response to larger canopy openings, suggesting their role in plant defence against increased sunlight, especially UV radiation. The saplings in more illuminated plots had reduced chlorophyll content, particularly chlorophyll b , which captures scattered light more efficiently. At the

same time, their increased carotenoid production likely helped protect the plants from damage caused by excessive direct light. Cutting all trees during the group selection harvest practice mimics micro-disturbances and, in this regard, represents a nature-based method for regenerating beech forests. However, the signs of increased stress on saplings in ES1-O observed in the present study were similar to those seen after a large disturbance (ES3-O), suggesting the need for more careful approach to patch opening. Further studies on the influence of orography on patch location may contribute to better understanding of the mechanistic control of illumination and, thus, the stress on saplings of shade-tolerant species like European beech.

Acknowledgements

The results of this study were obtained through several consecutive projects: Physiological aspects of natural regeneration in beech forests (NIS-159); Adaptive changes in forests of European beech (*Fagus sylvatica* L.) after cutting or natural disturbance (NIS-B-1010); and Assessment of the damage and recovery rate of the Ice-breaking forests in the 'Petrohan' training and experimental forest range using remote sensing methods (NIS-B-1292). The authors thank the teams involved in these projects for their assistance with field measurements.

References

- AEBI H. 1984. Catalase in vitro. Methods in enzymology 105: 121–126. [https://doi.org/10.1016/s0076-6879\(84\)05016-3](https://doi.org/10.1016/s0076-6879(84)05016-3)
- AHRENS C.D., HENSON R. 2015. Meteorology Today. Cengage Learning. 656 p.

- ABOATTA W.F. 2020. Plant responses and tolerance to combined salt and drought stress. In: Hasanuzzaman M., Tanveer M. (Eds), Salt and drought stress tolerance in plants. Signaling and Communication in Plants. Springer, Cham: 17–52. https://doi.org/10.1007/978-3-030-40277-8_2
- ANEV S. 2024. Light acclimation of European beech (*Fagus sylvatica* L.) saplings after canopy destruction. *Foresry Ideas* 30(1): 66–78.
- ANEV S., MARINOVA A. 2021. Physiological adaptation of European beech (*Fagus sylvatica* L.) and wild cherry (*Prunus avium* L.) saplings after windthrow. *Foresry Ideas* 27(2): 436–445.
- ARNON D.I. 1949. Copper Enzymes in Isolated Chloroplasts. Polyphenoloxidase in Beta Vulgaris. *Plant Physiology* 24(1): 1–15. <https://doi.org/10.1104/pp.24.1.1>
- ASHRAF M.A., RIAZ M., ARIF M.S., RASHEED R., IQBAL M., HUSSAIN I., MUBARIK M.S. 2019. The role of non-enzymatic antioxidants in improving abiotic stress tolerance in plants. In: Hasanuzzaman M., Fujita M., Oku H., Islam M.T. (Eds), Plant tolerance to environmental stress. CRC Press: 129–144.
- BEAUCHAMP C., FRIDOVICH I. 1971. Superoxide dismutase: Improved assays and an assay applicable to acrylamide gels. *Analytical Biochemistry* 44(1): 276–287. [https://doi.org/10.1016/0003-2697\(71\)90370-8](https://doi.org/10.1016/0003-2697(71)90370-8)
- BURGUIERES E., MCCUE P., KWON Y.-I., SHETTY K. 2007. Effect of vitamin C and folic acid on seed vigour response and phenolic-linked antioxidant activity. *Bioresource Technology* 98(7): 1393–1404. <https://doi.org/10.1016/j.biortech.2006.05.046>
- CADAHÍA E., FERNÁNDEZ DE SIMÓN B., ARANDA I., SANZ M., SÁNCHEZ-GÓMEZ D., PINTO E. 2015. Non-targeted metabolomic profile of *Fagus sylvatica* L. leaves using liquid chromatography with mass spectrometry and gas chromatography with mass spectrometry. *Phytochemical analysis* 26(2): 171–182. <https://doi.org/10.1002/pca.2549>
- CARVALHO C.D., HELENA M. 2008. Drought stress and reactive oxygen species. *Plant Signaling & Behavior* 3(3): 156–165. <https://doi.org/10.4161/psb.3.3.5536>
- CHANG C.C., YANG M.H., WEN H.M., CHERN J.C. 2020. Estimation of total flavonoid content in propolis by two complementary colometric methods. *Journal of Food and Drug Analysis* 10(3): 178–182. <https://doi.org/10.38212/2224-6614.2748>
- CLOSA I., IRIGOYEN J.J., GOICOECHEA N. 2010. Microclimatic conditions determined by stem density influence leaf anatomy and leaf physiology of beech (*Fagus sylvatica* L.) growing within stands that naturally regenerate from clear-cutting. *Trees* 24(6): 1029–1043. <https://doi.org/10.1007/s00468-010-0472-3>
- DESOTGIU R., CASCIO C., POLLASTRINI M., GEROSA G., MARZUOLI R., BUSSOTTI F. 2012. Short and long term photosynthetic adjustments in sun and shade leaves of *Fagus sylvatica* L., investigated by fluorescence transient (FT) analysis. *Plant Biosystems – An International Journal Dealing with all Aspects of Plant Biology* 146(sup1): 206–216. <https://doi.org/10.1080/11263504.2012.705350>
- DIETZE M.C., CLARK J.S. 2008. Changing the gap dynamics paradigm: vegetative regeneration control on forest response to disturbance. *Ecological Monographs* 78(3): 331–347. <https://doi.org/10.1890/07-0271.1>
- ESCHRICH W., BURCHARDT R., ESSIAMA S. 1989. The induction of sun and shade leaves of the European beech (*Fagus sylvatica* L.): anatomical studies. *Trees* 3(1): 1–10. <https://doi.org/10.1007/BF00202394>
- FOYER C.H., LELANDAIS M., KUNERT K.J. 1994. Photooxidative stress in plants. *Physiologia Plantarum* 92(4): 696–717. <https://doi.org/10.1111/j.1399-3054.1994.tb03042.x>
- HART M.A., TYSON H., BLOOMBERG R. 1971. Measurement of activity of peroxidase isoenzymes in flax (*Linum usitatissimum*). *Canadian Journal of Botany* 49(12): 2129–2137. <https://doi.org/10.1139/b71-301>
- IMPA S.M., NADARADJAN S., JAGADISH S.V.K. 2012. Drought stress induced reactive oxygen species and anti-oxidants in plants. In: Ahmad P. and Prasad M.N.V. (Eds), Abiotic stress responses in plants: metabolism, productivity and sustainability. Springer New York: 131–147. https://doi.org/10.1007/978-1-4419-9999-9_10

- org/10.1007/978-1-4614-0634-1_7
- KEVERS C., COUMANS M., DE GREEF W., HOFINGER M., GASPAR T. 1981. Habituation in sugarbeet callus: auxin content, auxin protectors, peroxidase pattern and inhibitors. *Physiologia Plantarum* 51(3): 281–286. <https://doi.org/10.1111/j.1399-3054.1981.tb04478.x>
- KOLEVA E., PENEVA R. 1990. Precipitation in Bulgaria. Bulgarian Academy of Sciences. 169 p.
- KOZŁOWSKI T.T. 2002. Physiological ecology of natural regeneration of harvested and disturbed forest stands: implications for forest management. *Forest Ecology and Management* 158(1): 195–221. [https://doi.org/10.1016/S0378-1127\(00\)00712-X](https://doi.org/10.1016/S0378-1127(00)00712-X)
- KRAJ W. 2016. Antioxidative enzyme activity as the factor causing differential autumn senescence in phenological forms of beech (*Fagus sylvatica* L.). *Acta physiologiae plantarum* 39(1), 16. <https://doi.org/10.1007/s11738-016-2316-2>
- KRAJ W., ŚLEPACZUK A. 2022. Morphophysiological acclimation of developed and senescing beech leaves to different light conditions. *Forests* 13(8), 1333. <https://doi.org/10.3390/f13081333>
- KUTCHUKOVA M. 1983. Air temperature, Soil temperature, Frost. *Science and Art*. 440 p.
- LAMLON S., GEORGIEVA S., DIMITROVA-MATEVA P., ANEV S., TZVETKOVA N., CHANEVA G. 2016. Changes of some oxidative stress markers in beech leaves after *Orchestes fagi* infestation. *Genetics and Plant Physiology* 6(3–4): 167–175.
- LEE B.R., LI L.S., JUNG W.J., JIN Y.L., AVICE J.C., OURRY A., KIM T.H. 2009. Water deficit-induced oxidative stress and the activation of antioxidant enzymes in white clover leaves. *Biologia Plantarum* 53(3): 505–510. <https://doi.org/10.1007/s10535-009-0091-2>
- LICHTENTHALER H.K., AČ A., MAREK M.V., KALINA J., URBAN O. 2007. Differences in pigment composition, photosynthetic rates and chlorophyll fluorescence images of sun and shade leaves of four tree species. *Plant Physiology and Biochemistry* 45(8): 577–588. <https://doi.org/10.1016/j.pla-phy.2007.04.006>
- LICHTENTHALER H.K., BUSCHMANN C., DÖLL M., FIETZ H.J., BACH T., KOZEL U., MEIER D., RAHMSDORF U. 1981. Photosynthetic activity, chloroplast ultrastructure, and leaf characteristics of high-light and low-light plants and of sun and shade leaves. *Photosynthesis Research* 2(2): 115–141. <https://doi.org/10.1007/BF00028752>
- MALINOVA L., PETROVA K. 2019. Petrohan training and experimental forest range cambisols classification. *Forestry Ideas* 25(1): 147–160.
- MAOKA T. 2020. Carotenoids as natural functional pigments. *Journal of Natural Medicines* 74(1): 1–16. <https://doi.org/10.1007/s11418-019-01364-x>
- MARJAMAA K., LEHTONEN M., LUNDELL T., TOIKKA M., SARANPÄÄ P., FAGERSTEDT K.V. 2003. Developmental lignification and seasonal variation in β -glucosidase and peroxidase activities in xylem of Scots pine, Norway spruce and silver birch. *Tree Physiology* 23(14): 977–986. <https://doi.org/10.1093/treephys/23.14.977>
- MARINOVA A., ANEV S. 2024. Impact of silvicultural interventions on growth and survival of *Fagus sylvatica* L. saplings. *Forestry Ideas* 30(2): 221–232.
- MARINOVA T., BOCHEVA L. 2023. Changed climate of Bulgaria – data and analyses. *National Institute of Meteorology and Hydrology*. 106 p.
- MATLACK G.R., LITVAITIS J.A. 1999. Forest edges. In: Hunter M. (Ed.), *Maintaining biodiversity in forest ecosystems*. Cambridge University Press: 210–227.
- NAIDU S.L., DELUCIA E.H. 1998. Physiological and morphological acclimation of shade-grown tree seedlings to late-season canopy gap formation. *Plant Ecology* 138(1): 27–40. <https://doi.org/10.1023/A:1009780114992>
- NAUTIYAL S. 1983. High altitude acclimatization in four *Artemisia* species: Changes in soluble sugars, starch and lignin contents in the leaves. *Biologia Plantarum* 25(5): 361–365. <https://doi.org/10.1007/BF02878281>
- OLIVER C.D. 1980. Forest development in North America following major disturbances. *Forest Ecology and Management* 3:

- 153–168. [https://doi.org/10.1016/0378-1127\(80\)90013-4](https://doi.org/10.1016/0378-1127(80)90013-4)
- PANCHE A.N., DIWAN A.D., CHANDRA S.R. 2016. Flavonoids: an overview. *Journal of Nutritional Science* 5, e47. <https://doi.org/10.1017/jns.2016.41>
- POLLE A., EIBLMEIER M., SHEPPARD L., MURRAY M. 1997. Responses of antioxidative enzymes to elevated CO₂ in leaves of beech (*Fagus sylvatica* L.) seedlings grown under a range of nutrient regimes. *Plant, Cell & Environment* 20(10): 1317–1321. <https://doi.org/10.1046/j.1365-3040.1997.d01-23.x>
- POLLE A., RENNENBERG H. 1994. Photooxidative stress in trees. In: Foyer C.H., Mullineaux P.M. (Eds), *Causes of photooxidative stress and amelioration of defense systems in plants*. CRC Press: 199–218.
- POLLE A., SCHWANZ P., RUDOLF C. 2001. Developmental and seasonal changes of stress responsiveness in beech leaves (*Fagus sylvatica* L.). *Plant, Cell & Environment* 24(8): 821–829. <https://doi.org/10.1046/j.1365-3040.2001.00726.x>
- POPOVIĆ M., ŠUŠTAR V., GRIČAR J., ŠTRAUS I., TORKAR G., KRAIGHER H., DE MARCO A. 2015. Identification of environmental stress biomarkers in seedlings of European beech (*Fagus sylvatica*) and Scots pine (*Pinus sylvestris*). *Canadian Journal of Forest Research* 46(1): 58–66. <https://doi.org/10.1139/cjfr-2015-0274>
- PUKACKA S., RATAJCZAK E. 2005. Production and scavenging of reactive oxygen species in *Fagus sylvatica* seeds during storage at varied temperature and humidity. *Journal of Plant Physiology* 162(8): 873–885. <https://doi.org/10.1016/j.jplph.2004.10.012>
- RENNENBERG H., LORETO F., POLLE A., BRILLI F., FARES S., BENIWAL R.S., GESSLER A. 2006. Physiological responses of forest trees to heat and drought. *Plant Biology* 8(5): 556–571. <https://doi.org/10.1055/s-2006-924084>
- RUDENKO N.N., VETOSHKINA D.V., MARENKOVA T.V., BORISOVA-MUBARAKSHINA M.M. 2023. Antioxidants of Non-Enzymatic Nature: Their Function in Higher Plant Cells and the Ways of Boosting Their Biosynthesis. *Antioxidants* 12(11), 2014. 53 p. <https://doi.org/10.3390/antiox12112014>
- SCARTAZZA A., DI BACCIO D., BERLOLOTTO P., GAVRICHKOVA O., MATTEUCCI G. 2016. Investigating the European beech (*Fagus sylvatica* L.) leaf characteristics along the vertical canopy profile: leaf structure, photosynthetic capacity, light energy dissipation and photoprotection mechanisms. *Tree Physiology* 36(9): 1060–1076. <https://doi.org/10.1093/treephys/tpw038>
- SCHULZE E.-D., BECK E., BUCHMANN N., CLEMENS S., MÜLLER-HOHENSTEIN K., SCHERER-LORENZEN M. 2019. *Plant Ecology*. Springer. 926 p. <https://doi.org/10.1007/978-3-662-56233-8>
- SINGLETON V.L., ORTHOFER R., LAMUELA-RAVENTÓS R.M. 1999. Analysis of total phenols and other oxidation substrates and antioxidants by means of folin-ciocalteu reagent. In: Packer L. (Ed.), *Methods in enzymology*. Academic Press: 152–178. [https://doi.org/10.1016/S0076-6879\(99\)99017-1](https://doi.org/10.1016/S0076-6879(99)99017-1)
- TODOROVA D., ALEKSANDROV V., ANEV S., SERGIEV I. 2022. Photosynthesis Alterations in Wheat Plants Induced by Herbicide, Soil Drought or Flooding. *Agronomy* 12(2), 390. 13 p. <https://doi.org/10.3390/agronomy12020390>
- TODOROVA D., ALEKSANDROV V., ANEV S., SERGIEV I. 2023. Comparative Study of Photosynthesis Performance of Herbicide-Treated Young Triticale Plants during Drought and Waterlogging Stress. *Agronomy* 13(8), 1992. 14 p. <https://doi.org/10.3390/agronomy13081992>
- TODOROVA D., ANEV S., ILIEV M., PETRAKOVA M., SERGIEV I. 2024. Changes of photosynthetic parameters in melatonin-treated wheat subjected to drought. *Plants* 13(23), 3414. 16 p. <https://doi.org/10.3390/plants13233414>
- VISINÉ-RAJCI E., NÉMETH L., ALBERT L., MÁTYÁS C., HOFMANN T. 2023. Applicability of beech (*Fagus sylvatica* L.) leaf polyphenols as indicators for growth and acclimation and their potential contribution to sustainable forestry. *Chemical Engineering Transactions* 107: 655–660. <https://doi.org/10.3303/CET23107110>

- VOGELMANN T.C., GORTON H.L. 2014. Leaf: Light Capture in the Photosynthetic Organ. In: Hohmann-Marriott M.F. (Ed.), The Structural Basis of Biological Energy Generation. Springer Netherlands: 363–377. https://doi.org/10.1007/978-94-017-8742-0_19
- WAGNER S., COLLET C., MADSEN P., NAKASHIZUKA T., NYLAND R.D., SAGHEB-TALEBI K. 2010. Beech regeneration research: From ecological to silvicultural aspects. *Forest Ecology and Management* 259(11): 2172–2182. <https://doi.org/10.1016/j.foreco.2010.02.029>
- WAGNER S., FISCHER H., HUTH F. 2011. Canopy effects on vegetation caused by harvesting and regeneration treatments. *European Journal of Forest Research* 130(1): 17–40. <https://doi.org/10.1007/s10342-010-0378-z>
- ZHENG D., CHEN J. 2000. Edge effects in fragmented landscapes: a generic model for delineating area of edge influences (D-AEI). *Ecological Modelling* 132(3): 175–190. [https://doi.org/10.1016/S0304-3800\(00\)00254-4](https://doi.org/10.1016/S0304-3800(00)00254-4)
- ZHIPONOVA M., YORDANOVA Z., PAVLOVA D., ROGOVA M., DIMITROVA M., DRAGOLOVA D., TASHEVA-TERZIEVA E., KAPCHINA-TOTEVA V. 2020. Importance of phenolics in populations of *Teucrium chamaedrys* (Lamiaceae) from serpentine soils. *Australian Journal of Botany* 68(5): 352–362. <https://doi.org/10.1071/bt19124>

Grown characteristics and effectiveness of common quail (*Coturnix coturnix*, Linnaeus 1758) raising for game restocking

Todor Petrov^{id} and Hristo Lukanov^{*id}

Faculty of Agriculture, Trakia University, Student campus, 6000 Stara Zagora, Bulgaria.

^{*}E-mail: hristo.lukanov@trakia-uni.bg

Received: 29 January 2025 / Accepted: 22 February 2025 / Available online: 6 March 2025



Open Access: This work is distributed under the Creative Commons Attribution 4.0 License.

Abstract

This study aimed to evaluate the growth characteristics and rearing effectiveness of cage-raised common quails for game restocking. Based on the origin of the quails, three groups of one-day-old birds were formed. Up to the age of 21 days, the quails were reared together, and subsequently, they were separated by sex. The test period lasted 56 days. The rearing conditions and feeding of the quails were analogous to those of domesticated quails. The following traits were monitored: mortality (%), live body weight (g), weight gain (g), feed intake (g), and feed conversion ratio. At 56-day-old, the average male live body weight was 110.68 g, while for the females, it was 127.24 g ($P < 0.001$). The cumulative feed intake was 826.9 g for males and 970.4 g for females. Quails raised until 35-day-old consumed half the amount of feed compared to those raised until 56-day-old, with feed conversion ratios of 4.39 for males and 4.58 for females, respectively. By 35-day-old, the males had reached approximately 87 % and the females about 80 % of the live weight of mature individuals. The results of the study provide grounds to recommend common quails raising intended for game restocking up to a maximum age of 35 days. This would increase the efficiency of their production, enable more production cycles, and optimise the utilisation of available facilities and equipment.

Key words: effectiveness, feed conversion ratio, game birds, restocking.

Introduction

In recent decades, poultry farming has become the fastest-developing subsector of animal husbandry worldwide (Mottet and Tempio 2017). In addition to the production from traditional poultry species

such as domestic chicken, domestic turkey, domestic duck, and domestic goose, less commonly farmed species, including game-type birds as quails, are also gaining significance. Beyond their role in poultry farming, some of these birds are also in focus of game farming. For hunting

purposes, common quail (*Coturnix coturnix*, Linnaeus 1758) or hybrid birds (*C. coturnix* × *C. japonica domestica*) are bred in game farms in some countries. These birds are used for game restocking, dog training, or other hunting-related activities (Caravaca et al. 2022). Game farms specialising in the breeding, sale, and game restocking of common quails were established as early as the 1960s and 1970s, primarily in some countries from Southern Europe like Spain, Italy, and Greece (Lukanov 2020, Caravaca et al. 2022). Similar efforts have also been made in countries like Bulgaria, where the species is a popular hunting object (Donchev and Angelov 1971).

The common quail belongs to the genus *Coturnix* within the subfamily *Perdiciinae*. The genus comprises six living and two extinct species (Lukanov 2020). According to some taxonomic classifications, the number of extinct species is higher, with some, such as the brown quail, being classified in a separate genus (del Hoyo et al. 2014). Until a few decades ago, the Japanese quail (*Coturnix japonica*, Temminck and Schlegel 1848–1850) was considered as a subspecies of the common quail. Today, however, the two species are taxonomically distinguished.

A distinctive characteristic of the common quail is its migratory behaviour, making it the only long-distance migratory bird in the family *Phasianidae* (Kosicki et al. 2014). A significant portion of the population migrates from North Africa and the Middle East to Southern and Eastern Europe for breeding. Vertical migration in the species has also been described, associated with agro-ameliorative measures in the lowlands or drought (Boev 1949, Michailov 1995a). It is estimated that between 5 % and 24 % of the global population breeds in Europe (EC 2009). The

common quail is classified as a species of Least Concern (BirdLife International 2025) with global population between 15–35 million mature individuals and extent of occurrence about 87,900,000 km². Estimates suggest that the European population, including European Russia and Turkey, is approximately 2.8–4.7 million pairs (WBRU 2016). Despite this status, a population decline has been observed since the late 20th century (Sanderson et al. 2009, Puigcerver et al. 2012). Similar trend has been established for the Bulgarian population of the species. It is placed among the top three most rapidly declining species in the country according to Hristov et al. (2023). Key factors contributing to the global population decline include habitat loss, uncontrolled pesticide use, climate changes (especially droughts), wind turbine installation, nets trapping, and other threats (Lukanov 2020). Detailed study of the biology and ecology of common quail in Bulgaria was presented by Michailov (1995b).

The domestic quail (*Coturnix japonica domestica*), which originates from the Japanese quail, is widely used in agriculture for egg and meat production, and as a laboratory animal (Lukanov 2019). Domestic quails are used to enhance the productive characteristics of captive common quail populations by crossing (Caravaca et al. 2022, González-Redondo et al. 2023). Some researchers suggest that a significant portion of quails released into the wild are such hybrids (Sánchez-Donoso et al. 2012). Despite the presence of hybrids, no substantial genetic impact on the wild population has been observed (Puigcerver et al. 2007).

Raising wild quails and their hybrids in controlled conditions can improve knowledge about these birds. From the perspective of quail production for restock-

ing, it is important what the growth rate of young birds is and at what stage of their rearing is most appropriate to be realised. To date, there is lack of available literature on the growth characteristics of the common quail or its hybrids from a poultry science perspective. Data on the suitability of these birds for cage-based rearing, which offers several advantages over traditional methods of raising game birds, are also absent. This context defined the aim of the present study: to evaluate the growth characteristics and rearing effectiveness of cage-raised common quails (*C. coturnix*) for game restocking.

Materials and Methods

Experimental design

The study was conducted from August to October 2023 at the Poultry Section Experimental Base at the Faculty of Agriculture, Trakia University, Stara Zagora, Bulgaria. Common quails (*Coturnix coturnix*), raised for game restocking in Greece and Italy, were used. Hatching eggs were received from parental flocks of the same age, originating from captive-bred quails, raised in the Poultry Section Experimental Base. The origin of the common quails used was Greece (two different flocks) and Italy (one flock).

Based on the origin, three groups were established and labelled as follows: I (GR first flock), II (GR second flock), and III (IT). Each group consisted of 60-day-old quails. Up to 21-day-old, the quails were reared in mixed-sex groups (due to low sexing accuracy before that age). At 21-day-old, sexing was performed based on sexual dimorphism in breast plumage colouration: appearance of rusty coloura-

tion on the chest in males and its absence in females, as described by Lyon (1962). Following sexing, the birds were reared in separate male and female groups (I_m , I_f , II_m , II_f , III_m , and III_f) until the end of the study at 56-day-old. Each newly formed group (21-day-old) consisted of 20 males or 20 females with body weights close to the average for the respective population.

Experimental bird management

The quails were housed in wire-mesh floor cages measuring 80×100×80 cm (W/L/H), providing about 130 cm² floor area per bird until 21-day-old and 400 cm² after that age. Hand-fillable trough feeders, protected from feed spillage were used. Watering was provided with hand-fillable vacuum drinkers of 2 L capacity with a low water level until 14-day-old, and 3 L universal hand-fillable vacuum drinkers were used thereafter. Temperature and lighting programs in the bird area were maintained on the detailed recommendations for domestic quails as presented by Genchev (2014). During the brooding period (up to 21-day-old), combined heating was applied: local and general. After that, the birds were kept at a temperature of 20–23 °C. The relative humidity was in the range of 60–75 %. Quails were reared for the first three days under continuous high-intensity lighting (80–100 lx) to facilitate feed and water finding. After which, by 4 weeks of age, the light phase was gradually reduced to 14 h, remaining until the end of the test period. The lighting intensity was about 20–25 lx.

Feeding was conducted *ad libitum*, in three-phase manner (starter, grower, and finisher) according to the birds' age (Table 1), following feeding recommendations for domestic quails (Genchev 2014).

Table 1. Component and nutritional characteristics of the feed used.

Components	Starter <14 days	Grower 14-21 day	Finisher >21 days
Corn, %	29.2	35.5	38.8
Wheat, %	21	23.8	27
Soybean meal 44 CP, %	34.6	25.8	20
Sunflower meal 34 CP, %	8	8.5	9
Fish meal 72 CP, %	2	1	0
Sunflower oil, %	0.615	0.905	1
CaHPO ₄ ·2H ₂ O, %	1.92	1.82	1.71
CaCO ₃ , %	1.52	1.48	1.43
Vitamin-mineral pre-mix, %	0.6	0.6	0.5
NaCl, %	0.2	0.2	0.2
NaHCO ₃ , %	0.1	0.1	0.1
L-Lysine, %	0.11	0.175	0.15
DL-Methionine, %	0.135	0.12	0.11
Nutritional characteristic			
Energy-protein ratio	110.27	134.28	156.31
Metabolizable energy, MJ·kg ⁻¹	11.06	11.51	11.79
Crude protein, %	24.00	20.51	18.04
Crude fiber, %	5.28	5.02	4.90
Ca, %	1.20	1.10	1.00
Av. P, %	0.50	0.45	0.40
Lysine, %	1.30	1.10	0.91
Methionine, %	0.52	0.45	0.40
Methionine + Cysteine, %	0.92	0.81	0.73
Linoleic acid, %	1.30	1.62	1.75

Note: CP is crude protein.

Data collection

During the study, the following parameters were monitored: live body weight (g), weight gain (g), feed consumption (g), and feed conversion ratio (FCR). Live body

weight was measured weekly by using a CB 2000 scale, with an accuracy of 0.1 g for measurements at 1–7-day-old, and 0.2 g at 14-, 21-, 28-, 35-, 42-, 49-, and 56-day-old. The amount of feed supplied and the remaining feed from the previous day were determined daily with an accuracy of 0.1 g. Based on the consumed feed and achieved weight gain, the FCR, and the cumulative feed consumption was calculated. From the point of view of practical application, generalisations of the studied parameters have been made, with group data being summarised.

Statistical analysis

Statistical processing of the obtained results was performed using the IBM® SPSS® Statistics software package (V26) and applying One Way ANOVA. For statistical analysis and result interpretation, the following parameters were used: mean value ($\bar{x}$), standard deviation (SD), and standard error of the mean (SEM). The text indicates the mean $\pm$ SD values. Inter-group and inter-sex differences were considered statistically sig-

nificant at $P < 0.05$, using LSD *Post Hoc* Test, if the data were normally distributed (Shapiro–Wilk test, $n < 50$) and in significant model (F-test) ($P < 0.05$). A Microsoft Excel 16.0 (2018, for Windows) software

product was used for graphic layout purposes.

Results

The average weight of the quail from the three groups at 1 day of age was 6.16 ± 0.74 g (group I – 6.15 ± 0.66 g; group II – 5.97 ± 0.76 g; group III – 6.48 ± 0.75 g). The live weight of quails at 7-day-old ranged from 20.89 ± 3.36 g (group I) to 22.49 ± 3.38 g (group II). At 14-day-old, was the last weighing conducted without accounting for sex differences. The quails from all three groups showed relatively close average weights, ranging from 45.30 ± 5.29 g in group I to 42.71 ± 4.05 g in group III ($P < 0.05$) (Table 2).

After sexing, during the first weighing (on 21-day-old), female quails exhibited a trend of higher live weight compared to males, which persisted until the end of the study. Statistically significant sex differences in live weight were observed

Table 2. Live weight of common quails from the different studied populations before sexing ($\bar{x} \pm \text{SD}$).

Age, days	Group		
	I	II	III
7	20.89 ± 3.36	22.49 ± 3.38	21.81 ± 2.84
14	$45.30 \pm 5.29a$	45.23 ± 6.15	$42.71 \pm 4.05a$

Note: With the same letters (a-a, b-b) are marked statistically significant between-group differences for each sex at $P < 0.05$.

after 42-day-old ($P < 0.01$). By the time of sexual maturity at the end of the experiment (56-day-old) the average weight of males from the three groups was 110.68 ± 7.1 g (Fig. 1), with intergroup variations from 109.43 ± 7.9 g (group III_m) to 111.35 ± 5.4 g (group I_m) ($P > 0.05$). The live weight of females at 56-day-old averaged 127.24 ± 11.3 g across the three groups, with intergroup variations from 120.67 ± 11.4 g (group I_f) to 131.78 ± 11.2 g (group III_f).

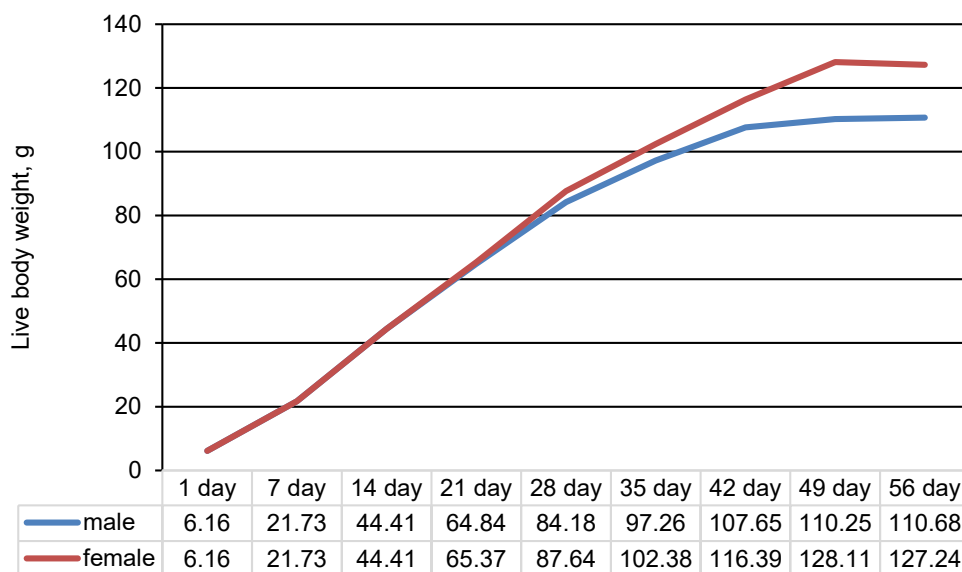


Fig. 1. Live body weight of male and female common quails.

Unlike males at 56-day-old, where no statistically significant differences were observed in live weight, females from group I_f showed statistically significant differences compared to those from groups II_f and

III_f ($P < 0.05$) (Table 3).

The results for cumulative feed consumption in male and female common quails during the period of the study are presented in Figure 2. After the sex-mixed

Table 3. Live weight of common quails from the different studied populations after sexing ($\bar{x} \pm \text{SD}$).

Age, days	Sex					
	Male			Female		
Group	I _m	II _m	III _m	I _f	II _f	III _f
21	66.96 $\pm$ 5.5	64.17 $\pm$ 8.8	63.39 $\pm$ 7.3	64.86 $\pm$ 9.2	68.47 $\pm$ 8.2	62.78 $\pm$ 7.5
28	85.38 $\pm$ 6.5	85.14 $\pm$ 10.7	82.02 $\pm$ 8.5	88.26 $\pm$ 9.7	89.76 $\pm$ 7.9	84.89 $\pm$ 7.6
35	95.06 $\pm$ 5.4*	99.51 $\pm$ 8.7	97.2 $\pm$ 7.9	105.04 $\pm$ 12.8*	104.41 $\pm$ 9.8	97.69 $\pm$ 8.6
42	105.16 $\pm$ 6.5a*	110.52 $\pm$ 7.5a*	107.28 $\pm$ 6.8	118.32 $\pm$ 9.0*	119.88 $\pm$ 10.3a*	110.95 $\pm$ 11.4a
49	109.53 $\pm$ 4.6*	111.79 $\pm$ 7.7*	109.44 $\pm$ 7.2*	127.24 $\pm$ 14.0*	131.29 $\pm$ 13.7*	125.79 $\pm$ 13.2*
56	111.35 $\pm$ 5.4*	111.24 $\pm$ 7.8*	109.43 $\pm$ 7.9*	120.67 $\pm$ 11.4ab*	129.26 $\pm$ 8.9a*	131.78 $\pm$ 11.2b*

Note: With the same letters (a-a, b-b) are marked statistically significant between-group differences for each sex at $P < 0.05$. With * are marked the within-group intersexual differences at $P < 0.01$.

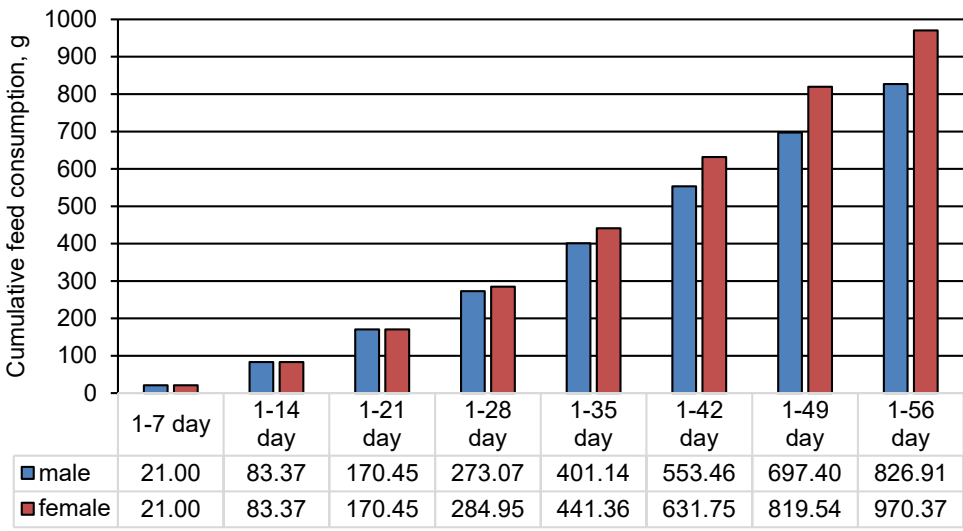


Fig. 2. Cumulative feed consumption in male and female common quails.

raising period (21-day-old), differences between the sex feed consumption became apparent, deepening with age and reaching approximately 143.5 g (14.8 %) by the end of the study. The cumulative feed consumption of male quails up to 56-day-old in our study was 826.9 g, while for females, it was 970.4 g. The observed intersexual differences are directly connected to the sex-related distinctions in live body weight (Fig. 1). Male maturation was associated with a constant and even a decline in feed consumption, reaching an average daily consumption of 18.5 g during the final week. Despite the growth of the reproductive system in females and their preparation for egg-laying, a similar trend was observed, characterised by a slight decline in average daily consumption, reaching 21.5 g in the last week of the experiment. Figure 2 illustrates the age-related changes in cumulative feed consumption in the all tested quails, separated by sex.

The data for FCR showed relatively

close values for feed conversion between the two sexes, raised until 35-day-old, with 4.39 kg for males and 4.58 kg for females (average 4.48 kg for both sexes) (Fig. 3). As expected, with the increase in the quails rearing period, feed utilisation efficiency worsens, reaching an average FCR value of 7.95 for both sexes at the end of the test period (56-day-old).

Discussion

Mihaylov (2006) reported a similar weight for 1-day-old common quail (*C. coturnix*) – 5.99 g as in this study. Lower values, ranging between 5.0–5.5 g, were presented by Botev (1985). It should be noted that the weight of 1-day-old quail is influenced by various factors, with the most significant being the size of the hatching egg and the duration of the chicks' stay in the incubator (Genchev and Lukanov 2023). The growth of the studied populations of common quails up to 14-day-old

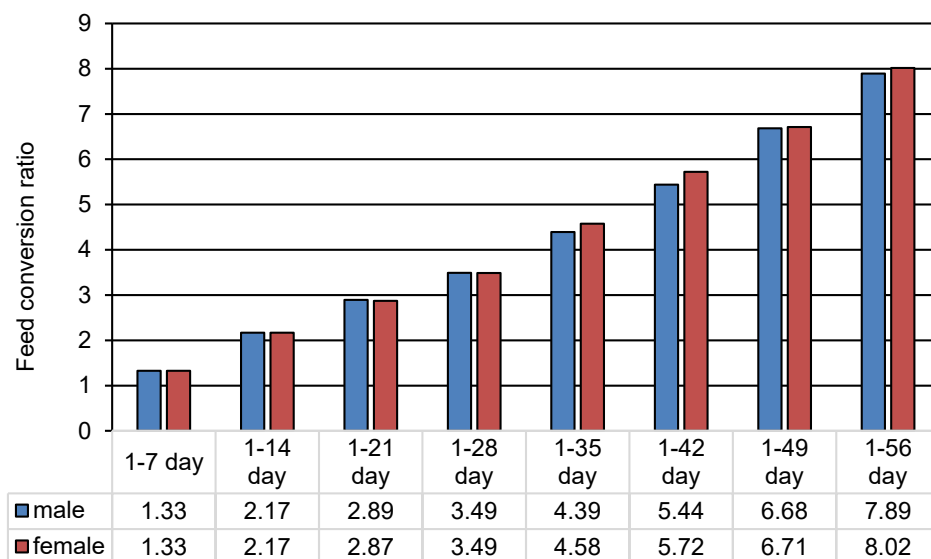


Fig. 3. FCR in male and female common quails.

is comparable to that of light (egg-laying) domestic quails (Anang et al. 2017, Grieser et al. 2018). At this age, in addition to rapid changes in the live weight of the birds, changes in their plumage were also observed. From day 14th, quails enter the phase of intensive feathering, initiating a complete replacement of embryonic down with juvenile feathers (Genchev et al. 2008). Consequently, sex determination based on breast colouration in common quails can be performed as early as 13-day-old, but it is most reliably done about and after day 21st – at the beginning of second juvenal plumage development (Lyon 1962).

Analysing the data on average weekly growth, it can be concluded that quails exhibit the most active growth during the period up to 7-day-old. Relatively close growth values were observed during the control weighing on days 14th and 21st. Up to 21-day-old, the growth of common quails accounts for approximately 60% of the total growth in males and about 54.5 % in females. After this age, the average growth values gradually decrease, even reaching negative levels in some subgroups during the final week of the test period. This decline may be associated with the birds reaching maturity. Similar results regarding growth intensity in common quails were reported by Mihaylov (2006). In contrast, domestic quails of the light egg-laying type demonstrate higher growth rates (Saatci et al. 2002, Sezer et al. 2006, Nankinov 2016, Grieser et al. 2018), indicating a more intensive growth pattern. Regarding the weight differences of sexually mature male and female individuals, our findings align with those presented by several authors studying common quails (*C. coturnix*) in field investigations (Michailov 1995b, Derégnacourt et al. 2002, Tsachalidis et al. 2007,

Qureshi et al. 2016, Bagarić and Dumić 2019). Compared to the cited sources, the live weight of the mature quails used in the present study shows higher values. This can be explained by the better raising conditions and feeding of the birds in captivity or by hybridisation. When comparing wild common and wild Japanese quail (*C. japonica*), no significant differences in live weight were observed (Lyon 1962, McGowan and Kirwan 2020). It can be stated that selection has resulted in higher live weights in domestic quails (*C. japonica domestica*) comparing with their ancestor (Japanese quail) and common quail. In domestic quails, live weight is one of the traits most strongly influenced by selection, with differences from their wild ancestors up to three times (Lukanov and Pavlova 2020a).

The available scientific literature does not provide information regarding feed consumption quantity in the different common quail age periods. In this context, the present study can serve as a foundation for the economic evaluation of the efficiency of their captive raising, as feed costs constitute a major component in determining the production cost of a single quail (Lukanov and Pavlova 2020b). By analysing the feed consumption data, averaged for male and female quails, it is possible to quantify the feed requirements across the different feeding phases (starter, grower, and finisher) for rearing a quail until their restocking. Based on this study, a single quail consumes an average of about 80 g of starter feed (up to 14-day-old), 90 g of grower feed (up to 21-day-old), and 730 g of finisher feed (21–56-day-old). This allows for accurate planning of the feed needed for raising quails in game farms. The primary rearing method for common quails intended for game restocking involves floor rearing during the brooding

period (brooder houses), followed by aviary housing (open-air flight pens) (Caravaca et al. 2022). Typically, higher feed consumption is observed raising birds under non-caged systems due to the increased activity levels of the birds (Ahmed et al. 2014). Therefore, for the purposes of game farming practice and planning, we recommend that feed calculations for game farms be increased by about 10 % during the brooding period and by about 20 % thereafter, compared to the values presented in this study where cage-rearing system was used.

Analysing the results regarding common quails' live body weight, their physical development, and feed consumption, it can be recommended that most effective restocking age is about 35 days. This corresponds to the average age of transfer to open-air flight pens (Caravaca et al. 2022). By this point, the quails have achieved live body weights (approximately 87 % in males and 80 % in females) and physical development levels comparable to those of adult birds. Keeping them on the farm beyond this age would increase their production cost, reduce the number of batches processed, and necessitate additional rearing facilities. Quails reared up to 35-day-old consume half the amount of feed (on average 421.2 g) compared to those raised to sexual maturity. This would lead to a threefold reduction in the finisher phase (approximately 250 g of finisher feed per bird). In game farms, common quails and their hybrids with Japanese quails are typically marketed for purposes such as game restocking, training hunting dogs, or shooting practice at an age range from 45 to 85 days (Caravaca et al. 2022).

In contrast to common quail, feed utilisation in domestic quails is generally more efficient. FCR values for domestic quails raised up to 35-day-old typically

range from 3.0 to 3.9 (Ray et al. 2014, Razee et al. 2016, Pavlova et al. 2018, Lukanov 2022, Arunrao et al. 2023, Taleb et al. 2024). The results provided by the feed conversion ratio are significant when any form of production is achieved, in this case, growth. This information could be of importance when tracking the efficiency of converting feed into 'meat' i.e., when quails are fattened for slaughter. Typically, game farms raise common quails for game restocking or for breeding purposes. Fattening common/hybrid quails and producing game type meat falls into a market niche primarily occupied by domestic quails. The possibility of marketing meat from captive-raised common quails is an opportunity that, with an appropriate marketing strategy, could offer new prospects and economic advantages compared to their classic use for restocking.

Conclusions

The present study provides a basis to conclude that the origin of the population of common quails does not significantly influence their growth characteristics. By 35-day-old, common quails reach approximately 87 % of the body weight of adult males and 80 % of adult females, consuming an average of 421.2 g of compound feed. This gives reason to recommend raising common quail until about 35-day-old for restocking purpose as the most effective.

Acknowledgments

The authors would like to express their sincere gratitude to all those who contributed to this work. We also wish to acknowledge the financial support from Project 8 AF/24

‘Support for Publication of Scientific Articles in Referenced Journals and Journals with Impact Factor’, which facilitated the publication of this article.

References

- AHAMMED M., CHAE B., LOHAKARE J., KEOHAVONG B., LEE M.H., LEE S.J., KIM D.M., LEE J.Y., OHH S.J. 2014. Comparison of aviary, barn and conventional cage raising of chickens on laying performance and egg quality. *Asian-Australasian Journal of Animal Sciences (AJAS)* 27(8): 1196–1203. <https://doi.org/10.5713/ajas.2013.13394>
- ANANG A., INDRIJANI H., SUJANA E. 2017. Mathematical model of growth of two pure lines of Padjadjaran female quail aged 0 to 6 weeks. *Journal of the Indonesian Tropical Animal Agriculture* 42(2): 66–71. <https://doi.org/10.14710/jitaa.42.2.66-71>
- ARUNRAO K., KANNAN D., AMUTHA R., THIRUVENKADAN A., YAKUBU A. 2023. Production performance of four lines of Japanese quail reared under tropical climatic conditions of Tamil Nadu, India. *Frontiers in Genetics* 14, 1128944. 13 p. <https://doi.org/10.3389/fgene.2023.1128944>
- BAGARIĆ M.Z., DUMIĆ T. 2019. Morphometric characteristics of the common quail (*Coturnix coturnix* L.) on Duvno field. *Book of Abstracts 54th Croatian & 14th International Symposium on Agriculture*: 143–144 (in Croatian). <https://www.croris.hr/crosbi/publikacija/prilog-skup/673187>
- BIRDLIFE INTERNATIONAL 2025. Species fact-sheet: Common Quail *Coturnix coturnix*. <https://datazone.birdlife.org/species/fact-sheet/common-quail-coturnix-coturnix> (Accessed on 31 January 2025).
- BOEV N. 1949. Quail. *Hunting and Fishing* 7: 8–9 (in Bulgarian).
- BOTEV N. 1985. *Game Farming*. Zemizdat, Sofia. 270 p. (in Bulgarian).
- CARAVACA F., CAMACHO-PINTO T., GONZÁLEZ-REDONDO P. 2022. The Quail Game Farming Sector in Spain. *Animals* 12(22), 3118. 14 p. <https://doi.org/10.3390/ani12223118>
- DEL HOYO J., COLLAR N.J., CHRISTIE D.A., ELLIOTT A., FISHPOOL L.D.C., BOESMAN P., KIRWAN G.M. 2014. *HBW and BirdLife International Illustrated Checklist of the Birds of the World. Volume 1: Non-passerines*. Lynx Edicions BirdLife International, Barcelona, Spain and Cambridge, UK. 94 p.
- DERÉGNAUCOURT S., GUYOMARC'H J.-C., AEBISCHER N.J. 2002. Hybridization between European Quail (*Coturnix c. coturnix*) and Japanese Quail (*Coturnix c. japonica*). *Ardea* 90(1): 15–21. <https://hal.science/hal-01327133>
- DONCHEV R., ANGELOV I. 1971. Industrial farming of Japanese quail in our country. *Poultry farming* 7: 49 (in Bulgarian).
- EC (EUROPEAN COMMISSION) 2009. Common quail *Coturnix coturnix*. European Union Management Plan 2009–2011. Natura 2000, Luxembourg: Office for Official Publications of the European Communities. 71 p. <https://op.europa.eu/en/publication-detail/-/publication/8b39bddb-c3f3-41e1-9ac7-3653da2af1ad>
- GENCHEV A. 2014. Japanese quails. In: Kabakchiev M., Gerzilov V. (Eds.). *Poultry farming*. Academic Publishing – Agricultural University, Plovdiv: 308–318 (in Bulgarian).
- GENCHEV A., LUKANOV H. 2023. *Poultry Incubation with Biological Control Basis*. Academic Press, Trakia University, Stara Zagora: 139–142 (in Bulgarian).
- GENCHEV A., MIHAYLOVA G., RIBARSKI S., PAVLOV A., KABAKCHIEV M. 2008. Meat quality and composition in Japanese quails. *Trakia Journal of Sciences* 6(4): 72–82.
- GONZÁLEZ-REDONDO P., ROBUSTILLO P., CARAVACA F.P. 2023. Effects of Long-Term Storage on Hatchability and Incubation Length of Game Farmed Quail Eggs. *Animals* 13(13), 2184. 13 p. <https://doi.org/10.3390/ani13132184>
- GRIESER D., MARCATO S., FURLAN A., ZANCANELA V., PAULA A., BATISTA A., TON A., PERINE T. 2018. Estimation of growth parameters of body weight and body nutrient deposition in males and females of meat- and laying-type quail using the

- Gompertz model. Brazilian Journal of Animal Science 47, e20170083. 8 p. <https://doi.org/10.1590/rbz4720170083>
- HRISTOV J., POPGEORGIEV G., SPASOV S., PETKOV N., PLACHIJSKI D., STOYCHEV S. 2023. Status of common bird species in Bulgaria 2023. BSPB. Conservation series 39. Sofia. 30 p. (in Bulgarian).
- KOSICKI J.Z., CHYLARECKI P., ZDUNIAK P. 2014. Factors affecting Common Quail's *Coturnix coturnix* occurrence in farmland of Poland: is agriculture intensity important? Ecological Research 29(1): 21–32. <https://doi.org/10.1007/s11284-013-1093-2>
- LUKANOV H. 2019. Domestic quail (*Coturnix japonica domestica*), is there such farm animal? World's Poultry Science Journal 75(4): 547–558. <https://doi.org/10.1017/S0043933919000631>
- LUKANOV H. 2020. Quails from genus *Coturnix* in Nature and Agriculture. Alfa Visia, Stara Zagora, Bulgaria. 154 p. (in Bulgarian).
- LUKANOV H. 2022. Growth performance and carcass characteristics of dual-purpose and heavy Japanese quails. Trakia Journal of Sciences 1: 18–30. <https://doi.org/10.15547/tjs.2022.01.003>
- LUKANOV H., PAVLOVA I. 2020a. Domestication changes in Japanese quail (*Coturnix japonica*): a review. World's Poultry Science Journal 76(4): 787–801. <https://doi.org/10.1080/00439339.2020.1823303>
- LUKANOV H., PAVLOVA I. 2020b. Economic analysis of meat production from two types of Domestic quails. Agricultural Science and Technology 12(2): 148–152. <https://doi.org/10.15547/ast.2020.02.025>
- LYON D.L. 1962. Comparative growth and plumage development in Coturnix and Bobwhite. Wilson Bulletin 74: 5–27. <https://sora.unm.edu/sites/default/files/journals/wilson/v074n01/p0005-p0027.pdf> (Accessed on 31 January 2025).
- MCGOWAN P.J.K., KIRWAN G.M. 2020. Japanese Quail (*Coturnix japonica*), version 1.0. In: del Hoyo J., Elliott A., Sargatal J., Christie D.A., de Juana E. (Eds), Birds of the World. Cornell Lab of Ornithology, Ithaca, NY, USA. <https://doi.org/10.2173/bow.japqua.01>
- MICHAÏLOV CH. 1995a. Seasonal changes in the population of the quail (*Coturnix coturnix* L.1758) in the southwest of Bulgaria. In: Botev N., Golovatch S., Penev L. (Eds), Proceedings of the Congress of the International Union of Game Biologists XXII Congress 'The Game and the Man', 4–8 September, 1995, Sofia, Bulgaria: 14–19.
- MICHAÏLOV CH. 1995b. A study on the Ecology and Biology of Quail (*Coturnix coturnix* L.) in the higher fields of western Bulgaria. PhD thesis, Higher Institute of Forestry and Wood Technology, Sofia. 131 p. (in Bulgarian).
- MIHAYLOV R. 2006. Comparative morphological studies of the alimentary canal between Japanese (*Coturnix coturnix japonica*) and Wild Quail (*Coturnix coturnix coturnix*). PhD Thesis, Trakia university, Stara Zagora (in Bulgarian).
- MOTTET A., TEMPIO G. 2017. Global poultry production: current state and future outlook and challenges. World's Poultry Science Journal 73(2): 245–256. <https://doi.org/10.1017/S0043933917000071>
- NANKINOV D. 2016. The Quail (*Coturnix coturnix*) – a unique bird and a popular hunting object. Sofia. 52 p. (in Bulgarian).
- PAVLOVA I., LUKANOV H., IVANOV V., PETROVA Y., GENCHEV A. 2018. Simultaneous administration of Silymarin and Doxycycline in Japanese quails suggests probable herb-drug interaction. Bulgarian Journal of Agricultural Science 24(1): 126–131.
- PUIGCERVER M., SARDA-PALOMERA F., RODRIGUEZ-TEIJEIRO J.D. 2012. Determining population trends and conservation status of the common quail (*Coturnix coturnix*) in Western Europe. Animal Biodiversity and Conservation 35(2): 343–352. <https://doi.org/10.32800/abc.2012.35.0343>
- PUIGCERVER M., VINYOLÉS D., RODRIGUEZ-TEIJEIRO J.D. 2007. Does restocking with Japanese quail or hybrids affect native populations of common quail *Coturnix coturnix*? Biological Conservation 136(4): 628–635. <https://doi.org/10.1016/j.biocon.2007.01.007>
- QURESHI N.A., ALI S., ABBASI A., RAKHA B.A. 2016. Morphometrics of Common Quail

- (*Coturnix coturnix*) in Pothohar, Pakistan. *Pakistan Journal of Wildlife* 7(2): 37–40.
- RAY S., DAS S., MISHRA S., SWAIN R., MAITY A., SWAIN P., DAS A. 2014. Performance of Japanese quail on organically complexed minerals by replacing inorganic sources. *The Indian Journal of Animal Sciences* 84(1): 60–67. <https://doi.org/10.56093/ijans.v84i1.37312>
- RAZEE A., MAHBUB A., MIAH M., HASNATH M., HASAN M., UDDIN M., BEAL S. 2016. Performance of Japanese Quails (*Coturnix coturnix japonica*) on Floor and Cage Rearing System in Sylhet, Bangladesh: Comparative Study. *Iranian Journal of Applied Animal Science* 6(4): 931–936.
- SAATCI M., AP DEWI I., AKSOY A.R., KIRMIZIBAYRAK T., ULUTAS Z. 2002. Estimation of genetic parameters for weekly live-weights in one to one sire and dam pedigree recorded Japanese quail. *Proceedings of the 7th World Congress on Genetics Applied to Livestock Production*, August 19–23, 2002, Montpellier, France. 4 p.
- SÁNCHEZ-DONOSO I., VILÀ C., PUIGSERVER M., BUTKAUSKAS D., CABALLERO DE LA CALLE J.R., MORALES-RODRÍGUEZ P., RODRÍGUEZ-TEIJEIRO J.D. 2012. Are farm-reared quails for game restocking really common quails (*Coturnix coturnix*)? A Genetic Approach. *PLoS ONE* 7(6), e39031. 8 p. <https://doi.org/10.1371/journal.pone.0039031>
- SANDERSON F.J., KLOCH A., SACHANOWICZ K., DONALD P.F. 2009. Predicting the effect of agriculture change on farmland bird population in Poland. *Agriculture, Ecosystems & Environment* 129(1–3): 37–42. <https://doi.org/10.1016/j.agee.2008.07.001>
- SEZER M., BERBEROGLU E., ULUTAS Z. 2006. Genetic association between sexual maturity and weekly live-weights in laying-type Japanese quail. *South African Journal of Animal Science* 36(2): 142–148. <https://doi.org/10.4314/sajas.v36i2.3997>
- TALEB H.M., ABDEL-HALIM A.A., RAMADAN G.S., SHAZLY S.A., KAMAL M., ALWAILI M.A., RUDAYNI H.A., ALLAM A.A., TAHA A.E., AL-SAYED H.M.A., MOUSTAFA M., ALSHAHARNI M.O., MAHROSE K., FOUAD A.M. 2024. Does the marketing age impact growth performance, carcass traits, economic feasibility and hemato-biochemical properties of genetically-modified quails? *Poultry Science* 103(7), 103793. 9 p. <https://doi.org/10.1016/j.psj.2024.103793>
- TEMMINCK C.J., SCHLEGEL H. 1844–1850. Description des oiseaux, observes au Japon par les voyageurs Hollandais. In: Siebold Ph.Fr. von (Ed.), *Fauna Japonica sive description animalium, quae in itinere per Japoniam, jussu et auspiciis superiorum, qui summum in India Batava imperium tenent, suscepto, annis 1823–1830. Collegit, notis, observationibus et adumbrationibus illustravit*. 4. Aves: 1–142. *Lugduni Batavorum, Apud Auctorem*. <https://www.biodiversitylibrary.org/item/223586#page/27/mode/1up> (Accessed on 31 January 2025).
- TSACHALIDIS E.P., PARALIKIDIS N., TSIOMPA-NOUDIS A., TRIKILAS K. 2007. Morphometry, body mass and autumn diet of European quail (*Coturnix coturnix coturnix*) in Evros and Chios, Greece. *Wildlife Biology in Practice* 3(1): 9–17. doi:10.2461/wbp.2007.3.2
- WBRU 2016. Report on the Conversation Status of the Common Quail (*Coturnix coturnix*). Wild Birds Regulation Unit. Parliamentary Secretariat for Agriculture, Fisheries and Animal Rights Ministry for Sustainable Development, the Environment and Climate Change. 34 p. <https://wbru.gov.mt/wp-content/uploads/2024/08/consStaJan-16TurQua.pdf> (Accessed on 31 January 2025).

Effect of invasion by *Robinia pseudoacacia* on floristic diversity of *Quercus suber* forests in Chrea, Algeria

Rym Barhoumi¹, Leila Kadik¹, Ettayib Bensaci^{2*}, and Rabah Bounar^{2,3}

¹Department of Ecology and Environment, Faculty of Biological Sciences, Laboratory of Vegetal Ecology and Environment, Houari Boumediene University of Sciences and Technology (USTHB), El Alia, BP 32, Bab Ezzouar, 16111 Algiers, Algeria. E-mails: rbarhoumi@usthb.dz (R.B.), lkadik@usthb.dz (L.K.)

²Department of Natural and Life Sciences, University of Mohamed Boudiaf, M'sila, 28000, Algeria. *E-mail: tayeb.bensaci@univ-msila.dz (E.B.)

³Laboratory of Biodiversity and Biotechnological Techniques for the Valorisation of Plant Resources, Department of Natural and Life Sciences, University of Mohamed Boudiaf, M'sila, 28000, Algeria. E-mail: rabah.bounar@univ-msila.dz (R.B.)

Received: 31 December 2024 / Accepted: 01 March 2025 / Available online: 12 March 2025



Open Access: This work is distributed under the Creative Commons Attribution 4.0 License.

Abstract

The floristic composition and diversity analysis of forests is considered an essential aspect of cork oak ecosystem. Both can contribute to our knowledge of their functioning, and assist in our conservation efforts. Chrea woodland is located in the central part of the Tellian Atlas region of the Atlas Mountains in northern Africa. *Quercus suber* L. (cork oak) is a dominant tree in this woodland. A number of non-native species have established themselves in this woodland, including black locust (*Robinia pseudoacacia*). Urbanization, uncontrolled cutting, and wildfires are the main processes that affect at present the species composition and ecological dynamics of these woodlands. To investigate the floristic richness and diversity patterns of Chrea woodland, and the possible effects of invasive spreading of *R. pseudoacacia*, we sampled stands dominated by black locust and dominated by cork oak, during April, May, and June 2019–2021, collected species abundance for each plot. Overall, we identified 171 species representing 136 genera, belonging to 49 botanical families, with significant differences in species richness and species heterogeneity on the stands dominated by cork oak and stands co-dominated with black locust. The analysis of this flora also enabled us to identify medicinal plants, aromatic plants, and plants of economic interest in this region. Our data showed that the flora of Chrea woodland is dominated by Mediterranean vegetation, with life forms represented by Therophytes, Hemicryptophytes, Cryptophytes, Chamephytes and Phanerophytes. The dominance of therophytes and hemicryptophytes in both stand types illustrates how the woodland may be affected by processes, such as urbanization, uncontrolled cutting, wildfires, and the introduction of non-native species. The conservation of these peculiar woodlands with high values of plants diversity must be part of a sustainable development programme that will make it possible to protect existing heritage and improve the socio-economic conditions of local populations.

Key words: black locust, cork oak, medicinal plants, native oak, plant diversity, richness.

Introduction

One of the fundamental ecological justifications for protecting biodiversity is that its decline could affect ecosystem functions that support human life, such as primary productivity, carbon storage, water retention, and clean water supply (Lazaro et al. 2018). Often the specific and generic richness of the region is threatened because the biodiversity continues to be reduced very rapidly due to human pressure, which leads to fragmentation, degradation, and loss of habitat (Rabhi et al. 2018). The Mediterranean region is known as one of the most important 51 areas in the world for ecosystem diversity. However, there is not much information on the 52 habitats present in the southern and eastern Mediterranean (Médail and Quézel 1997, Véla 2018).

Cork oak (*Quercus suber* L.) forests are common within the Tellian Atlas region of the Mediterranean forest. Nevertheless, comparatively little research has been conducted on the floristic richness of these cork oak woodlands (Agrillo et al. 2018, Casella et al. 2020).

Cork oak is an endemic species of the Mediterranean basin, a descendant of the Upper Pliocene flora, which dates back to the Tertiary (Boudy 1950). It is considered to be of economic and ecological importance. The cork oak forest, which mostly stretches along the humid coastal regions of north-eastern Algeria until the Tunisian border, is one of the most significant forest types in Algeria in terms of covered area. These forests contain several biodiversity hotspots, including the Kabylia-Numidia-Kroumiria region (Véla and Benhouhou 2007, Meddour et al. 2022) and Chrea Park (Meyers et al. 2000).

Containing numerous rare and endemic species, this flora is being affected by a

variety of events and processes, including urbanization, uncontrolled cutting, wild-fires, and the introduction of non-native species. In particular, the effect of non-native plant species on native vegetation diversity has not been previously studied (Bennadja et al. 2013). At present, alien species, that has become abundant in the cork oak forests, is black locust (*Robinia pseudoacacia* L.) (GBIF Secretariat 2023).

The objective of this study was to assess how *R. pseudoacacia* may affect the species composition and dynamics of the cork oak forest in Chrea Park. To accomplish this, we compared the species richness and species heterogeneity of cork oak stands and co-dominated by *R. pseudoacacia*. We also wanted to categorize the life forms of the species and to identify species of medicinal, aromatic, and economic value.

Material and Methods

Study area

Chrea woodland occupies a mountainous territory, culminating at 1627 m a. v. in Koudiat Sidi Abdelkader (Sbabdji et al. 2015). It is characterized by significant topographical and floristic heterogeneity, including ecosystems dominated by *Q. suber* and *Q. ilex* L. (Derridj 1990). *R. pseudoacacia*, an introduced species, is common in *Q. suber* stands. The study area is located between the two sites of Hakou Feraoun and Béni Ali, between 700 to 1000 m altitude, among the northern latitudes 36°25'00" to 36°30'00" and the eastern longitudes 2°50'00" to 2°52'30" (Fig. 1). Using aerial photos with a scale of 1/20.000, dated 1999 (I.N.C.T), we were able to highlight the different iso-

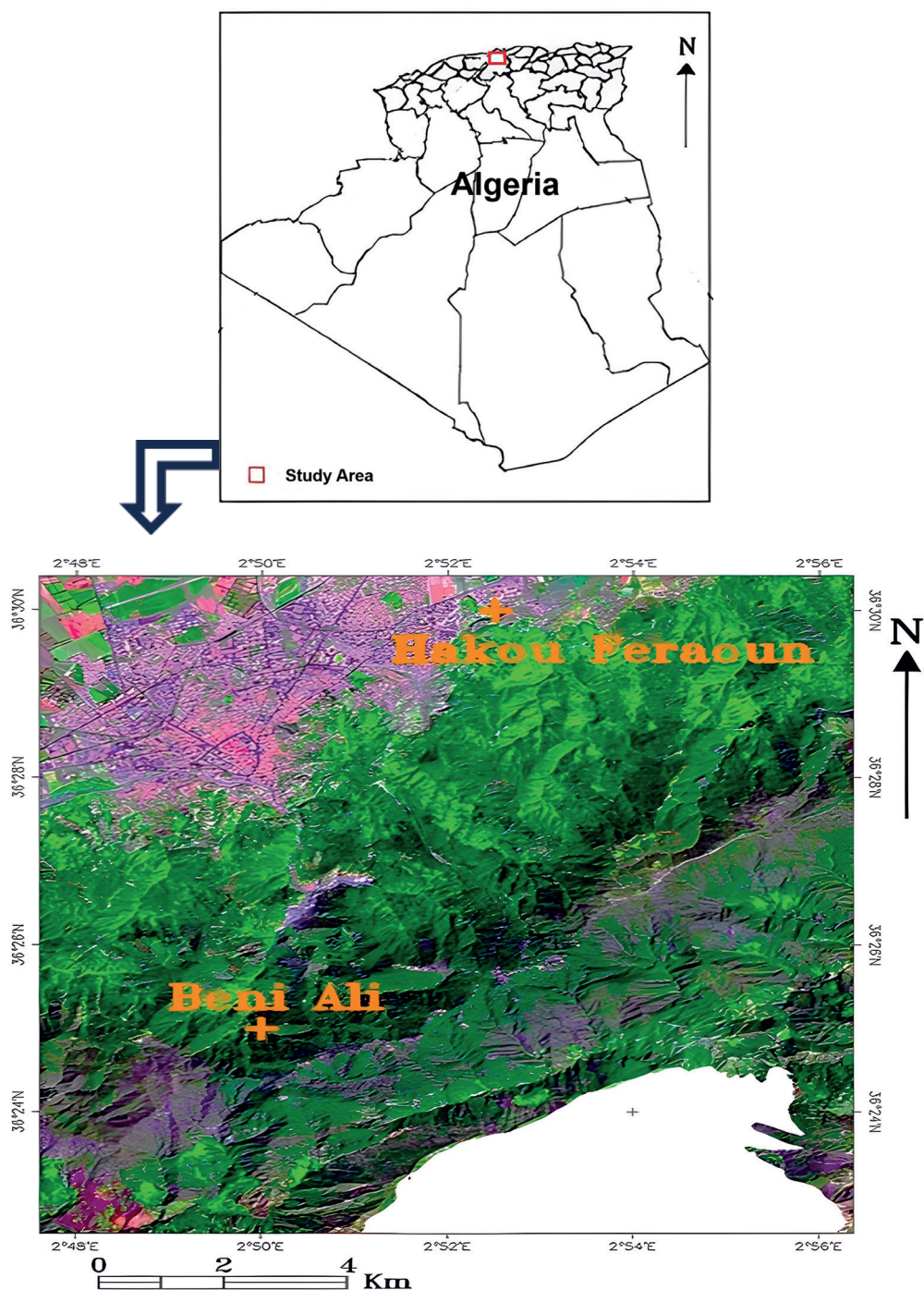


Fig. 1. Geographical location of the study area of the Chrea forest (INCT 2022).

phenes zones (large homogeneous plant formations).

The bioclimate location of the study area is subhumid at low altitudes (661 m) with an average maximum temperature 32 °C in July and an average minimum temperature of 2 °C in January, with annual average rainfall of 686 mm. The dry season lasts three months at low altitudes and two and a half months at high altitudes. The two study sites are located in the Meso-Mediterranean vegetation stage dominated by sclerophyll oaks (*Q. suber* and *Q. ilex*) in the altitudinal range from (600 and 1000 m) (Halimi 1980).

Data collection

To investigate the floristic richness and heterogeneity of Chrea woodland, species lists were extracted from floristic surveys conducted between 2019 and 2021 during April, May and June in Hakou Ferraouin and Béni Ali sites between 700 and 1000 m a.s.l.

The floristic surveys were carried out in plots with a minimum area of 100 m² with presence of the cork oak and black locust. Overall, 32 plot surveys were collected by the Braun-Blanquet (1932) method (16 plots on cork oak stands dominated by black locust tree, 16 control plots in native cork oak forest). We sampled 100 m² as a minimum area for all stands with and without black locust. We used the plant species check-list 'New Flora of Algeria' (Quézel and Santa 1962–1963) and 'Flora of North Africa Maire' (1952–1987), supplemented also by 'Flora Corsica' (Jeanmonod and Gamisans 2007). The rarity and plants endemism in Algeria were checked from 'New Flora of Algeria' list. The assessed species were divided in four categories namely rare, very rare, fairly rare and extremely rare according to

the criteria of rarity provided in the Algerian flora (Quézel and Santa 1962–1963). Life of found species list were categorized in: phanerophytes, chamaephytes, hemicryptophytes, cryptophytes and therophytes according to the Raunkiaer classification. The Raunkiaer's classification is the most accepted and used classification system for plants life form (Klimeš 2003, Leuschner and Ellenberg 2017). The Raunkiaer classification system groups terrestrial plants are: therophytes (annual plants surviving harsh conditions as seeds), hemicryptophytes (plants with buds at or near to soil surface), chamaephytes (plants with buds within 0.25 m above the soil surface), phanerophytes (plants taller than 0.25–0.5 m, with buds on aerial shoots) and geophytes (plants with belowground buds as storage organs, i.e., rhizomes or bulbs) (Ellenberg and Müller-Dombois 1967, Müller-Dombois and Ellenberg 1974).

Moreover, by the analysis of this the flora list of vegetation plot allowed us to develop a list of medicinal plants, aromatic plants, plants of economic interest, in Chrea Park 'New Flora of Algeria' (Quézel and Santa 1962–1963).

Data analysis

Independent t-tests (SPSS v17.0) were applied to compare the means of two independent groups in order to determine whether there is statistical evidence of stand type on: 1) species richness calculated as the number of species per plot; 2) species heterogeneity, which was calculated based on the additive components of diversity (Lande 1996, Roschewitz et al. 2005), by subtracting the mean number of species per plot from the total number of species found in each stand type; 3) Species abundance calculated as the number

of individuals of all species combined per plot. All tests were performed at the 0.05 level of significance. The mean values of richness, heterogeneity and abundance for both stands, were calculated with standard deviation.

Moreover, we computed the proportion of species collected in all plots in each life form class.

Results and Discussion

Floristic diversity in native and black locust stands

Our sampling yielded 171 species (143 in stands with black locust and 133 in stands dominated by cork oak), representing 136 genera and 49 families. This number of species represents 6 % of the flora of northern Algeria, estimated at 3150 species (Médail and Quézel 1997). The documentation of 171 species in the study area illustrates the higher level of plants biodiversity in Mediterranean cork oak savannas (Bugalho et al. 2011).

However, the species richness is lower than other Algerian regions, such as Kabylia cork oak forest, 311 species (Meddour et al. 2022); the Kéfrida woodlands, 332 species (Bouchibane et al. 2017); the Akfadou forest, 435 species (Messaoudene et al. 2007). It is also lower than those reported in eastern Numidia, 292 species (Bennadja et al. 2013) and the cork oak forests in the Tlemcen mountains, 429 taxa (Medjahdi et al. 2018). However, this richness was higher than that obtained in other regions, such as in Edough peninsula 123 species (Iboukassene 2008); in Djebel Bissa, 151 (Letreuch-Belarouci et al. 2009); in Theniet El Had, 157 (Naggar et al. 2019); in El Kala, 162 (Bennadja et al. 2013); in Bissa forest, Chlef, 151 (Zem-

mar et al. 2020). The most represented families in our study were Asteraceae and Fabaceae, each with 22 species, followed by Poaceae (20), Caryophyllaceae (9), and Brassicaceae, Lamiaceae, and Rosaceae, each one represented with 7 species, other families were less represented (Fig. 2).

The species richness is significantly different between cork oak stands and stands with the black locust ($t(30) = 2.62$, $p = 0.014$), with the mean richness in stands with black locust (43.50 ± 12.00) being higher than in stands without black locust (34.06 ± 7.98). However, there was no difference in species abundance between native and invaded stands ($t(30) = 1.13$, $p = 0.264$), where the mean abundance of black locust (62.87 ± 14.7) being higher than in native stands (57.94 ± 9.19). Our results showing that species richness is greater in plots with black locust differ from the findings of Benesperi et al. (2012), who found that plant communities were more diverse in areas without black locust. This diversity due probably to effect of black locust, which is known to significantly increase soil nitrogen reserves (Rice et al. 2004). As a result, this process is probably going to affect the understorey's composition and plant diversity.

Our findings are similar to reported by Levine and D'Antonio (1999) and Stohlgren et al. (2003), where local species richness might positively correlate with numbers of non-native species due to common promoting factors. With respect to species heterogeneity, stands without black locust exhibited reduced species heterogeneity (25.6 ± 6.06) vs (30.41 ± 8.39) in the stands with black locust ($t(30) = 1.86$, $p = 0.072$), with no significance difference between them.

The higher species heterogeneity in the stands with black locust in our study

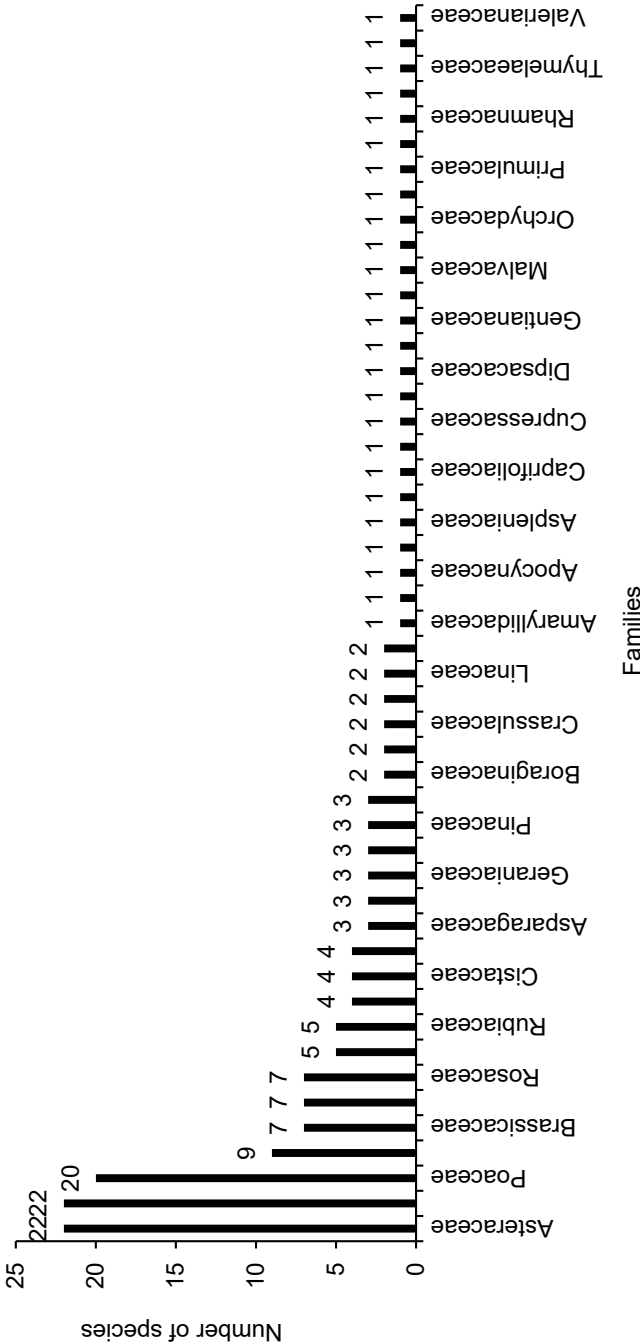


Fig. 2. Distribution of species in the Chrea forest according their taxon (families).

contrast with those reported by Benesperi et al. (2012), where forests species heterogeneity was higher in native stands than those of black locust. Whereas, some of the earliest evidence of heterogeneity-diversity-relationships in forest stands (MacArthur and MacArthur 1961), are similar to our finding on the high heterogeneity related to diversity in non-native stands. Alternatively, Huston and DeAngelis (1994) demonstrate that the heterogeneity is the result of large number of species can coexist.

Medicinal plants

Considering plants used in traditional medicine, our results included 47 medicinal species belonging to 29 families. Asteraceae had the highest number of species (7). Three medicinal species were found in Lamiaceae, Rosaceae and Papavveraceae, and two species were found in Fabaceae, Pinaceae, Cistaceae, Apiaceae and Plantaginaceae (Fig. 3).

That many of the medicinal species were found in the Asteraceae and Lamiaceae families are consistent with findings for the whole of the Mediterranean region (González-Tejero et al. 2008), particularly in Algeria (Meddour and Meddour-Sahar 2015), and Morocco (Ennabili and Gharnit 2000).

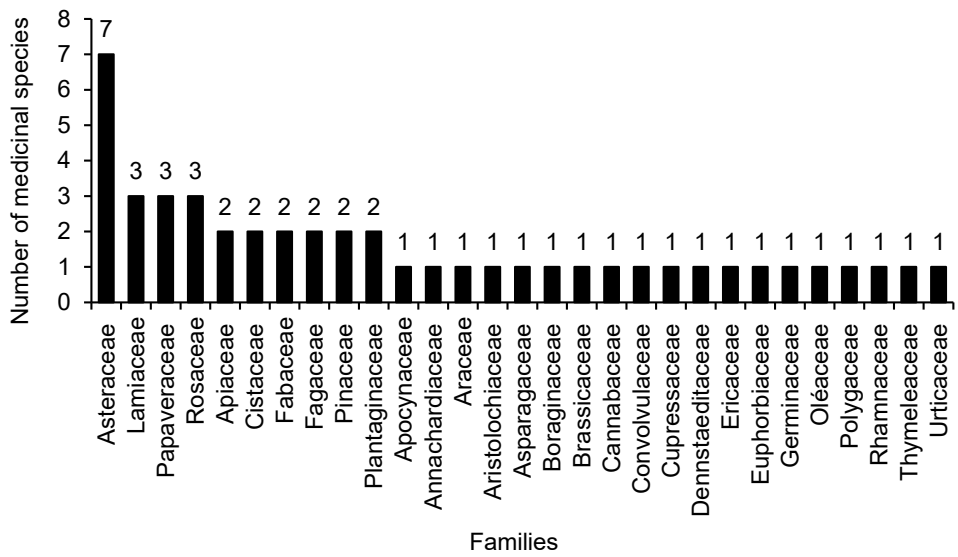


Fig. 3. Distribution of medicinal plant species in the Chrea forest according their taxon (families).

Rare species

According to the floristic diversity analysis, we found 14 rare species representing 12

families (Fig. 4), their abundances ranging from rare (6), very rare (4), fairly rare (2), to extremely rare (2) (Fig. 5).

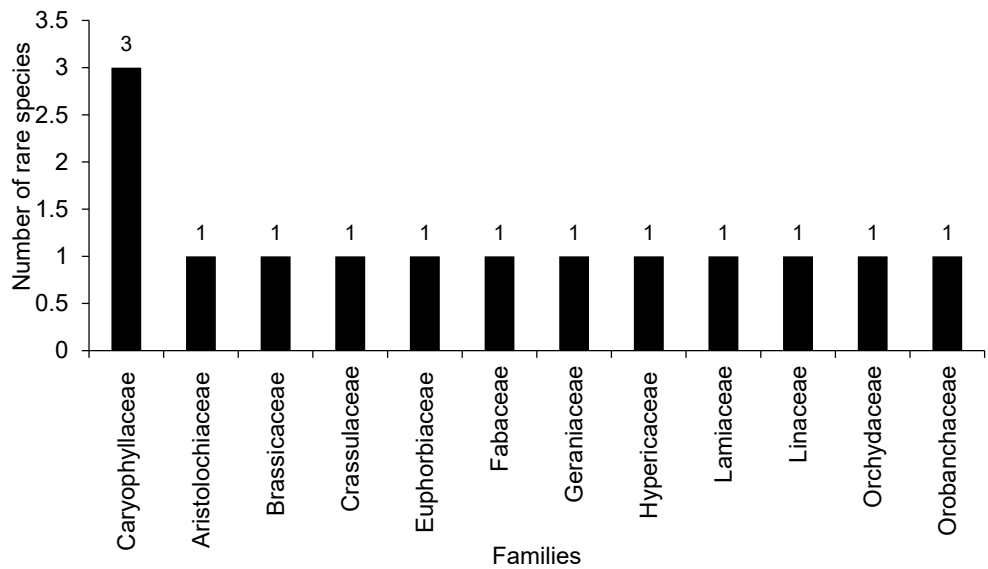


Fig. 4. Distribution of rare species per family in the Chrea forest.

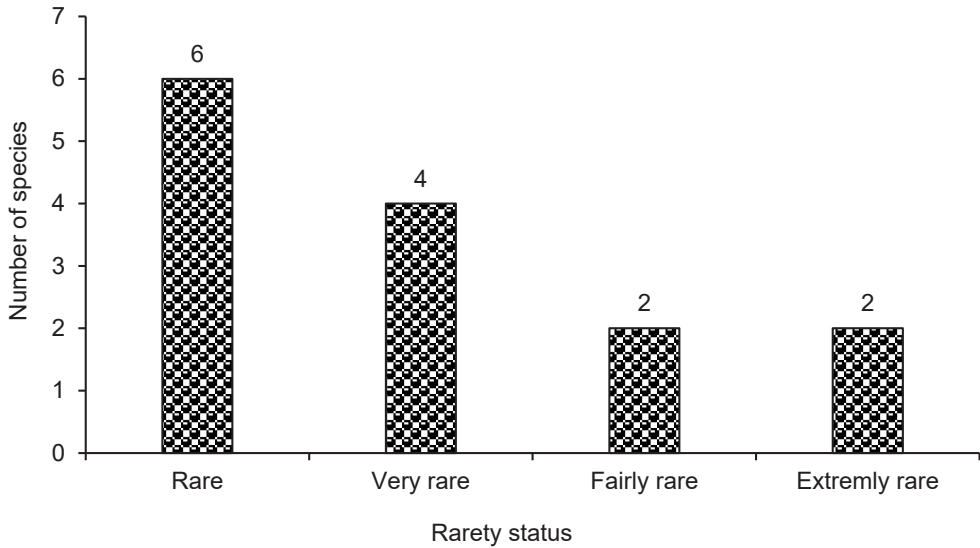


Fig. 5. Distribution of species following their rarity status.

Raunkiaer life forms species in Chrea woodland

Therophytes were by far the dominant life form in both types of stands, 50 % of the species in the stands with black locust (Fig. 6), and 53 % in the stands without it (Fig. 7). Phanerophytes and hemicryptophytes were the second and third most common life form types, again with comparable abundances in both stand types. Cryptophytes and chamephytes were the least common life forms, neither exceeding 10 %.

The relative proportion of the life forms in an ecosystem is a descriptive and physiognomic value, in addition to having ecological significance (Berghen 1984). The relatively high number

of therophytes illustrates adaptation to the Mediterranean bioma (warm, and periodically dry climate conditions), as well

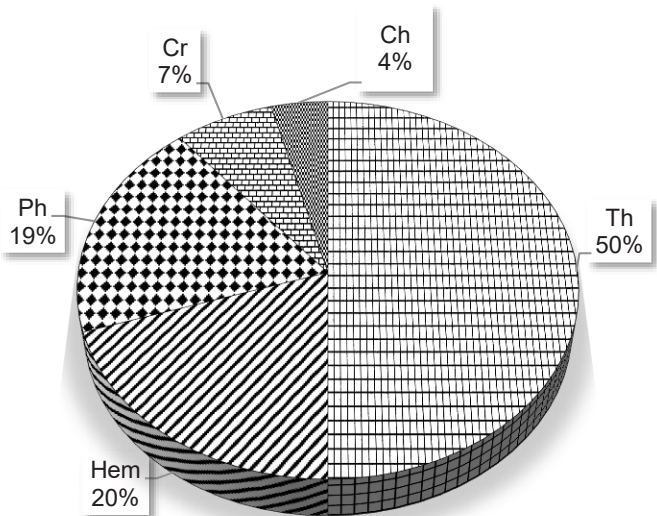


Fig. 6. Raunkiaer life forms species of the invaded woodland by *Robinia pseudoacacia* L.

Note: Th, He, Cr, Ch, and Ph indicate Therophytes, Hemicryptophytes, Cryptophytes, Chamephytes, and Phanerophytes, respectively.

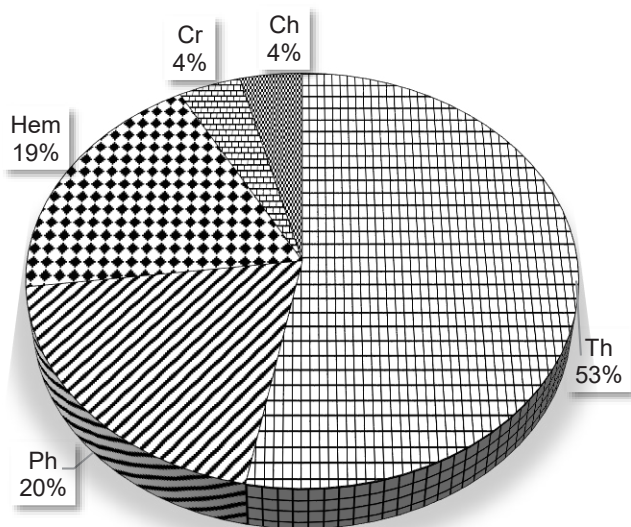


Fig. 7. Raunkiaer life forms of the woodland not invaded by *Robinia pseudoacacia* L.

Note: Th, He, Cr, Ch, Ph, and Ge indicate Therophytes, Hemicryptophytes, Cryptophytes, Chamephytes, Phanerophytes, and Geophytes, respectively.

as the effects of human disturbance, such as overgrazing (Letreuch-Belarouci et al. 2009, Rožac et al. 2018). The dominance of therophytes and hemicryptophytes in both stand types may indicate changes in both environments associated with increased wildfire frequencies, anthropization, and land clearing, all of which would be expected to make the landscape warmer and drier. The proportion plants found to be therophytes in this study is similar to that documented by Naggar et al. (2019) at Theniet el Had National Park in Algeria (50 %) and in the Mamora forest in Morocco (50.5 %) (Aafi et al. 2005).

The relative abundance of therophyte life forms in the study area is higher than that recorded in El Kala cork oak forest (38 %) (Ouelmouhoub and Benhouhou 2007), this lower rate may be explained by its location in the sub-humid climatic stage. Overall, the high presence of thero-

phytes is due to characteristics of arid Mediterranean zones, in which high-water stress dominates (Médail and Myers 2004). Contrary to that found in our study results, the hemicryptophytes are the dominant life form (43.8 %) in the forest woodlands of Babors, in Algeria (Bouchibane et al. 2021).

Conclusions

The present study investigated the effects of the introduction of black locust into a cork oak forest on the species composition, species richness, species heterogeneity, species abundance and plant life forms of the forest. The results

demonstrated that in the cork oak forest sampled, species richness, species diversity and species heterogeneity were predominantly higher in stands with locust than in stands without locust. Vítková et al. (2017) reported significant differences between habitats with and without black locust. In accordance with the results of our study and those of other researchers, this suggests that the introduction of species can, on occasion, increase local species richness (Sax et al. 2002, Stohlgren et al. 2003). However, species richness did not differ between stands with and without *Robinia*.

It is recommended to establish a programme that integrates general forest management with the objective of preserving highly desirable species, including rare or endangered species, as well as the valorisation of medicinal species.

References

- AAFI A., ACHHAL EL KADMIRI A., BENABID A., ROUCHDI M. 2005. Richesse et diversité floristique de la subéraie de la Mamora (Maroc). *Acta Botanica Malacitana* 30: 127–138. <https://doi.org/10.24310/abm.v30i0.7187>
- AGRILLO E., ALESSI N., JIMÉNEZ-ALFARO B., CASELLA L., ANGELINI S., ARGAGNON O., CRESPO G., FERNÁNDEZ-GONZÁLEZ F., MONTEIRO-HENRIQUES S., SILVA NETO C., ATTORRE F. 2018. The use of large databases to characterize habitat types: the case of *Quercus suber* woodlands in Europe. *Rendiconti Lincei. Scienze Fisiche e naturali* 29(2): 283–293. <https://doi.org/10.1007/s12210-018-0703-x>
- BENESPERI R., GIULIANI C., ZANETTI S., GENNAI M., MARIOTTI LIPPI M., GUIDI T., FOGGI B. 2012. Forest plant diversity is threatened by *Robinia pseudoacacia* (black locust) invasion. *Biodiversity and conservation* 21: 3555–3568. <https://doi.org/10.1007/s10531-012-0380-5>
- BERGHEN C.V. 1984. Observations sur la végétation du woodland forestier des Ka-lounayes (Casamance, Sénégal Méridional) 1e partie. *Bulletin de la Société Royale de Botanique de Belgique/Bulletin van de Koninklijke Belgische Botanische Vereniging* 117(2): 359–381. <https://www.jstor.org/stable/20794013>
- BENNADJA S., DE BÉLAIR G., TLILI AIT KAKI Y. 2013. La subéraie de la Numidie orientale: une source de biodiversité. *Quaderni di Botanica Ambientale e Applicata* 24: 49–53. https://www.herbmedit.org/quaderni/24_049.pdf
- BOUCHIBANE M., VÉLA E., BOUGAHAM A.F., ZEMOURI M., MAZOUZ A., SAHNOUNE M. 2017. Étude phytogéographique des woodlands forestiers de Kéfrida, un secteur méconnu de la zone importante pour les plantes des Babors (Nord-est algérien). *Revue d'Ecologie (La Terre et La Vie)* 72(4): 374–386. https://www.persee.fr/doc/revec_0249-7395_2017_num_72_4_1899
- BOUCHIBANE M., ZEMOURI M., TOUMI R. 2021. Contribution à l'étude de la végétation de certains woodlands montagneux de la Kabylie des Babors (Nord-Est algérien). Contribution to the study of the vegetation of some mountains to the Kabylia of Babors (Northeastern Algeria). *Bulletin de la Société Royale des Sciences de Liège* 90: 317–360. <https://doi.org/10.25518/0037-9565.10696>
- BOUDY P. 1950. *Economie forestière nord-africaine*. Tome 2(1): Monographie et traitements des essences forestières. Larousse, Paris. 525 p.
- BRAUN-BLANQUET J. 1932. *Plant sociology. The study of plant communities*. New York, London, Mc Graw-Hill. 439 p.
- BUGALHO M.N., CALDEIRA M.C., PEREIRA J.S., ARONSON J., PAUSAS J.G. 2011. Mediterranean cork oak savannas require human use to sustain biodiversity and ecosystem services. *Frontiers in Ecology and the Environment* 9(5): 278–286. <https://doi.org/10.1890/100084>
- CASELLA L., ALESSI N., SPADA F., AGRILLO E. 2020. Evergreen Oak Woodlands Southern Europe and Northern Africa. *Encyclopedia of World's Biomes*: 129–137. <https://doi.org/10.1016/B978-0-12-409548-9.12112-8>
- DERRIDJ A. 1990. Etude des populations de *Cedrus atlantica* Man. En Algérie. PhD thesis. Ès Sc, University Paule Sabatier, Toulouse. 228 p.
- ELLENBERG H., MÜLLER-DOMBOIS D. 1967. A key to Raunkiaer plant life-forms with revised subdivisions. *Ber. Goebot. Inst. ETH. Stifftg Rubel Zurich* 37: 56–73.
- ENNABILI A., GHARNIT N. 2000. Inventory and social interest of medicinal, aromatic and honeyplants from Mokrisset region (NW of Morocco). *Studia Botanica* 19: 57–74. <https://revistas.usal.es/historico/index.php/0211-9714/article/view/6081>
- GBIF SECRETARIAT 2023. *Robinia pseudoacacia* L. GBIF Backbone Taxonomy. Checklist dataset <https://doi.org/10.15468/39omei> accessed via GBIF.org on 2025-02-16. <https://www.gbif.org/pt/species/5352251>
- GONZÁLEZ-TEJERO M.R., CASARES-PORCEL M., SÁNCHEZ-ROJAS C.P., RAMIRO-GUTIÉRREZ J.M., MOLERO-MESA J., PIERONI A.,

- ELJOHRIG S. 2008. Medicinal plants in the Mediterranean area: synthesis of the results of the project Rubia. Journal of ethnopharmacology 116(2): 341–357. <https://doi.org/10.1016/j.jep.2007.11.045>
- HALIMI A. 1980. L'Atlas blidéen: climat et étages végétaux. Alger, Algérie, Office des publications universitaires. 523 p.
- HUSTON M.A., DEANGELIS D.L. 1994. Competition and Coexistence: The Effects of Resource Transport and Supply Rates. American Naturalist 144(6): 954–977. <https://doi.org/10.1086/285720>
- IBOUKASSENE S. 2008. Dynamique de la végétation des forêts à *Quercus suber* anthropisées du Nord-Est de l'Algérie (Parc National d'El-Kala). PhD thesis. Université Catholique de Louvain, Belgium. 274 p.
- INCT 2022. Carte Géologie d'Algérie 1/50 000 (Nord). Série de cartes topographiques \Institut National de Cartographie et de Télédétection de l'Algérie.
- JEANMONOD D, GAMISANS J. 2007. Flora corsica. Edisud, Aix-en-Provence (FR). 920 p.
- KLIMEŠ L. 2003. Life-forms and clonality of vascular plants along an altitudinal gradient in E Ladakh (NW Himalayas). Basic Applied Ecology 4(4): 317–328. <https://doi.org/10.1078/1439-1791-00163>
- LANDE R. 1996. Statistics and partitioning of species diversity, and similarity among multiple communities. Oikos 76(1): 5–13. <https://doi.org/10.2307/3545743>
- LAZZARO L., MAZZA G., D'ERRICO G., FABIANI A., GIULIANI C., INGHILESI A.F., LAGOMARSINO A., LANDI S., LASTRUCCI L., PASTORELLI R., ROVERSI P.F., TORRINI G., TRICARICO E., FOGGI B. 2018. How ecosystems change following invasion by *Robinia pseudoacacia*: Insights from soil chemical properties and soil microbial, nematode, microarthropod and plant communities. Science of the Total Environment 622–623: 1509–1518. <https://doi.org/10.1016/j.scitotenv.2017.10.017>
- LETREUCH-BELAROUCI A.M., LETREUCH-BELAROUCI N., BENABDELI K., MEDJAH B. 2009. Impact des incendies sur la structure des peuplements de chêne-liège et sur le liège: le cas de la subéraie de Tlemcen (Algérie). Forêt méditerranéenne 30(3): 231–238. https://www.foret-mediterraneenne.org/upload/biblio/FORET_MED_2009_3_231-238.pdf
- LEUSCHNER C., ELLENBERG H. 2017. Ecology of Central European Forests: Vegetation ecology of Central Europe; Springer International Publishing: Basel, Switzerland. Springer. Volume I. 779 p.
- LEVINE J.M., D'ANTONIO C.M. 1999. Elton revisited: a review of evidence linking diversity and invasibility. Oikos 87(1): 15–26. <https://doi.org/10.2307/3546992>
- MACARTHUR R.H., MACARTHUR J.W. 1961. On bird species diversity. Ecology 42(3): 594–598. <https://doi.org/10.2307/1932254>
- MAIRE R. 1952–1987. Flore de l'Afrique du Nord (Maroc, Algérie, Tunisie, Tripolitaine, Cyrénaïque et Sahara). Éditions Le Chevalier, Paris, vol. 1. 366 p.
- MÉDAIL F., QUÉZEL P. 1997. Hot-spots analysis for conservation of plant biodiversity in the Mediterranean basin. Annals of the Missouri Botanical Garden 84(1): 112–127. <https://doi.org/10.2307/2399957>
- MÉDAIL F., MYERS N. 2004. Mediterranean Basin. In: Mittermeier R.A., Gil P.R., Hoffman M., Pilgrim J., Brooks T., Mittermeier C.G., Lamoreux J., Fonseca G.A.B. (Eds), Hot-spots revisited: Earth's biologically richest and most endangered terrestrial ecoregions. CEMEX (Monterrey), Conservation International, Washington and Agrupación Sierra Madre: 144–147.
- MEDDOUR R., MEDDOUR-SAHAR O. 2015. Medicinal plants and their traditional uses in Kabylia (Tizi Ouzou, Algeria). Arabian Journal of Medicinal and Aromatic Plants 1(2): 137–151. <https://doi.org/10.48347/IMIST.PRSM/ajmap-v1i2.4331>
- MEDDOUR R., MEDDOUR-SAHAR O., BOUXIN G. 2022. Syntaxonomical survey of cork oak forests (*Quercus suber* L.) in the province of Tizi Ouzou, Kabylia, Northern Algeria. Hacquetia 21(2): 297–325. <https://doi.org/10.2478/hacq-2022-0007>
- MEDJAHDI B., LETREUCH-BELAROUCI A., MAZZOUZ S., TAÏBI K. 2018. Diversité floristique des subéraies des monts de Tlemcen (Nord Ouest Algérien). Flora Mediteranea

- 28: 67–77. doi: 10.7320/FIMedit28.067
- MESSAOUDENE M., LARIBI M., DERRIDJ A. 2007. Etude de la diversité floristique de la forêt de l'Akfadou (Algérie). *Bois and Forêts des Tropiques* 291: 75–81. <https://doi.org/10.19182/BFT2007.291.A20359>
- MÜLLER-DOMBOIS D., ELLENBERG H. 1974. *Aims and Methods in Vegetation Ecology*. John Wiley & Sons, New York, NY, USA. 547 p. doi: 10.2307/213332
- NAGGAR O., BOUHRAOUA R.T., TORRES E., ZEDEK M. 2019. Étude de l'influence des facteurs du milieu sur la croissance et la production du liège de la suberaie du Parc national de Theniet El Had (Tissemsilt, Algérie). *Bois & Forêts des Tropiques* 342: 41–54. <https://doi.org/10.19182/bft2019.342.a31793>
- OUELMOUHOUB S., BENHOUBOU S.S. 2007. Evolution floristique des suberaies incendiées dans la région d'El Kala (nord-est Algérie). *Ecologia mediterranea* 33(1): 85–94. <https://doi.org/10.3406/ec-med.2007.1410>
- QUÉZEL P., SANTA S. 1962–1963. Nouvelle flore de l'Algérie et des régions désertiques méridionales. Centre national de la recherche scientifique, Paris. 459 p.
- RABHI K., AKLI A., DJOUHRI A., YAHYI N., BOUDEDJA S., MESSAOUDENE M. 2018. Bilan et croissance des reboisements de cèdre de l'Atlas, *Cedrus atlantica* (Endl.) Carrière, en Algérie: cas du Djurdjura et de l'Atlas blidéen. *Bois et Forêts des Tropiques* 337: 3–15. <https://doi.org/10.19182/bft2018.337.a31627>
- RICE S.K., WESTERMAN B., FEDERICI R. 2004. Impacts of the exotic, nitrogen-fixing black locust (*Robinia pseudoacacia*) on nitrogen-cycling in a pine-oak ecosystem. *Plant Ecology* 174: 97–107
- ROSCHWITZ I., GABRIEL D., TSCHARNTKE T. 2005. The effects of landscape complexity on arable weed species diversity in organic and conventional farming. *Journal of Applied Ecology* 42(5): 873–882. <https://doi.org/10.1111/j.1365-2664.2005.01072.x>
- ROŽAC V., PRILIĆ D., OZIMEC S. 2018. The vascular flora of Kopački rit Nature Park (Croatia). *Acta biologica slovenica* 61(2): 47–70. <https://doi.org/10.14720/abs.61.2.15894>
- SAX D.F., GAINES S.D., BROWN J.H. 2002. Species invasions exceed extinctions on islands worldwide: a comparative study of plants and birds. *The American Naturalist* 160(6): 766–783. <https://doi.org/10.2307/3078859>
- SBABDI M., LAMBS L., HADDAD A., KADIK B. 2015. Effect of periodic defoliations by *Thaumeto poeapityocampa* Schiff. on radial growth in cedar woodland in Chréa, Algeria. *Revue d'Ecologie (Terre et Vie)* 70(4): 371–386. <https://doi.org/10.3406/revec.2015.1798>
- STOHLGREN T.J., BARNETT D.T., KARTESZ J.T. 2003. The rich get richer: patterns of plant invasions in the United States. *Frontiers in Ecology and the Environment* 1(1): 11–14. [https://doi.org/10.1890/1540-9295\(2003\)001\[0011:TRGRPO\]2.0.CO;2](https://doi.org/10.1890/1540-9295(2003)001[0011:TRGRPO]2.0.CO;2)
- VÉLA E. 2018. De l'inventaire de la biodiversité aux priorités de conservation dans le hotspot du bassin méditerranéen: peut-on combler les déficits de connaissance? PhD thesis. Université Montpellier. 61 p. doi: 10.13140/RG.2.2.17303.68008
- VÉLA E., BENHOUBOU S. 2007. Évaluation d'un nouveau point chaud de biodiversité végétale dans le bassin méditerranéen (Afrique du nord). *C.R. Biologies* 330(8): 589–605. <https://doi.org/10.1016/j.crv.2007.04.006>
- VÍTKOVÁ M., MÜLLEROVÁ J., SÁDLO J., PERGL J., PYŠEK P. 2017. Black locust (*Robinia pseudoacacia*) beloved and despised: a story of an invasive tree in Central Europe. *Ecological management* 384: 287–302. <https://doi.org/10.1016/j.foreco.2016.10.057>
- ZEMMAR N., M'HAMMEDI B. M., ABABOU A., HEDIDI D. 2020. Analysis of the floristic diversity in a Southern Mediterranean ecosystem. Case of Bissa forest, Chlef (Algeria). *Botanica Complutensis* 44: 19–28. <https://doi.org/10.5209/bocm.64447>

Assessment of ice-storm damage in forests using remote sensing

Svetoslav Anev 

Department of Dendrology, Faculty of Forestry, University of Forestry, 10 Kliment Ohridski Blvd., 1797 Sofia, Bulgaria. E-mail: svetoslav.anev@ltu.bg

Received: 16 March 2025 / Accepted: 16 April 2025 / Available online: 23 April 2025



Open Access: This work is distributed under the Creative Commons Attribution 4.0 License.

Abstract

Extreme weather events such as ice-storms increasingly impact forest ecosystems, yet effective methods for assessing their damage remain limited. This study aims to compare the applicability of three vegetation indices based on imagery obtained from Sentinel-2 satellites in assessing damage from large-scale forest disturbance caused by an ice-storm in the Western Stara Planina Mts. The rate of damages was assessed using the temporal comparison in the Normalized Difference Vegetation Index (NDVI), Plant Phenology Index (PPI), and Leaf Area Index (LAI) between August 2020 and August 2021. The results showed that NDVI is less sensitive for canopy changes in complex phytocoenosis such as forests. Due to the forest's understory phenology, PPI has a low relation with canopy destruction and indexes false positive changes between 2020 and 2021. LAI reduction was closely related to terrain assessment results, but there was still an index increase in stands with high damage values established during field assessments. A significant challenge in forest disturbance damage analysis based on changes in vegetation indices remains the objectivity of the field assessments used as a control for comparing the applicability of indices. Quality and quantitative assessment of disturbance impacts on forests using remote sensing requires precise ground-based data and integration of this information with vegetation indices. Due to partial crown destruction in some affected trees, remotely sensed indices incorporating canopy depth are well-suited for assessing damage caused by natural forest disturbances.

Key words: Leaf Area Index, Normalized Difference Vegetation Index, Plant Phenology Index.

Introduction

Natural disturbances are part of forest dynamics (Grebner et al. 2012), but unlike micro-disturbances, which diversify the functions, structure, and development of stands (Oliver and Larson 1996), large-scale natural disturbances lead to rapid change in the forest environment. Ac-

cording to Voller and Harrison (2011), the scale of a natural disturbance can vary significantly, depending on the nature of the event that causes it, as well as on the orography of the terrain and the structure of the forest. The period between two large-scale natural disturbances is often shorter than the potential lifespan of late-successional species (Oliver and Lar-

son 1996). Therefore, large-scale natural disturbances free up space for the accommodation of pioneer plant species, restarting succession and changing the species composition of forests.

Forest ecosystems are often represented by a mosaic of stands that vary in age, composition, structure, and functionality. Their dynamic appearance is formed primarily by disturbances, which can be natural or anthropogenic. Lazarov et al. (2009) point out that periodic natural disturbances are a crucial factor in the life cycle of forest ecosystems and maintain their diversity and functions over a long period. Wind, snow or ice, torrential rains and floods, fires, avalanches, etc., cause natural disturbances. The frequency and intensity of ice-storms are expected to increase with climate change, leading to more frequent and severe damages. Ice-storm damage can range from minor twig breakage to complete trunk break or uprooting (Guo and Xue 2012), depending on the spatial and temporal extent of the damaging event (Olthof et al. 2004). This structural damage can significantly alter forest dynamics and recovery processes (Cao et al. 2020). Ice-storm damage to the forest canopy affects understory light conditions, influencing species regeneration and forest dynamics. It also impacts soil, litter, disease fungi, and wildlife (Guo and Xue 2012).

Damage assessment after a natural disturbance is still labour-intensive and requires solid human resources. It is subjective mainly because primitive scales and criteria are used. Moreover, assessors often vary due to the large scale of the affected territories, which could contribute to an increase in errors.

Several methods and indices can be employed to assess ice-storm forest damages using vegetation indices, primarily

leveraging remote sensing data (Frolking et al. 2009). According to Lechner et al. (2020), remote sensing can demonstrate high potential in monitoring forest changes over long periods or comparing different sites. Remote sensing has been used in a diverse range of forest ecology and management applications from mapping invasive species to monitoring land-cover changes, such as habitat fragmentation, to estimating biophysical and biochemical properties of forests. Some crucial advantages of remote monitoring methods for forest ecosystems are related to the ability to capture a comprehensive picture of the current state of forests, track this state over time based on periodic surveys of the same territory, digitize the data, and link it geographically (Lechner et al. 2020). Satellite remote sensing is emerging as an efficient tool for monitoring vegetation dynamics due to natural disturbances, using frequent observation, wide coverage and easy data collection (Lechner et al. 2020, Zhao et al. 2024a). According to Asenova and Angelov (2022), a remote sensing assessment can save time and effort, use objective criteria, and allow the analysis of natural disturbances' principal risks and prerequisites. Forests have a specific absorption capacity for red and infrared light (Treitz and Howarth 1999), so it is possible to assess the damage based on satellite images taken in these light ranges. The relationship between remotely sensed vegetation indices and forest damage caused by natural disturbances is still hardly studied. Factors such as mixed species complexes, vertical structure, topography, time of day and year, vegetation phenology, weather conditions, moisture, and stress, complicate computer-based analysis procedures by increasing spectral variance and reducing the spectral separability of classes (Pitt et

al. 1997). This can add variations in tracking long-term trends and cause false positive or negative signals in forest dynamics. The atmosphere varying transmittance to light can also distort the results of long-term monitoring. Even if we exclude clouds with some modern approaches, causes of inaccuracies, such as humidity and dustiness of the atmosphere, remain more difficult to identify and compensate for (Kaufman et al. 1997). The diversity of reasons for change in forests complicates identifying and analysing disturbances. Human activity in forest management leads to significant changes in their natural dynamics and can enhance or mask some natural processes (Barbero et al. 1990). Studies that require detailed information on smaller plants (<0.5 m tall) and/or individual or rare plant species are unlikely to be supported by current remote sensing technologies (Pitt et al. 1997).

One of the most commonly used vegetation indices in environmental studies determined from satellite images is the Normalized Difference Vegetation Index (NDVI) proposed by Rouse et al. (1974), which is calculated using images of reflected light in the red (RED) and infrared (NIR) parts of the light spectrum (Pettorelli et al. 2005):

$$NDVI = \frac{NIR - RED}{NIR + RED} \quad (1)$$

The equation (1) is based on the fact that infrared light is reflected more intensely by plants' leaves with more hydrated and healthy cell walls. At the same time, leaves with more chlorophyll reflect less red light. Therefore, higher NDVI values show a higher life potential and a better ability to absorb the carbon of the vegetation (Tucker et al. 1991).

Several authors point to the direct relationship between NDVI and forest productivity (Sellers et al. 1992, Vourlitis et

al. 2003, Bailey et al. 2004). However, NDVI has one significant drawback when studying vegetation dynamics in forest areas. After quickly reaching the maximum value for the season, NDVI remains high for an extended period because it is less sensitive to fluctuations in water content and chlorophyll in summer, especially in compact forests (Huete et al. 2002). For this reason, Grabska-Szwagrzyk and Ty mińska-Czabańska (2024) recommend for monitoring in forests to use indices that reflect in more detail the state of the leaf apparatus during individual months of the year, such as the Enhanced Vegetation Index (EVI), calculated by equation (2).

$$EVI = 2.5 \cdot \frac{NIR - RED}{NIR + 6 \cdot RED - 7.5 \cdot BLUE + 1} \quad (2)$$

By using the blue channel in the calculation of EVI, the background influence of soil and particles in the atmosphere is reduced. Blue light, on the other hand, is scattered strongly in the atmosphere (Ahrens and Henson 2015). According to Jin and Eklundh (2014), with static sensors such as those on the Sentinel-2 satellites, there is often considerable variation and a decrease in the accuracy of the determined index, especially at higher latitudes. The authors propose a new approach for calculating a vegetation index based on biophysical laws such as the diffuse reflectance law of Hapke (2012). Based on Buschmann and Nagel (1993) assumptions, that the logarithm of the ratio between NIR and RED shows a much stronger relationship with chlorophyll content, and considering the advantages of normalized indices, Jin and Eklundh (2014) formulated a Plant Phenology Index (PPI).

$$PPI = -K \cdot \ln \left(\frac{DVI_{MAX} - DVI}{DVI_{MAX} - DVI_{Soil}} \right) \quad (3)$$

In the PPI equation (3), DVI (Differ-

ence Vegetation Index) is the difference between NIR and red reflectance; DVI_{MAX} is the maximum DVI value for the most extended possible period, and DVI_{Soil} is the soil DVI, which is used as the minimum PPI correction value. Factor K is a PPI gain factor that depends on the canopy's density, the leaves' light transmission, the inclination of the leaves to the horizontal, and the angle of incidence of the sun's rays (Jin and Eklundh 2014). One of the most significant advantages of PPI as a biophysical index is its strong correlation with the Leaf Area Index (LAI), which is widely used in forest research because it shows a strong relationship with forest productivity. LAI is broadly defined as the amount of leaf area (m^2) in a canopy per unit ground area (m^2) (Watson 1947). It determines the size of the interface for exchange of energy (including radiation) and mass between the canopy and the atmosphere. LAI is an intrinsic canopy primary variable that is independent of observation conditions (WEKEO 2023). Weiss et al. (2004) described the methodology for deriving LAI from Sentinel-2 products. It's based on INRA's 5-level neural network (Fernandes et al. 2014). The relationship between LAI and PPI is linear, unlike the non-linear relationship of the widely used NDVI and EVI, whose levels saturate as LAI increases above 2–3 $m^2 \cdot m^{-2}$.

A change between the spectral indices of pre-disturbance and post-disturbance images is a widely used approach to assess rate of damages (Miller and Yool 2002, Olthof et al. 2004, Brewer et al. 2005, Röder et al. 2008, Sharma et al. 2022, Zhao et al. 2024b). Differencing can result in a measure of absolute or relative change correlated to the pre-disturbance image. A significant change in live biomass will be measured in a pixel experiencing complete mortality that contained a

large amount of photosynthetically active vegetation in the pre-disturbance image (Miller and Yool 2002). Damage classification typically requires assignment of a continuous damage measure into discrete damage classes. A limitation of the classification approach is that the boundaries between damage classes are artificial and subjective (Olthof et al. 2004).

The approach of using the difference between pre- and post-disruption images to assess damage from natural disturbances has the potential to save time and effort in field surveys. Remotely sensed indices can help differentiate areas of low or medium damage from areas of severe damage. Such classification methods can provide regional damage maps more objectively than point-based visual estimates and aid in identifying areas of severe damage where management intervention may be advantageous (Olthof et al. 2004). The three studied vegetation indices have different advantages when used as criteria for remote assessment. NDVI is easy to calculate (Pettorelli 2013), and the literature provides numerous examples of its use for similar purposes (Nedkov et al. 2020, Pettorelli et al. 2005, Sharma et al. 2022). The use of PPI makes the assessment significantly more complex, as this index responds not only to changes in the main forest stand but also to changes in the vegetation community's lower biotic horizons (Jin and Eklundh 2014, Anev 2023). LAI is most closely related to forest productivity and records damage in a way that is closest to the visual assessment method (Clark et al. 2008, Fernandes et al. 2014). However, each index also has its drawbacks, which became apparent from the study. NDVI quickly saturates to relatively high values, making it less sensitive to minor damage (Gamon et al. 1995).

A significant problem when comparing vegetation indices from two years is the interannual variation of the index due to specific meteorological conditions in individual years. Establishing a threshold for damage assessment involves comparing pre- and post-disturbance vegetation index values, which can be done by calculating the standard deviation of pixels in undamaged areas and setting a threshold based on this deviation (Wu et al. 2016). Myneni et al. (1998) observed 10% interannual variation of NDVI in Alaska over nine years (1981–1990). For the same period, Tucker et al. (1991) point out that the coefficient of variation of NDVI above 0.25 corresponds well to the Sahel. Xiao-Bing et al. (2003) established approximately 20% interannual variation of NDVI over 17 years (1983–1999) for the temperate steppe in Northern China. Rowhani et al. (2011) showed that temperate broadleaf forests experienced 5.63% interannual variations in EVI from 2000 to 2006 but also pointed out that around 14 % of the global vegetation experienced more than 20% of interannual variability in land surface attributes relative to the median year over the six years. Cheng et al. (2024) found that China's vegetation status (based on EVI) exhibits a notable intra-annual variation pattern of high in summer and low in winter, and the changes are more pronounced in the northern regions than in the southern regions. The interannual dynamics of vegetation indices in forests, especially those of a biophysical nature such as PPI and LAI, are often due to interannual fluctuations in phenological dynamics related to cumulative temperatures, the main tree species, the stage of development, the structure of the forest, etc. (Peaucelle et al. 2019, Olthof et al. 2004). Anev (2023) found that for 2017–2023, the PPI in 'Petrohan' Training and

Experimental Forest Range varied (based on the standard deviation) from 1 % in December-January, to 23 % in June-July, and the average for the year was 10 %. Wu et al. (2016) recommended the same values for deviation from the mean of NDVI and EVI as a threshold to identify damaged areas.

In Bulgaria, vegetation indices are barely entering the study of ecosystems. At this stage, the NDVI index finds a broader application in precision agriculture. It is used to assess the production potential of crops and the need for fertilisation and watering (Oliver 2014, Hristov et al. 2020). Attempts are being made to use data from vegetation indices to assess the risk of calamities in forests (Stoyanova et al. 2018) or forest fires (Nedkov et al. 2020), which is regrettably not made by plant physiologists or foresters. There is still a broad scope for using vegetation indices to analyse forest dynamics, management activities, and decision-making.

This study aims to compare the applicability of three vegetation indices based on satellite imagery in assessing damage from large-scale forest disturbance caused by an ice-storm in the Western Stara Planina Mts.

Object and Methods

Object

'Petrohan' is located on the northern macro slope of Western Stara Planina Mountains. The territory is 7290.4 ha. The average altitude is 958 m, varying from 319 m to 1794 m (Fig. 1).

According to the climate norms for the last reference period (1991–2000), the average annual temperature is 8.0 °C. It varies from 3.5 °C in the highest altitude

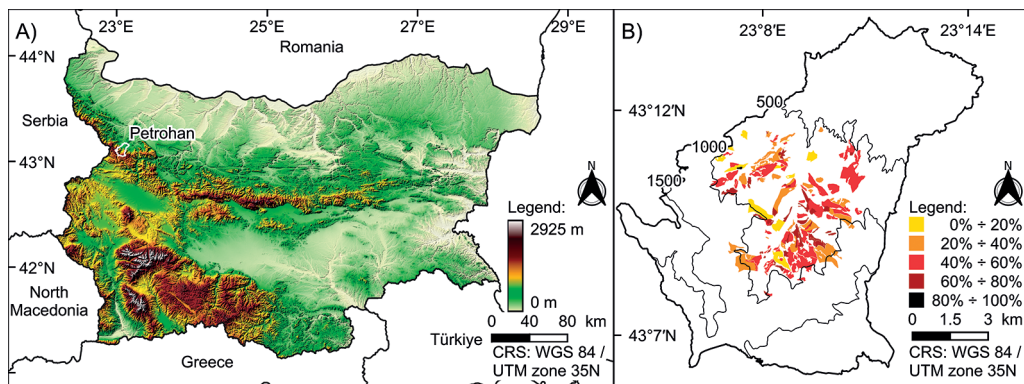


Fig. 1. Location of the study object (A) and damage assessed in the field (B).

to 11.7 °C in the lowest. Precipitation varies significantly across the region. The average annual amount is about 1200 mm, but in individual years, it can reach over 1500 mm; in other years, it can drop to 850 mm (Marinova and Bocheva 2023). With climate change, extreme events causing forest damage are becoming more frequent. An extreme climate event is associated with the forest damages examined in this study. On the evening of January 7, 2021, precipitation began in the Western Stara Planina region. At the same time, air temperatures at 900 m a.s.l. remaining above freezing (2.7 °C). By the night of January 8, temperatures fell below 0 °C and remained negative until January 13. During this period (January 8 to 06 h on January 13), the mean air temperature at 900 m was -3.14 °C, with total precipitation reaching 44.3 L·m⁻². Persistent snow accumulation on tree crowns culminated in widespread structural damage on the morning of January 13, including uprooted trees and breakage of stems and crown segments, opening wounds for various pathogens.

The damages were described in 199 stands over about two years, which required daily, intensive field visits by forest rangers. The extent of damages, includ-

ing the area and rate of the affected part of the stands, were determined during the field assessments on a visible scale in percent (Fig. 1B). More objective and spatially explicit approaches to assessing ice-storm damage were needed to help understand the risk factors and effects of the storm and to provide a baseline for monitoring forest recovery.

Data collection, preparation, and analysis

Archived database, such as Sentinel-2 satellite images from the European Space Agency's Copernicus program, may enable pre- and post-storm change analysis. The High-Resolution Vegetation Phenology and Productivity (HR-VPP) Database from the Copernicus Land Monitoring Service (WEkEO 2023) was used to calculate the changes of three vegetation indices (VI) for the period 2020 ÷ 2021. The VI database comprises three daily vegetation indices: Plant Phenology Index, Normalized Difference Vegetation Index, and Leaf Area Index, as well as quality information that is part of the Copernicus Land Monitoring Service (CLMS) HR-VPP product suite. Images captured by the S2A Sentinel-2 satellite on 31.08.2020

and 16.08.2021 were used to calculate relative changes of PPI, NDVI and LAI for each 'Petrohan' stand.

Data processing was carried out in the following sequence:

1. The polygons of the stands in 'Petrohan' were downloaded from the national forest inventory database (<https://maps.iag.bg/>). Out of a total of 2506 polygons, only those 2093 that are closed canopy forests were filtered.

2. The images S2A_T34TFN-010m_V101 for the PPI, NDVI and LAI indices for the dates 31.08.2020 and 16.08.2021 were downloaded from the site of Wekeo (2023);

3. In QGIS (v. 3.36.1-Maidenhead), the images were clipped along forest stands polygons with the 'clip raster by mask layer' plugin (GDAL, v. 3.8.4).

4. The relative differences in vegetation indices were calculated using the built-in raster calculator by equation (4).

$$\Delta VI_{20 \div 21} = \frac{VI_{20} - VI_{21}}{VI_{20}} \cdot 100, \quad (4)$$

where: $\Delta VI_{20 \div 21}$ is relative changes of NDVI, PPI, and LAI between 2020 and 2021; VI_{21} is value of index' pixel from image of 16.08.2021; VI_{20} is value of index' pixel from image of 31.08.2020.

5. Using the built-in 'zonal statistics' tool, the arithmetic mean values, standard deviations, and number of pixels of the relative difference images $\Delta NDVI_{20 \div 21}$, $\Delta PPI_{20 \div 21}$, and $\Delta LAI_{20 \div 21}$ were calculated only for those 199 described with damages in a field assessment forests polygons.

6. Using the 'join attributes by field value' add-on, the data were merged into one attribute table and this table was exported in CSV format for subsequent analysis in MS Excel.

7. In MS Excel, some statistical parameters (Spearman rank correlation coefficient, root mean square error, and covariance) were calculated between $\Delta VI_{20 \div 21}$ and observed in terrain assessment damages.

Results

The change in vegetation indices, determined through relative difference images from 2021 and 2020, shows that the negative changes in indices were concentrated in the altitude range of 500 to 1100 m. In relative terms, among the examined indices, NDVI was changed the least – the average raster value was -3.88 %, meaning a slightly higher average NDVI in 2021 compared to 2020. More than 81 % of the pixels in the $\Delta NDVI_{20 \div 21}$ image have negative values close to zero. Among the positive pixels, 92.7 % fall within the range (0 % ÷ 20 %], 6.5 % have values in the range (20 % ÷ 40 %], 0.8 % have values in the range (40 % ÷ 60 %], and only 0.05 % (65 pixels) have values above 60 %. The average value of $\Delta NDVI_{20 \div 21}$ at the stand level for the 199 stands with damage described during the field assessment is 7.21 ± 0.36 %, with a highest value of 26.37 %. However, in 193 (97 %) of these stands, a minimal increase in $\Delta NDVI_{20 \div 21}$ was recorded within the range (0% ÷ 20%], while only six stands (3 %) show an increase in NDVI within the following range (20% ÷ 40%]. There were no stands with an increase in $\Delta NDVI_{20 \div 21}$ above 40 %. The Spearman rank correlation coefficient between the field-described damage and the recorded reduction in NDVI from 2020 to 2021 is 0.253 (P -value < 0.001), with a Root Mean Square Error (RMSE) of 47.4. The covariance between the two series was positive, however, it was only 19.6 (Fig. 2A).

Unlike NDVI, $\Delta PPI_{20 \div 21}$ image was

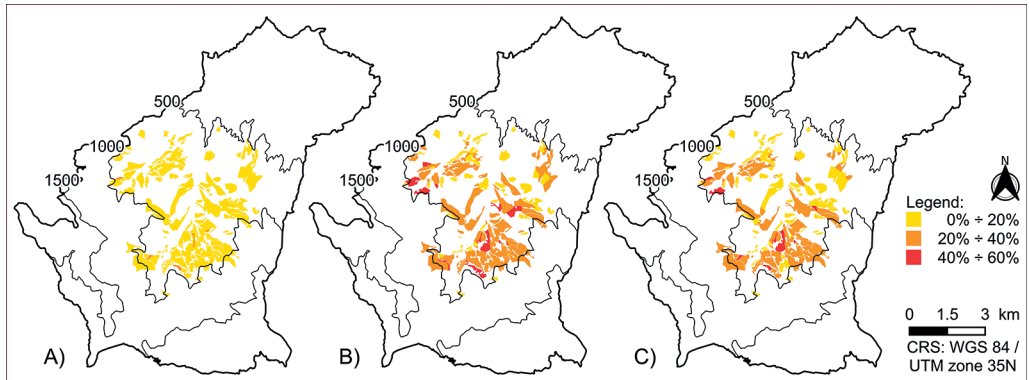


Fig. 2. ΔVI_{20+21} for 199 stands with damage assessed in the field. A) $\Delta NDVI_{20+21}$; B) ΔPPI_{20+21} ; C) ΔLAI_{20+21} .

much more saturated with negative pixels. Despite this, the average raster value was -61.9 %, indicating significantly higher PPI levels in 2021 compared to 2020. A total of 82.4 % of the pixels in the ΔPPI_{20+21} image have negative values. Among the pixels with positive values, 47.3 % fall within the range (0 % ÷ 20 %], 30.9 % have values in the range (20 % ÷ 40 %], 16 % have values in the range (40 % ÷ 60 %], 5.2 % have values in the range (60 % ÷ 80 %], and 0.7 % (773 pixels) have values above 80 %. The average value of ΔPPI_{20+21} at the stand level for the 199 stands with damage described during the field assessment is 25.1 %, which was higher among studied indices. In 71 (35.7 %) ΔPPI_{20+21} fall within the range (0 % ÷ 20 %], 106 (53.3 %) were in the range (20 % ÷ 40 %], and 22 (11.0 %) were in the range (40 % ÷ 60 %]. Spearman rank correlation coefficient between the field-described damage and ΔPPI_{20+21} was 0.742 (P -value < 0.001), Root Mean Square Error (RMSE) is 31.9, and the covariance was the highest (52.3) among the studied indices. (Fig. 2B).

ΔLAI_{20+21} image was more saturated with positive pixels than $\Delta NDVI_{20+21}$ but less saturated than ΔPPI_{20+21} . The average raster value was -27.1 %, confirming

the trend for forests in 'Petrohan' to have higher indices levels in 2021 than in 2020. Among the pixels with positive values, 58.7 % fall within the range (0 % ÷ 20 %], 27.5 % have values in the range (20 % ÷ 40 %], 10.9 % have values in the range (40 % ÷ 60 %], 2.6 % have values in the range (60 % ÷ 80 %], and 0.2 % (277 pixels) has a value above 80 %. The average value of ΔLAI_{20+21} at the stand level for the 199 stands with damage described during the field assessment is 20.9 %. However, in 107 (53.8 %) stands ΔLAI_{20+21} fall within the range (0 % ÷ 20 %], 79 (39.7 %) stands were in the range (20 % ÷ 40 %], and 13 (6.5 %) were in the range (40 % ÷ 60 %]. Spearman rank correlation coefficient between the field-described damage and ΔLAI_{20+21} was the highest – 0.937 (P -value < 0.001), Root Mean Square Error (RMSE) was the lowest – 30.2, and the covariance was 57.3 (Fig. 2C).

Discussion

Although NDVI is the most commonly used vegetation index in assessing vegetation cover conditions, it is insufficiently sensitive for evaluating natural distur-

bances. On the one hand, as pointed out by some authors (Pettorelli et al. 2005, Jin and Eklundh 2014, Cheng et al. 2024), this is due to its rapid saturation in spring and the maintenance of relatively high values for an extended period during the summer and even into autumn. On the other hand, the simple calculation mechanism of NDVI, based on the use of IR light that reacts to the moisture content of objects (Pettorelli 2013), results in falsely high values for non-vegetated objects with high moisture, such as wet soils (Yang et al. 2019). The minimal number of stands, categorized only in the weakest damage category, indicates that NDVI is low sensitive and unsuitable for assessing damage from natural disturbances, especially in complex vegetation communities such as forests.

Plant Phenological Index (PPI) was designed to include a biophysical component (Jin and Eklundh 2014) that accounts for canopy density, making it significantly more suitable for assessing the condition of forest communities (Junttila et al. 2023). Furthermore, PPI accounts for soil and snow reflectance (Smets et al. 2022), making it helpful in evaluating areas stripped of vegetation (Yang et al. 2019), as observed after large-scale natural disturbances. On the other hand, PPI is based on the degree of greening, relying on a simple difference between the reflectance of red and IR light (Jin and Eklundh 2014). This means that regardless of damage to the main canopy layer, which formed the canopy cover, if the lower biotic horizons of the vegetation community (such as the shrub and grass horizons) contain green leaves, PPI will remain high or may even exceed the pre-disturbance value (Smets et al. 2022). A serious risk of mistakes also exists because PPI is strongly influenced by leaf aging (Jin and Eklundh 2014), which is only partially

related to the observation date but is much more affected by the complex hydro-thermal conditions preceding the observation (Zhao et al. 2016). In the case of damage assessment from an ice-storm, these shortcomings are evident from the large number of stands with $\Delta PPI_{20 \times 21} < 0\%$, including those with reported 60 % damage during field assessment. Thus, despite the high covariance, the correlation coefficient between $\Delta PPI_{20 \times 21}$ and field-described damages remains the lowest, and RMSE is the highest among the indices studied.

The established changes in LAI most closely match the field-determined damage. The highest correlation and covariation among studied indices are probably because the crowns and canopy, from which LAI depends mostly, were evaluated during the terrain assessment. LAI indirectly accounts for canopy density, which helps to index even minor damage, such as broken crowns or snapped individual branches. At the same time, Leaf Area Index is calculated based on the fraction of photosynthetically active radiation absorbed by the terrain (Fernandes et al. 2014). Excluding IR light when determining LAI helps to some extent reduce noise caused by the water content of objects (Weiss et al. 2004).

Conclusions

The three indices considered have specific features that make them suitable for various aspects of forest monitoring. We confirmed that NDVI is insufficiently sensitive for evaluating natural disturbances in forests. Even with larger-scale disturbances, such as the ice-storm assessed in the present study, NDVI changes by about one-quarter, complicating damage severity differentiation. In cases of mod-

erate damage, where only branches are broken or even single crowns are affected, PPI tends to increase because the altered light regime in the affected stand favours the phenology of the understory. Earlier unfolding and a more extended vegetation period of the understory lead to many false positive ΔPPI_{20+21} values. Our results showed that among the studied vegetation indices, LAI is the most suitable for assessing damage caused by natural disturbances in forests. A significant challenge in damage analysis based on changes in vegetation indices remains the objectivity of the reference data used for comparison, namely field assessments conducted by different evaluators, often based on subjective criteria and scales and carried out over an extended period. Quality and quantitative assessment of disturbance impacts on forests with remote sensing requires precision ground-based data and linking this information to vegetation indices. Due to partial crown destruction in some of the affected trees, remotely sensed indices that include the canopy depth are suitable for assessing damage from natural forest disturbances.

Acknowledgements

The research that led to these results was carried out with the help of infrastructure LTER-BG (Agreement No TO1-320/30.11.2023), purchased under the National Roadmap for Scientific Infrastructure, financially coordinated by the Ministry of Education and Science. The collection and processing of the data was carried out with implementing the project NIS-B-1292/2023 at the University of Forestry, Bulgaria.

References

- AHRENS C.D., HENSON R. 2015. Meteorology Today. Cengage Learning. 656 p.
- ANEV S. 2023. Altitudinal and latitudinal variation in leaf phenology of European beech (*Fagus sylvatica* L.) in Western Bulgaria. *Foresry Ideas* 29(2): 245–257.
- ASENOVA M., ANGELOV S. 2022. Remote methods of investigating abiotic damage on forest stands. *Forest Science (Nauka za Gorata)* 2: 85–104 (in Bulgarian with English Summary).
- BAILEY S.A., HORNER-DEVINE M.C., LUCK G., MOORE L.A., CARNEY K.M., ANDERSON S., BETRUS C., FLEISHMAN E. 2004. Primary productivity and species richness: relationships among functional guilds, residency groups and vagility classes at multiple spatial scales. *Ecography* 27(2): 207–217. <https://doi.org/10.1111/j.0906-7590.2004.03631.x>
- BARBERO M., BONIN G., LOISEL R., QUÉZEL P. 1990. Changes and disturbances of forest ecosystems caused by human activities in the western part of the mediterranean basin. *Vegetatio* 87(2): 151–173. <https://doi.org/10.1007/BF00042952>
- BREWER C.K., WINNE J.C., REDMOND R.L., OPITZ D.W., MANGRICH M.V. 2005. Classifying and mapping wildfire severity. *Photogrammetric Engineering & Remote Sensing* 71(11): 1311–1320. <https://doi.org/10.14358/pers.71.11.1311>
- BUSCHMANN C., NAGEL E. 1993. In vivo spectroscopy and internal optics of leaves as basis for remote sensing of vegetation. *International Journal of Remote Sensing* 14(4): 711–722. <https://doi.org/10.1080/01431169308904370>
- CAO Y., ZHOU B., WANG X., GU L. 2020. Resprouting responses dynamics of *Schima superba* following a severe ice storm in early 2008 in southern China: A six-year study. *Forests* 11(2), 184. 17 p. <https://doi.org/10.3390/f11020184>
- CHENG X., LUO M., CHEN K., SUN J., WU Y. 2024. Intra-annual vegetation changes and spatial variation in China over the past two

- decades based on remote sensing and time-series clustering. *Environmental Monitoring and Assessment* 196(7), 675. <https://doi.org/10.1007/s10661-024-12816-7>
- CLARK D.B., OLIVAS P.C., OBERBAUER S.F., CLARK D.A., RYAN M.G. 2008. First direct landscape-scale measurement of tropical rain forest Leaf Area Index, a key driver of global primary productivity. *Ecology Letters* 11(2): 163–172. <https://doi.org/10.1111/j.1461-0248.2007.01134.x>
- FERNANDES R., WEISS M., CAMACHO F., BERTHELOT B., BARET F., DUCA R. 2014. Development and assessment of leaf area index algorithms for the Sentinel-2 multispectral imager. 2014 IEEE Geoscience and Remote Sensing Symposium, Québec, Canada: 3922–3925. <https://doi.org/10.1109/IGARSS.2014.6947342>
- FROLKING S., PALACE M.W., CLARK D.B., CHAMBERS J.Q., SHUGART H.H., HURTT G.C. 2009. Forest disturbance and recovery: A general review in the context of spaceborne remote sensing of impacts on aboveground biomass and canopy structure. *Journal of Geophysical Research: Biogeosciences* 114(G2), G00E02. 27 p. <https://doi.org/10.1029/2008JG000911>
- GAMON J.A., FIELD C.B., GOULDEN M.L., GRIFFIN K.L., HARTLEY A.E., JOEL G., PEÑUELAS J., VALENTINI R. 1995. Relationships Between NDVI, Canopy Structure, and Photosynthesis in Three Californian Vegetation Types. *Ecological Applications* 5(1): 28–41. <https://doi.org/10.2307/1942049>
- GRABSKA-SZWAGRZYK E., TYMIŃSKA-CZABAŃSKA L. 2024. Sentinel-2 time series: a promising tool in monitoring temperate species spring phenology. *Forestry: An International Journal of Forest Research* 97(2): 267–281. <https://doi.org/10.1093/forestry/cpad039>
- GREBNER D.L., BETTINGER P., SIRY J.P. 2012. *Introduction to Forestry and Natural Resources* (1 ed.). Elsevier Science. 496 p.
- GUO S., XUE L. 2012. Effects of ice-snow damage on forests. *Acta Ecologica Sinica* 32(16): 5242–5253. <https://doi.org/10.5846/stxb201201120072>
- HAPKE B. 2012. Specular reflection. In: Hapke B. (Ed.), *Theory of Reflectance and Emission Spectroscopy*. Cambridge University Press: 45–65. <https://doi.org/10.1017/CBO9781139025683.004>
- HRISTOV G., KINANEVA D., GEORGIEV G., ZAHARIEV P., KYUCHUKOV P. 2020. An overview of the use of Unmanned Aerial Vehicles for Precision Agriculture. 2020 International Conference on Biomedical Innovations and Applications (BIA), Varna, Bulgaria: 137–140. <https://doi.org/10.1109/BIA50171.2020.9244519>
- HUETE A., DIDAN K., MIURA T., RODRIGUEZ E.P., GAO X., FERREIRA L.G. 2002. Overview of the radiometric and biophysical performance of the MODIS vegetation indices. *Remote Sensing of Environment* 83(1): 195–213. [https://doi.org/10.1016/S0034-4257\(02\)00096-2](https://doi.org/10.1016/S0034-4257(02)00096-2)
- JIN H., EKLUNDH L. 2014. A physically based vegetation index for improved monitoring of plant phenology. *Remote Sensing of Environment* 152: 512–525. <https://doi.org/10.1016/j.rse.2014.07.010>
- JUNTILA S., ARDÖ J., CAI Z., JIN H., KLJUN N., KLEMEDTSSON L., KRASNOVA A., LANGE H., LINDROTH A., MÖLDER M., NOE S.M., TAGGESSON T., VESTIN P., WESLIEN P., EKLUNDH L. 2023. Estimating local-scale forest GPP in Northern Europe using Sentinel-2: Model comparisons with LUE, APAR, the plant phenology index, and a light response function. *Science of Remote Sensing* 7, 100075. 14 p. <https://doi.org/10.1016/j.srs.2022.100075>
- KAUFMAN Y.J., TANRÉ D., GORDON H.R., NAKAJIMA T., LENOBLE J., FROUIN R., GRASSL H., HERMAN B.M., KING M.D., TEILLET P.M. 1997. Passive remote sensing of tropospheric aerosol and atmospheric correction for the aerosol effect. *Journal of Geophysical Research: Atmospheres* 102(D14): 16815–16830. <https://doi.org/10.1029/97JD01496>
- LAZAROV S., CENOV C., GOGUSHEV G. 2009. Forest management following natural disturbances – traditional and/or new approach. *Management and Sustainable Development* 22(1): 69–73 (in Bulgarian).
- LECHNER A.M., FOODY G.M., BOYD D.S. 2020.

- Applications in Remote Sensing to Forest Ecology and Management. *One Earth* 2(5): 405–412. <https://doi.org/10.1016/j.oneear.2020.05.001>
- MILLER J.D., YOOL S.R. 2002. Mapping forest post-fire canopy consumption in several overstory types using multi-temporal Landsat TM and ETM data. *Remote Sensing of Environment* 82(2): 481–496. [https://doi.org/10.1016/S0034-4257\(02\)00071-8](https://doi.org/10.1016/S0034-4257(02)00071-8)
- MYNENI R.B., TUCKER C.J., ASRAR G., KEELING C.D. 1998. Interannual variations in satellite-sensed vegetation index data from 1981 to 1991. *Journal of Geophysical Research: Atmospheres* 103(D6): 6145–6160. <https://doi.org/10.1029/97JD03603>
- NEDKOV R., VELIZAROVA E., AVETISYAN D., GEORGIEV N. 2020. Assessment of forest vegetation state through remote sensing in response to fire impact. Eighth International Conference on Remote Sensing and Geoinformation of the Environment (RSCy2020), Paphos, Cyprus: 115240Q. <https://doi.org/10.1117/12.2570808>
- OLIVER C.D., LARSON B.C. 1996. Forest stand dynamics. John Wiley and Sons. 520 p.
- OLIVER M.A. 2014. Geostatistical Applications for Precision Agriculture. Springer Netherlands. 331 p.
- OLTHOF I., KING D.J., LAUTENSCHLAGER R.A. 2004. Mapping deciduous forest ice storm damage using Landsat and environmental data. *Remote Sensing of Environment* 89(4): 484–496. <https://doi.org/10.1016/j.rse.2003.11.010>
- PEAUCELLE M., JANSSENS I.A., STOCKER B.D., DESCALS FERRANDO A., FU Y.H., MOLOWNY-HORAS R., CIAIS P., PEÑUELAS J. 2019. Spatial variance of spring phenology in temperate deciduous forests is constrained by background climatic conditions. *Nature Communications* 10(1), 5388. 10 p. <https://doi.org/10.1038/s41467-019-13365-1>
- PETTORELLI N. 2013. The Normalized Difference Vegetation Index. Oxford University Press. 194 p. <https://doi.org/10.1093/acprof:osobl/9780199693160.001.0001>
- PETTORELLI N., VIK J.O., MYSTERUD A., GAILLARD J.-M., TUCKER C.J., STENSETH N.C. 2005. Using the satellite-derived NDVI to assess ecological responses to environmental change. *Trends in Ecology & Evolution* 20(9): 503–510. <https://doi.org/10.1016/j.tree.2005.05.011>
- PITT D.G., WAGNER R.G., HALL R.J., KING D.J., LECKIE D.G., RUNESSON U. 1997. Use of remote sensing for forest vegetation management: A problem analysis. *The Forestry Chronicle* 73(4): 459–477. <https://doi.org/10.5558/tfc73459-4>
- RÖDER A., HILL J., DUGUY B., ALLOZA J.A., VALLEJO R. 2008. Using long time series of Landsat data to monitor fire events and post-fire dynamics and identify driving factors. A case study in the Ayora region (eastern Spain). *Remote Sensing of Environment* 112(1): 259–273. <https://doi.org/10.1016/j.rse.2007.05.001>
- ROUSE J.W., HAAS R.H., SCHELL J.A., DEERING D.W. 1974. Monitoring vegetation systems in the great plains with ERTS. Third ERTS-1 Symposium NASA, Washington DC: 309–317.
- ROWHANI P., LINDERMAN M., LAMBIN E.F. 2011. Global interannual variability in terrestrial ecosystems: sources and spatial distribution using MODIS-derived vegetation indices, social and biophysical factors. *International Journal of Remote Sensing* 32(19): 5393–5411. <https://doi.org/10.1080/01431161.2010.501042>
- SELLERS P.J., BERRY J.A., COLLATZ G.J., FIELD C.B., HALL F.G. 1992. Canopy reflectance, photosynthesis, and transpiration. III. A reanalysis using improved leaf models and a new canopy integration scheme. *Remote Sensing of Environment* 42(3): 187–216. [https://doi.org/10.1016/0034-4257\(92\)90102-P](https://doi.org/10.1016/0034-4257(92)90102-P)
- SHARMA S.K., ARYAL J., RAJABIFARD A. 2022. Leveraging Google Earth Engine (GEE) and Landsat images to assess bushfire severity and postfire short-term vegetation recovery. In: *Advances in remote sensing for forest monitoring*: 196–220. <https://doi.org/10.1002/9781119788157.ch10>
- SMETS B., CAI Z., EKLUNDH L., TIAN F., BONTE K., HOOST R.V., ROO B.D., JACOBS T., CAMACHO F., SÁNCHEZ-ZAPERO J., MARTÍNEZ-SÁNCHEZ E., SWINNEN E., SCHEI-

- FINGER H., HUFKENS K., JÖNSSON P. 2022. HR-VPP ATBD Seasonal Trajectories and VPP parameters [User Manual]. European Environment Agency. 75 p.
- STOYANOVA M., KANDILAROV A., KOUTEV V., NITCHEVA O., DOBREVA P. 2018. Potential of multispectral imaging technology for assessment coniferous forests bitten by a bark beetle in Central Bulgaria. 13th National Congress on Theoretical and Applied Mechanics, MATEC Web Conference 145, 01005. 10 p. <https://doi.org/10.1051/mateconf/201814501005>
- TREITZ P.M., HOWARTH P.J. 1999. Hyperspectral remote sensing for estimating biophysical parameters of forest ecosystems. *Progress in Physical Geography: Earth and Environment* 23(3): 359–390. <https://doi.org/10.1177/030913339902300303>
- TUCKER C.J., NEWCOMB W.W., LOS S.O., PRINCE S.D. 1991. Mean and inter-year variation of growing-season normalized difference vegetation index for the Sahel 1981–1989. *International Journal of Remote Sensing* 12(6): 1133–1135. <https://doi.org/10.1080/01431169108929717>
- VOLLER J., HARRISON S. 2011. *Conservation Biology Principles for Forested Landscapes*. UBC Press. 256 p.
- VOURLITIS G.L., VERFAILLIE J., OECHEL W.C., HOPE A., STOW D., ENGSTROM R. 2003. Spatial variation in regional CO₂ exchange for the Kuparuk River Basin, Alaska over the summer growing season. *Global Change Biology* 9(6): 930–941. <https://doi.org/10.1046/j.1365-2486.2003.00639.x>
- WATSON D.J. 1947. Comparative physiological studies on the growth of field crops: I. Variation in net assimilation rate and leaf area between species and varieties, and within and between years. *Annals of Botany* 11(1): 41–76. <https://doi.org/10.1093/oxfordjournals.aob.a083148>
- WEISS M., BARET F., SMITH G.J., JONCKHEERE I., COPPIN P. 2004. Review of methods for in situ leaf area index (LAI) determination: Part II. Estimation of LAI, errors and sampling. *Agricultural and Forest Meteorology* 121(1–2): 37–53. <https://doi.org/10.1016/j.agrformet.2003.08.001>
- WEKEO 2023. High Resolution Vegetation Phenology and Productivity (HR-VPP) service. Copernicus. <https://www.wekeo.eu> (Accessed on 10 August 2023).
- WU J., WANG T., PAN K., LI W., HUANG X. 2016. Assessment of forest damage caused by an ice storm using multi-temporal remote-sensing images: a case study from Guangdong Province. *International Journal of Remote Sensing* 37(13): 3125–3142. <https://doi.org/10.1080/01431161.2016.1194544>
- XIAO-BING L., YUN-HAO C., YI-DA F., YUN-XIA Z. 2003. Detecting inter-annual variations of vegetation growth based on satellite-sensed vegetation index data from 1983 to 1999. *International Geoscience and Remote Sensing Symposium, Toulouse*: 3263–3265. <https://doi.org/10.1109/IGARSS.2003.1294750>
- YANG W., KOBAYASHI H., WANG C., SHEN M., CHEN J., MATSUSHITA B., TANG Y., KIM Y., BRET-HARTE M.S., ZONA D., OECHEL W., KONDOH A. 2019. A semi-analytical snow-free vegetation index for improving estimation of plant phenology in tundra and grassland ecosystems. *Remote Sensing of Environment* 228: 31–44. <https://doi.org/10.1016/j.rse.2019.03.028>
- ZHAO C., PAN Y., ZHANG P. 2024a. Development of a new indicator for identifying vegetation destruction events using remote sensing data. *Ecological Indicators* 166, 112553. 13 p. <https://doi.org/10.1016/j.ecolind.2024.112553>
- ZHAO J., WANG Y., ZHANG Z., ZHANG H., GUO X., YU S., DU W., HUANG F. 2016. The Variations of Land Surface Phenology in Northeast China and Its Responses to Climate Change from 1982 to 2013. *Remote Sensing* 8(5), 400. 23 p. <https://doi.org/10.3390/rs8050400>
- ZHAO P.F., CHEN X.Y., XUE X.Y., WANG Y.X., WANG Y.X., LI H., XUE R.L., LI Y. 2024b. Improvement of polyamine synthesis maintains photosynthetic function in wheat during drought stress and rewatering at the grain filling stage. *Plant Growth Regulation* 102(3): 497–513. <https://doi.org/10.1007/s10725-023-01075-0>

Floristic diversity, composition and biomass of neglected riparian forests in Southern Côte d'Ivoire

Bi Tra Aimé Vroh^{1*} , Kouassi Bruno Kpangui² , and Abdoulaye Cissé¹ 

¹UFR Biosciences, University of Félix Houphouët-Boigny, Côte d'Ivoire.

*E-mail: vrohbitra@gmail.com

²UFR Environnement, University of Jean Lorougnon Guédé, Côte d'Ivoire.

Received: 09 April 2025 / Accepted: 12 May 2025 / Available online: 04 June 2025



Open Access: This work is distributed under the Creative Commons Attribution 4.0 License.

Abstract

With the loss of most of Côte d'Ivoire's forests, it is time to focus conservation and protection strategies on the remaining fragments scattered throughout agro-systems. However, these forests remain neglected and little known in terms of their value for biodiversity conservation. The aim of this study was to report the overall ecological value of different fragments of riparian forests scattered in the agro-systems of Southern Côte d'Ivoire. The level of floristic diversity, the conservation interest of these forests, the structural characteristics of the vegetation and the aboveground biomass were assessed. Trees with a diameter of at least 2.5 cm were counted in 222 plots in dry-land forests and periodically or permanently flooded forests. Qualitative and quantitative diversity indices, density and aboveground biomass were calculated. The results showed that these forests are home to 267 species, 94 % of which are present in dry-land forests, compared to 28–32 % in permanently and periodically flooded forests, respectively. The high abundance of *Alchornea cordifolia* (18 to 23 % of the stems) leads to an imbalance in the distribution of stems between species. Despite the low levels of aboveground biomass (5.6 to 20.3 t·ha⁻¹), the abundance of species from the Guinean-Congolese phytogeographic region (67.10 to 75.3 %) and the presence of 37 rare, threatened and/or endemic species are encouraging signs for the conservation of these remnant forests. These forests therefore deserve a census and the development of a specific strategy for their conservation.

Key words: conservation value, flooded forest, remnant forest, secondary landscape, West Africa.

Introduction

The West African rainforests are considered to be rich ecosystems with complex structures containing many endemic species (Sayer et al. 1992). They have been described as one of the most important biodiversity hotspots hosting rare and/

or threatened species (Holmgren et al. 2004).

In this part of Africa, the territory of Côte d'Ivoire has been historically explored by botanists, who described the southern coastal zone as a dense evergreen humid forest (Aké Assi and Pfeffer 1975). These floristic studies have shown that the flora

of the forests of Southern Côte d'Ivoire is highly diverse.

In order to preserve this floristic heritage, the Ivorian government has created a network of protected areas (national parks and reserves) and classified forests throughout the country. In this southern zone, the Taï, Azagny and Ehotilé Island National Parks and the Tanoé-Ehy Marshes Voluntary Nature Reserve contain relatively exclusive flora in terms of the endemism that characterises them (Poorter et al. 2004). In contrast, much of the classified forest in the Southern Forest has been invaded by farmers who are clearing it to grow cash crops, such as cocoa, rubber and oil palm. Outside protected areas and classified forests, the situation is alarming in rural areas, where large-scale industrial oil palm and rubber plantations have developed alongside family plantations run by local farmers, leading to the loss of almost all forest cover in the south (Landrot and Dufour 2015).

The result of this loss of forests in the rural areas of Southern Côte d'Ivoire has been their gradual replacement by agricultural land and degraded riparian forests. This riparian vegetation includes secondary forests, the plant communities of watercourses, riverbanks and floodplains, and is an integral part of river ecosystems. There are degraded forest fragments, isolated and more or less heavily exploited. They appear in the secondary landscape after deforestation. Due to their state of degradation, these forests have numerous lianas with a discontinuous megaphanerophytic layer. In fact, in this rural area of the south of Côte d'Ivoire, the extraction of precious woods leads to a total depletion and the vegetation, except for a few emergents, resembles a secondary thicket (Chatelain et al. 1996). Elsewhere, these types of riparian forests have been

shown to be diverse in terms of animal and plant species, vegetation stratification and regeneration processes (Maingi and Marsh 2006). These forests represent a unique biological community adapted to anthropogenic disturbance (Ledec 1987). They are also considered biodiversity corridors (Corbacho et al. 2003), which provide the maintenance of ecological functions between terrestrial and aquatic areas (Hitoshi and Toshikazu 2008). In Côte d'Ivoire, however, these forests are little known. They are not often part of strategic priorities for biodiversity conservation. Despite the degradation of these riparian forests, a pragmatic approach to the conservation of flora and fauna in the area is urgently needed.

In January 2019, Côte d'Ivoire embarked on a national forest and wildlife inventory (NFI) to obtain the strategic information needed to continue public action and provide the sustainable management of these resources (Cuny et al. 2023). This approach was intended to provide the basis for the implementation of its strategy for the conservation, rehabilitation and expansion of forests. The NFI was also established to halt the loss of genetic resources and to address the challenges faced by industries and communities in accessing wood and wood energy. However, this NFI provided very little specific information on the quality of these riparian and/or community forests scattered in rural areas. Yet, Law No. 2019-675 of 23 July 2019 on the Forestry Code of the State of Côte d'Ivoire provides for the official registration of these rural community forests and tools for their management (regulations and incentives, committees and simple management plans).

In the dynamic promoted by the Forestry Code, it is essential to demonstrate the quality of these riparian forests in terms

of biodiversity conservation. Indeed, detailed knowledge of the floristic composition and diversity of plant species in these forests is the first step towards their conservation. In order to formulate policies to manage species decline and to control the ecological drivers of change, it is important to determine the status of the species present in these riparian forests, whether they are anthropophilic, rare, threatened, abundant or endangered.

This study, therefore, aims to report on the overall ecological value of different fragments of riparian forests scattered in the agro-systems of Southern Côte d'Ivoire. Specifically, the study made it possible to assess the level of floristic diversity of riparian forests, to analyse the conservation interest of these forests, to characterise the vegetation stratification, to estimate the aboveground biomass of trees and to analyse the relationships between

these different diversity parameters, the biomass and the density of trees in these riparian forests.

Materials and Methods

Study area

The study was conducted in the rural area of the Southern Forest of Côte d'Ivoire (Fig. 1). This area is located in the domain of evergreen forests and the Guineo-Congolese phytogeographic region. This area corresponds to the centres of heavy rainfall: 1500 to 2000 mm of rain per year (Konaté et al. 2023). The area is characterised by a generally low relief. The soils are of the desaturated ferralitic type (Kouamé and Zoro 2010). The hydrographic network is immense, dominated by coastal lagoons, the Bandama and Comoé rivers (to the south-east),

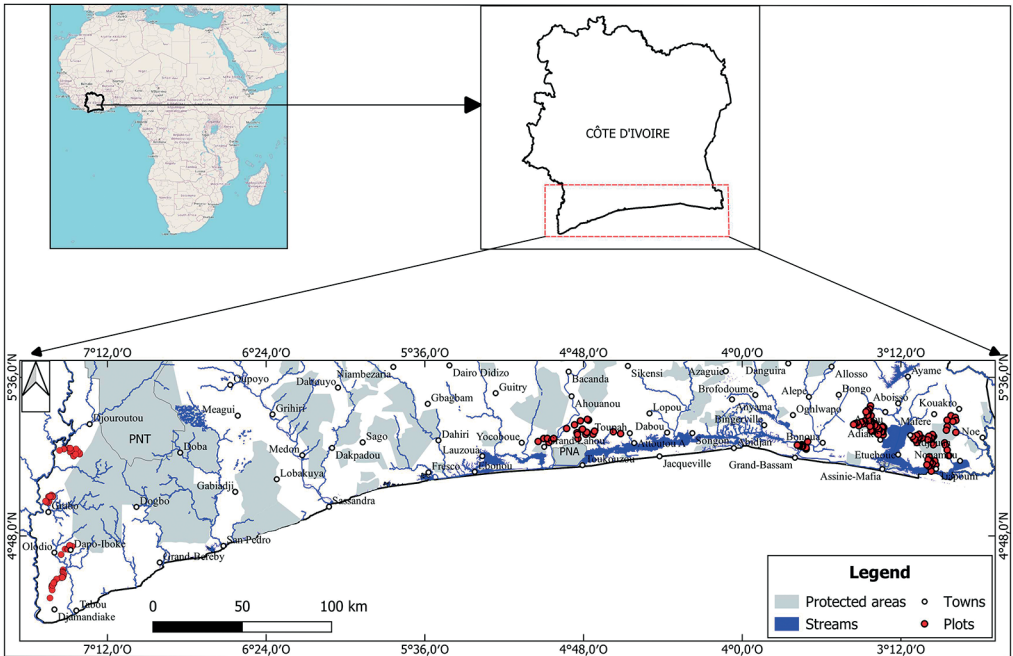


Fig. 1. Location of study area and inventory plots.

the Sassandra and Cavally rivers (to the south-west) and numerous small streams scattered throughout the agro-systems.

The area is dominated by rubber and oil palm plantations owned by agro-industrial companies, such as PALMCI, SAPH and SOGB. These companies work with the villagers and supervise the creation of village rubber and/or oil palm plantations.

In addition to classified forests and protected areas, this mosaic of land use includes unprotected and uncultivated plant formations owned by rural communities. The studied riparian forests are divided into three categories: dry-land forests, permanently flooded forests and periodically flooded forests. These different riparian formations were considered and compared in this study.

Data collection

Data were collected in 222 circular plots of 500 m² (11.1 ha in total). These plots were established in three forest types: dry-land forests ($N = 84$), periodically flooded forests ($N = 67$) and permanently flooded forests ($N = 71$).

For this study, to be considered 'forest', the habitat had to meet the definition of a forest in Côte d'Ivoire adopted in 2014: the surface area must be greater than or equal to 0.1 ha, the tree cover must be greater than or equal to 30 % and the height of mature trees must be greater than or equal to 5 m (République de Côte d'Ivoire 2019). Habitats that did not meet this definition were not considered.

In each plot, individual trees with a diameter at breast height (DBH) of at least 2.5 cm were counted. This minimum diameter allowed the inclusion of adult trees, saplings and young plants (Abdourhamane et al. 2017), which also maximises diversity (Vroh et al. 2010). The heights

of these trees were also measured. Tree species were considered because it has been shown that an inventory of these species can provide sufficient information on abundance and diversity, which are useful tools for plant conservation (Egbe et al. 2021).

The majority of species were identified in the field. For undetermined species, identification guides to the flora of the studied area were consulted (Hawthorne and Jongkind 2006). The POWO (2025) database was used to check the scientific names.

Data analysis

Floristic and ecological analyses

Species diversity was estimated using two facets: 'species richness' and 'species evenness' (Magurran and Phillip 2001). Species richness (S) was determined by counting the species recorded in the inventoried plots. Three non-parametric richness estimators were calculated to assess the completeness of the inventories: Chao 1 (Chao 1984); Jackknife 1 and Jackknife 2 (Burnham and Overton 1978). Evenness was measured by Pielou index (Pielou 1966) for each habitat. Species diversity was calculated by Shannon index (Shannon 1948). The Shannon index and Pielou's index were calculated using formulas (1) and (2).

$$H = -\sum_i^S p_i \cdot \ln p_i, \quad (1)$$

$$J = \frac{H}{\ln S}, \quad (2)$$

where: H = Shannon index, J = Pielou's index, S = species richness, p_i = relative abundance of species i , $\ln$ = natural logarithm.

A Venn diagram was constructed to as-

sess the degree of similarity between the different forest types. The graph allowed us to compare the floristic composition shared by these three forest types and the number of species unique to each.

To assess the ecological importance, species patterns were compared graphically through ranking of abundance. For each forest type, the abundance (N) of species was transformed to logarithm $10(N + 1)$ and the tabulated data from the most abundant species to the least abundant (Feinsinger 2001).

The conservation value of the different forest types was assessed by identifying species endemic to West African forests (White 1983) and threatened species on the IUCN Red List (2024).

Stem densities were calculated for each plot and averages were calculated for each forest type. Taking into account the diameter classes, stem distribution histograms were constructed and their shape allowed an assessment of the self-regeneration rate of the forests.

The pantropical allometric equation developed by Chave et al. (2014) was used to estimate aboveground biomass (AGB). This equation is considered to be more robust, recent, covers a wide range of vegetation types and incorporates data from other pantropical equations, such as the Chave et al. (2005) and Fayolle (2013) equations. The mathematical expression of this allometric is represented by equation (1).

$$AGB = 0.0673 \cdot (r \cdot DBH^2 \cdot H)^{0.976}, \quad (3)$$

where: AGB is the estimated aboveground biomass, kg; r is the specific density of wood, $g \cdot cm^{-3}$; DBH is the diameter at breast height, cm; H is the total height of the tree, m.

For biomass estimation, the minimum diameter considered was 5 cm (DBH $\geq$

5 cm), as recommended by Chave et al. (2014).

Statistical analysis

Analyses of variance (ANOVA) were used to compare the means of diversity parameters (species richness, Shannon, evenness), tree density and aboveground biomass between forest types. Principal component analysis (PCA) was used to test the relationships between these different parameters (richness, Shannon, evenness, density and aboveground biomass). The robustness of the relationships (according to the p-value) and the direction (negative or positive) between these parameters were assessed using Pearson correlation tests. These tests allowed us to verify the hypothesis that there is a common positive correlation between diversity, richness and biomass in *in situ* forests (Sintayehu et al. 2020). All calculated diversity indices and statistical analyses were performed using the program R4.3.1 (R Core Team 2023).

Results and Discussion

Floristic richness and diversity in the three habitat types

The number of stems (DBH ≥ 2.5 cm) was 15,435 individuals in the three habitat types. These stems were divided into 267 species. Comparing this finding, the studied habitats are less rich than those of the Monogaga Classified Forest with 296 species (Adou Yao et al. 2011), the Ehotilé Islands National Park with 315 species (Malan et al. 2007) and the Forêt Marais Tonoé-Ehy Reserve with 568 species (Abrou et al. 2019). On the other hand, it is higher than the tree richness (127 spe-

cies) of the Azagny National Park, an area dominated by swamps (Adiko et al. 2020).

If we take the habitats separately, the number of species is higher in dry-land forests ($S = 251$ species) than in the other two habitat types ($S = 77$ and 86 for permanently and periodically flooded forests, respectively). The three habitat types together account for 54 species or 20.2% of the species present (Fig. 2). Dry-land forests and periodically flooded forests are more similar (75 species, 28.1%). Conversely, periodically flooded forests are less similar to permanently flooded forests (20.6% of species in common). This finding may explain the relatively low similarity between the three habitat types, which reflects a high degree of floristic heterogeneity in the area as argued by Menino

et al. (2012). However, this similarity was based on sampled species only.

According to the estimators (Chao 1, Jackknife 1 and Jackknife 2), the sampling completeness in dry-land forests is 66.5 to 76.9% , i.e. 75 to 126 species were not observed (Table 1). In the other two forest types, 76 to 95% of the species were sampled. These results indicate that there are many more rare species (singletons and doubletons) in the dry-land forests. The similarity between dry-land forests and the other two forest types will be even lower in the case of exhaustive sampling. In the other two forests, only 3 to 26 species were not observed, indicating that sampling tends to be exhaustive in these habitats, which are constrained by the presence of water.

The average values of richness and Shannon index show also that species diversity is higher in dry-land forests than in the other two habitat types (Fig. 3). Indeed, the average richness per 500 m^2 plot is ~ 16 species in dry-land forests. However, it varies between 8 and 10 species in the other two types of forest. On the other hand, the three habitat types have the same species evenness.

The low species diversity in flooded forests can be explained by the fact that these habitats are subject to special conditions (permanent or temporary flooding), which make them favourable for some specialised species and unfavourable for a large diversity of species that colonise dry forests. Parolin et al. (2010) have also

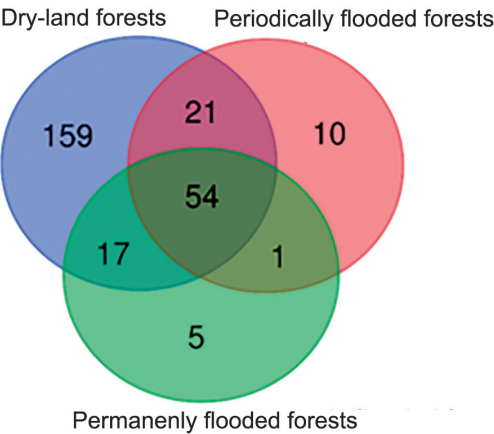


Fig. 2. Distribution of the number of species between the three forest types.

Table 1. Floristic richness observed and estimated in the different forest types.

Forest type	Richness observed	Richness estimates		
		Chao 1	Jackknife 1	Jackknife 2
		number of species		
Dry-land forests	251	368.2	326.0	377.0
Periodically flooded forests	86	107.3	102.0	112.0
Permanently flooded forests	77	80.6	83.0	84.0

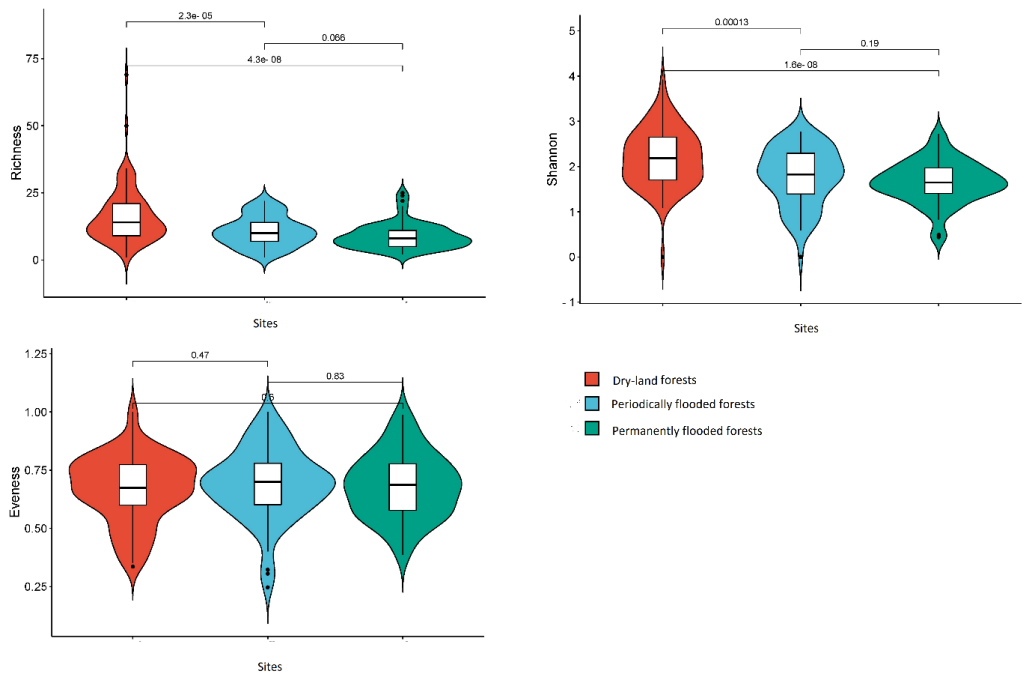


Fig. 3. Comparison of mean values of specific diversity parameters.

Note: The violin plots combined with summary statistics (mean $\pm$ SD) and box plots. The numbers above the violin plots indicate the p-values for comparing means in pairs (Tukey test): if the p-value is less than 0.05, the means are significantly different.

shown that plant diversity tends to be low in these water-stressed environments due to the environmental constraints associated with soil saturation.

Floristic composition

Alchornea cordifolia (Shum. & Thonn.) Müll. is the most abundant species in all habitats (Fig. 4): 20, 18.2 and 22.6 % of the stems in dry-land forests, periodically flooded and permanently flooded forests respectively. The high abundance of *A. cordifolia* could reflect a low homogeneity in the distribution of stems between the species recorded. This finding is consistent with that of Kurtz et al. (2015), who showed that *A. cordifolia* is therefore bet-

ter adapted to these anthropised forest types. This species, which has a wide distribution in the Guineo-Congolese tropical forest zone, is abundant in habitats with high sunlight penetration, such as the forests inventoried in this study (Friis and Harris 2013).

Funtumia africana (Benth.) Stapf (3.5 % of stems) is the second most abundant species in dry-land forests. *Hallea ledermannii* (K. Krause) Verdc. (9.5 % of the stems) and *Macaranga heudelotii* Baill. (7.3 % of the stems) are the most abundant species after *A. cordifolia* in periodically flooded forests. In permanently flooded forests, *H. ledermannii* (13.8 % of the stems) and *Ficus trichopoda* Baker (10.7 % of the stems) are the most abun-

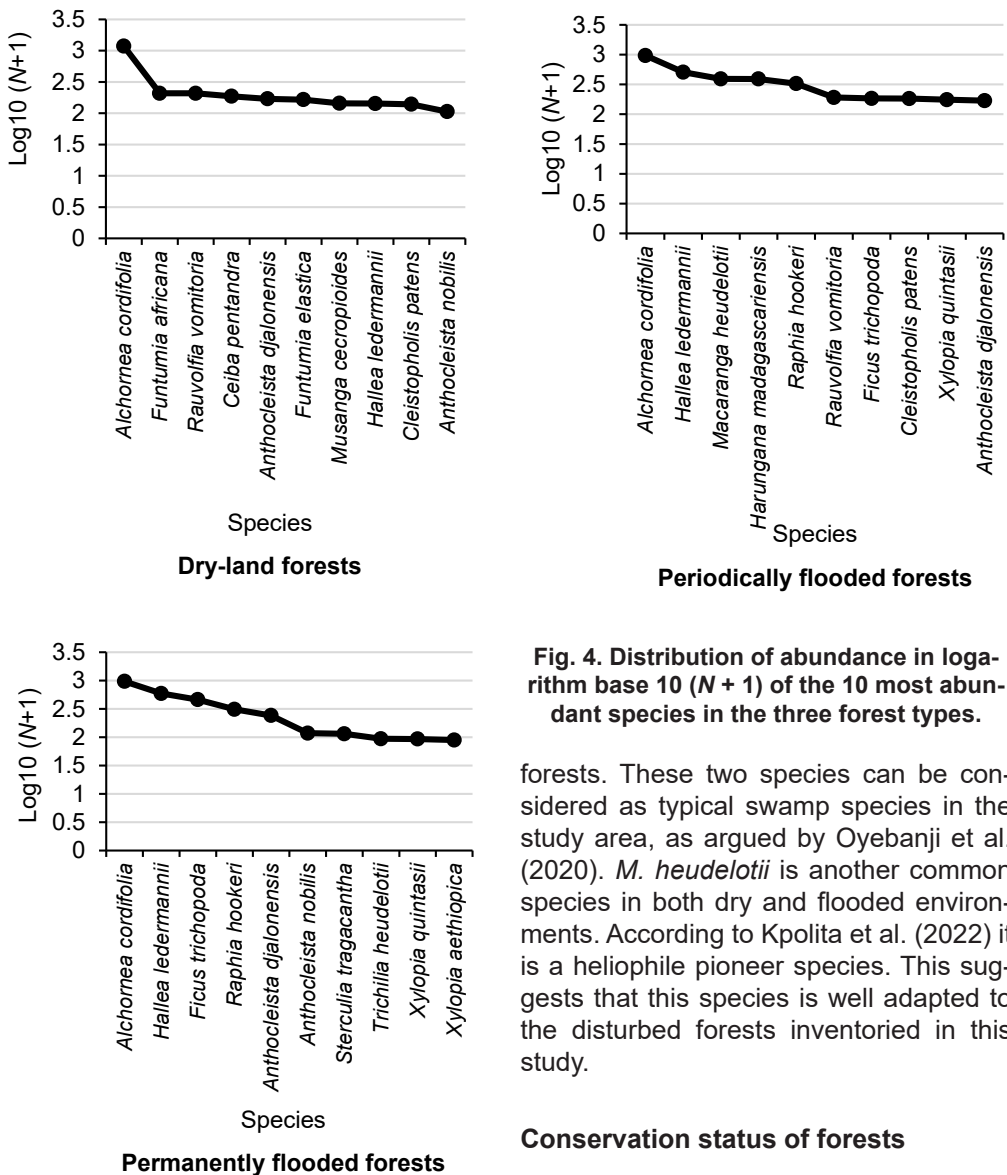


Fig. 4. Distribution of abundance in logarithm base 10 ($N + 1$) of the 10 most abundant species in the three forest types.

forests. These two species can be considered as typical swamp species in the study area, as argued by Oyebojani et al. (2020). *M. heudelotii* is another common species in both dry and flooded environments. According to Kpolita et al. (2022) it is a heliophile pioneer species. This suggests that this species is well adapted to the disturbed forests inventoried in this study.

Conservation status of forests

Of the present species, 24 are on the IUCN Red List, three of which are endangered (*Omphalocarpum ahia* A. Chev., *Dactyladenia hirsuta* (A. Chev. ex De Wild.) Prance & F. White and *Apodiscus chevalieri* Hutch.) and the others are vulnerable (IUCN 2024). The species *O. ahia* was only recorded in permanently flooded

dant species after *A. cordifolia*.
F. africana tends to prefer the degraded dry-land forests inventoried. This result confirms the pioneer-heliophile characteristic of this species, as reported by Carrière (2003). *H. ledermannii* and *F. trichopoda* were only recorded in flooded

forests, while the other two were recorded in dry-land forests (Table 2).

Table 2. Summary of the abundance of species with conservation status in the three forest types.

Species	Family	Conservation status	Dry-land forests	Periodical-ly flooded forest	Permanent-ly flooded forests
			number of stems		
<i>Whitfieldia lateritia</i> Hook.	Acanthaceae	GCW	2	-	-
<i>Anthonota crassifolia</i> (Baill.) J.Léonard	Anacardiaceae	Vu	-	-	2
<i>Antrocaryon micraster</i> A.Chev. & Guill.	Anysophyllaceae	VU / GCW	60	1	-
<i>Cussonia bancoensis</i> Aubrév. & Pellegr.	Araliaceae	Vu	25	-	-
<i>Cordia platythyrsa</i> Baker	Boraginaceae	Vu	16	6	-
<i>Dactyladenia hirsuta</i> (A.Chev. Ex De Wild.) Prance & F.White	Chrysobalanaceae	EN	1	-	-
<i>Magnistipula butayei</i> De Wild.	Chrysobalanaceae	Vu	1	-	-
<i>Garcinia kola</i> Heckel	Clusiaceae	Vu	-	1	-
<i>Terminalia ivorensis</i> A.Chev.	Combretaceae	Vu	9	-	9
<i>Diospyros heudelotii</i> Hiern	Ebenaceae	GCW	-	1	-
<i>Drypetes aubrevillei</i> Leandri	Euphorbiaceae	GCW	33	-	-
<i>Ricinodendron heudelotii</i> (Baill.) Heckel	Euphorbiaceae	Vu	22	4	10
<i>Azelia bella</i> Harms	Fabaceae	GCW	21	-	-
<i>Copaifera salicunda</i> Heckel	Fabaceae	Vu / GCW	4	-	-
<i>Dialium aubrevillei</i> Pellegr.	Fabaceae	GCW	6	-	-
<i>Dracaena fragrans</i> (L.) Ker. Gawl.	Fabaceae	GCW	1	-	-
<i>Millettia lane-poolei</i> Dunn	Fabaceae	GCW	3	-	-
<i>Millettia rhodantha</i> Baill.	Fabaceae	GCW	6	-	-
<i>Anthocleista nobilis</i> G.Don	Gentianaceae	GCW	65	53	84

Species	Family	Conservation status	Dry-land forests	Periodical-ly flooded forest	Permanent-ly flooded forests
			number of stems		
<i>Nesogordonia papaverifera</i> (A.Chev.) Capuron	Malvaceae	Vu	2	-	-
<i>Sterculia oblonga</i> Mast.	Malvaceae	Vu	1	-	-
<i>Entandrophragma angolense</i> (Welw.) C.DC.	Meliaceae	Vu	8	1	4
<i>Entandrophragma candollei</i> Harms	Meliaceae	Vu	1	-	-
<i>Entandrophragma cylindricum</i> Sprague	Meliaceae	Vu	6	-	-
<i>Khaya anthotheca</i> (Welw.) DC.	Meliaceae	Vu	4	-	-
<i>Khaya ivorensis</i> A.Chev.	Meliaceae	Vu	5	-	-
<i>Milicia regia</i> (A.Chev.) C.C.Berg.	Moraceae	Vu / GCW	30	10	6
<i>Lophira alata</i> Banks ex Gaertner	Ochnaceae	Vu	3	-	-
<i>Adenia dinklagei</i> Hutch & Dalz.	Passifloraceae	GCW	1	-	-
<i>Apodiscus chevalieri</i> Hutch.	Phyllantaceae	EN	8	-	-
<i>Anopyxis klaineana</i> (Pierre) Engl.	Rhizophoraceae	Vu	5	-	-
<i>Nauclea diderrichii</i> (De Wild. & T. Duran) Merr.	Rubiaceae	Vu	6	21	10
<i>Zanthoxylum chevalieri</i> Waterm.	Rutaceae	GCW	10	-	-
<i>Placodiscus boya</i> Aubrév. & Pellegr	Sapindaceae	Vu / GCW	1	-	-
<i>Omphalocarpum ahia</i> A.Chev.	Sapotaceae	EN / GCW	-	-	4
<i>Heritiera utilis</i> Sprague	Sterculiaceae	Vu / GCW	-	6	-
Total stems			366	104	129

Note: GCW – endemic to Guineo-Congolian West forests, Vu – vulnerable, EN – endangered species.

Sixteen of the recorded species are endemic to the Guineo-Congolian West forests (GCW). Of these, five are also vulnerable according to the Red List of Threatened Species: *Copaifera salicundata*, *Milicia regia*, *O. ahia*, *Placodiscus boya* and *Heritiera utilis*.

Overall, dry-land forests host more threatened and/or endemic species (35 species) than the other two habitat types (26 species each). The endemic and/or vulnerable species *Anthocleista nobilis*, *Milicia regia*, *Entandrophragma angolense*, *Nauclea diderrichii* and *Ricinodendron heudelotii* are present in all three habitat types (Table 1). All these species are used by rural and urban communities in various ways (seeds for food, timber, etc.), justifying their inclusion on the IUCN Red List of Threatened Species. Some species with a very restricted distribution, such as *Whitfieldia lateritia*, endemic to the hygrophilous forests of western Côte d'Ivoire (Mangenot 1955), are more sensitive to human disturbance (Iralu et al. 2020) and deserve special attention for their conservation. As confirmed by Tchouto (2004), the presence of these

rare, endemic and/or threatened species in these habitats, often considered to be of low ecological value for conservation, is an indication that they deserve to be included in national biodiversity conservation policies and/or strategies.

Density, biomass and structure of the vegetation

The mean density of all stems (DBH ≥ 2.5 cm) varies from 379.5 stems $\cdot$ ha $^{-1}$ in dry-land forests to 486.7 stems $\cdot$ ha $^{-1}$ in permanently flooded forests (Fig. 5). The difference between these mean densities is significant (ANOVA: p -value = 0.024). Considering only trees over 10 cm DBH, the densities ranged from 254 stems $\cdot$ ha $^{-1}$ in periodically flooded forests to 189 stems $\cdot$ ha $^{-1}$ in dry-land forests. According to Pascal (2003), stem density (DBH > 10 cm) in tropical forests is between 450 and 750 stems $\cdot$ ha $^{-1}$. According to the same author, in forests without particular constraints, the average is around 600 stems $\cdot$ ha $^{-1}$. We can therefore say that none of the studied forests tended to have the high stem density found in undisturbed

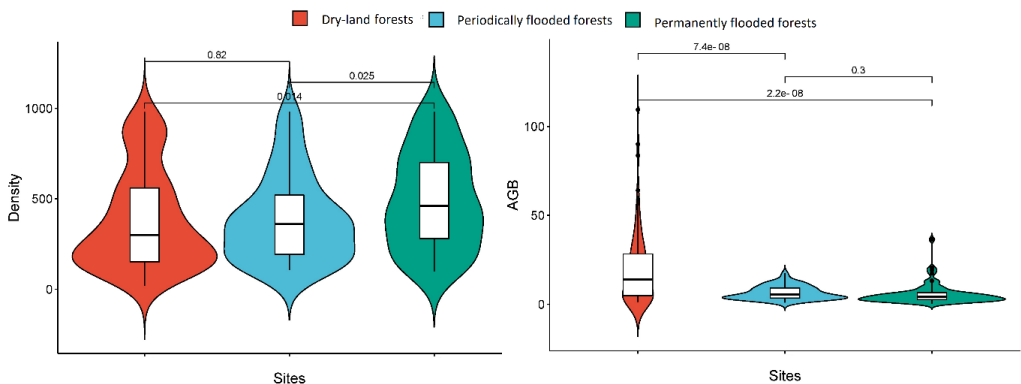


Fig. 5. Comparison of average density and aboveground biomass of inventoried forests.

Note: The violin plots combined with summary statistics (mean $\pm$ SD) and box plots. The numbers above the violin plots indicate the p -values for comparing means in pairs (Tukey test): if the p -value is less than 0.05, the means are significantly different.

forests. This means that the three types of forest have specific constraints that have a significant impact on tree density.

Aboveground biomass (AGB) is also higher in dry-land forest (20.3 t·ha⁻¹) and lower in the other two habitat types (6.4 to 5.6 t·ha⁻¹). The post-hoc test shows a significant difference between the means of AGB in dry-land forests and the other two forest types, but the latter are not significantly different (Fig. 5). These aboveground biomass values are very low compared to the reference values defined by Lewis et al. (2013) in 12 African countries. In fact, according to these authors, the aboveground biomass varied between 240 and 426 t·ha⁻¹ in the south of Côte d'Ivoire. This observation may be linked to the fact that the studied forests, which are not protected areas, are subject to various forms of exploitation, including the collection of non-timber forest products, the extraction of wood for the construction of canoes and buildings, and firewood.

The distribution of stems according to diameter classes shows that in all forest types the majority (47 to 53 %) of the in-

dividuals recorded have a diameter between 2.5 and 10 cm (Fig. 6). For larger diameter classes, stem density gradually decreases, giving all distribution histograms an 'inverted J' shape. In particular, in periodically flooded and permanently flooded forests, stems with a diameter greater than 60 cm are almost absent (less than 1 % of individuals). The 'inverted J' shape reflects the relative stability of the inventoried habitats, as reported by (Kakaï et al. 2016). Indeed, the abundance of stems with diameters between 2.5 and 10 cm reflects a strong regeneration potential (Koné and Vroh 2021). This regeneration seems to be more important in permanently flooded and periodically flooded forests, if we consider the stem densities in diameter classes less than 20 cm. On the other hand, species that can reach more than 20 cm in diameter are less present in these forests under the constraint of the presence of water. For example, *Alchornea cordifolia*, which represents up to 23 % of the stems in these flooded forests, is a species whose individuals do not reach 20 cm in diameter.

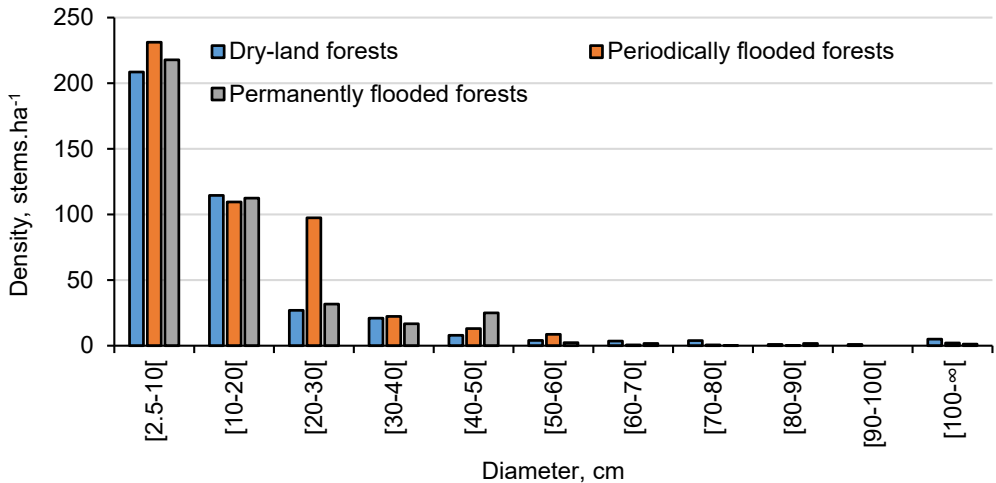


Fig. 6. Histograms of stem distribution by diameter class in different habitat types.

Relationships between species richness, diversity, density and biomass

The Principal Component Analysis (PCA) revealed the ordination between the sampled forests (Fig. 7). The plots of permanently flooded forests are the least rich, the least diverse and have the lowest biomass values. Conversely, the plots from dry-land forests are richer, more diverse and have the highest biomass values. The periodically flooded forest plots have an intermediate ordination to the other two forest types. These results confirmed the previous findings.

The diversity expressed by the Shannon index is significantly influenced by the richness of the three forest types: r -value between 1 and 8 depending on the forest and p -value < 0.05 . This means that rich-

ness is the key component of diversity in the studied forests, which explains why Shannon's entropy is correlated with it.

The other two parameters (evenness and density) do not depict a clear ordination of the plots from the three forest types. These two parameters are not related according to the Pearson correlation. On the other hand, species evenness is negatively correlated with richness in permanently flooded forests ($r = -0.452$; $p < 0.05$). Referring to Marcon (2025), this result could probably be due to a sampling effect in this forest type. However, according to Wilsey and Stirling (2007), species evenness and richness respond differently to habitat conditions. These authors suggest that evenness and richness may be influenced by different processes, with richness more influenced by the number of species in a given area and evenness

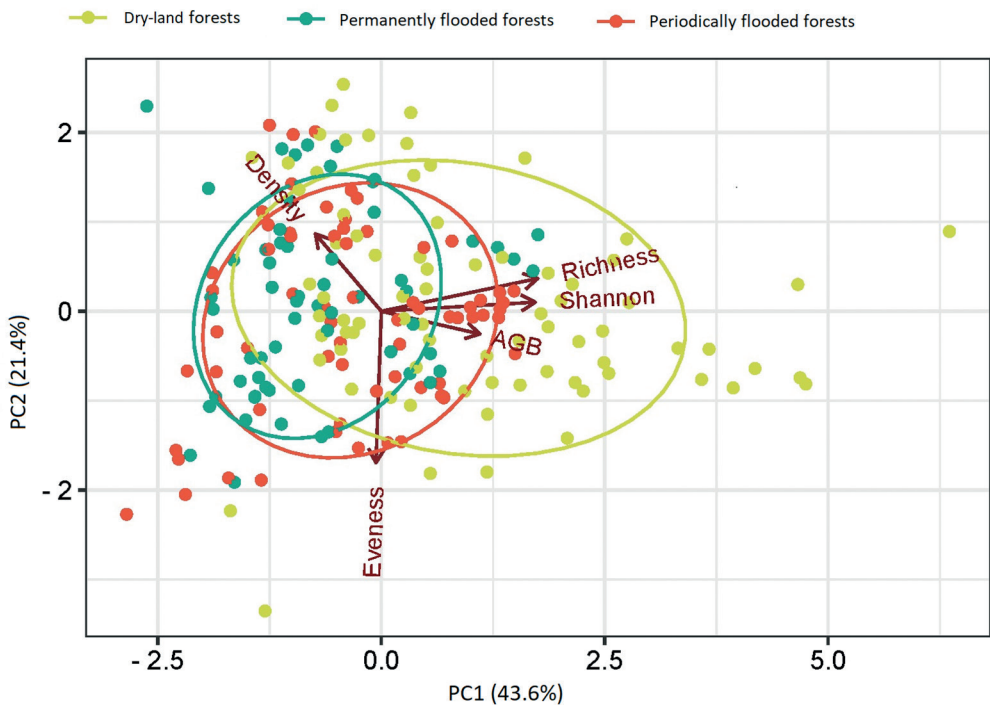


Fig. 7. Plots ordination based on floristic parameters, density and biomass.

more influenced by species interactions, such as competition. However, this last observation remains purely experimental and may not necessarily reflect the reality of permanently flooded forests.

The AGB is correlated with density for dry-land forests ($r = 0.447$ and $p < 0.05$), but this parameter remains insensitive to the other parameters. It has been shown that the lack of correlation between biomass and richness in natural ecosystems indicates that these ecosystems have reached species saturation (Cardinale et al. 2011). In the case of this study, such species saturation is likely in permanently or periodically flooded forests. Such results were also reported by Sullivan et al. (2017), who find no relationship between biomass and diversity in tropical forests. On the other hand, this result contradicts the positive association between diversity and biomass observed by Liang et al. (2016).

Conclusions and Recommendations

The results of this study have important benefits for the conservation of rural forests that are not protected by legal status. On one hand, it establishes a baseline of ecological attributes and characteristics, such as species richness and composition, biomass and rarity of woody species that make up the plant community. On the other hand, the study suggests that the abundance of *A. cordifolia* reflects a high level of degradation of these areas. Better management of this species could therefore promote the conservation value of these neglected and dispersed habitats in agrosystems.

In Côte d'Ivoire, there has been a significant increase in the development of voluntary community conservation programmes, with an emphasis on the crea-

tion of voluntary nature reserves and the protection of sacred forests. The case of the studied forest fragments is particularly interesting because these forests are home to large populations of rare, threatened and/or endemic species. These forests, therefore, deserve to be inventoried and included in processes that promote biodiversity conservation. These are initiatives being promoted by the government of Côte d'Ivoire in collaboration with local communities. However, further studies of these forests are needed to assess their extent, raise community awareness of their importance and develop simple management plans.

References

- ABDOURHAMANE H., RABIOU H., DIOUF A., MOU ROU B., MAHAMANE A., BELLEFONTAINE R. 2017. Structure démographique et répartition spatiale des populations de *Sclerocarya birrea* (A. Rich.) Hochst. du secteur sahélien du Niger. Bois et Forêts Des Tropiques 333(3): 55–66. doi: 10.19182/bft2017.333.a31468
- ABROU N.E.J., KOUAMÉ D., ADOU YAO C.Y. 2019. Diversité floristique des communautés végétales dans l'espace de la Forêt des Marais Tanoé-Ehy (FMTE), Sud-est de la Côte d'Ivoire. International Journal of Biological and Chemical Sciences 13(6): 2874–2887. <https://dx.doi.org/10.4314/ijbcs.v13i6.35>
- ADIKO A.E.G., HOUPHLET S.D.K., DOGBO S.F., VROH B.T.A., KOUAMÉ D., GONÉ BI Z.B., GNAGBO A., BÉNÉ K.J.C., ADOU YA C.Y. 2020. Variabilité des traits fonctionnels des espèces arborescentes dans la reconstitution de la végétation du Parc National d'Azagny (Côte d'Ivoire). International Journal of Biological and Chemical Sciences 14(2): 424–439. doi: <https://dx.doi.org/10.4314/ijbcs.v14i2.10>
- ADOU YAO C.Y., BAKAYOKO A., AKPATOU K. B., N'GUESSAN K. 2011. Impacts de pressions

- anthropiques sur la flore et la structure de la végétation dans la forêt classée de Mo-nogaga, Côte d'Ivoire. *Journal of Animal & Plant Sciences* 12(2): 1560–1572.
- AKÉ ASSI L., PFEFFER P. 1975. Etude d'aménagement touristique du Parc National de Taï. Tome 2: Inventaire de la flore et de la faune. BDPA, Paris. 58 p.
- BURNHAM K.P., OVERTON W.S. 1978. Estimation of the size of a closed population when capture probabilities vary among animals. *Biometrika* 65(3): 623–633. <https://doi.org/10.1093/biomet/65.3.625>
- CARDINALE B.J., MATULICH K.L., HOOPER D.U., BYRNES J.E., DUFFY E., GAMFELDT L., BALVANERA P., O'CONNOR M.I., GONZALEZ A. 2011. The Functional Role of Producer Diversity in Ecosystems. *American Journal of Botany* 98(3): 572–592. <https://doi.org/10.3732/ajb.1000364>
- CARRIÈRE S. 2003. Les orphelins de la forêt Pratiques paysannes et écologie forestière (Ntumu, Sud-Cameroun). IRD Ed, Collection à travers champs. 376 p.
- CHAO A. 1984. Nonparametric estimation of the number of classes in population. *Scandinavian Journal of Statistics* 11(4): 265–270. <https://www.jstor.org/stable/4615964>
- CHATELAIN C., GAUTIER L., SPICHIGER R. 1996. A recent history of forest fragmentation in southwestern Ivory Coast. *Biodiversity and Conservation* 5: 37–53. <https://doi.org/10.1007/BF00056291>
- CHAVE J., ANDALO C., BROWN S. 2005. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. *Oecologia* 145(1): 87–99. <https://doi.org/10.1007/s00442-005-0100-x>
- CHAVE J., RÉJOU-MÉCHAIN M., BÚRQUEZ A., CHIDUMAYO E., COLGAN M.S., DELITTI W.B.C. 2014. Improved allometric models to estimate the aboveground biomass of tropical trees. *Global Change Biology* 20(10): 3177–3190. <https://doi.org/10.1111/gcb.12629>
- CORBACHO C., SÁNCHEZ J.M., COSTILLO E. 2003. Patterns of structural complexity and human disturbance of riparian vegetation in agricultural landscapes of a Mediterranean area. *Agriculture, Ecosystems & Environment* 95(2–3): 495–507. [https://doi.org/10.1016/S0167-8809\(02\)00218-9](https://doi.org/10.1016/S0167-8809(02)00218-9)
- CUNY P., PLANCHERON F., BIO A., KOUACOU E., MORNEAU F. 2023. La forêt et la faune de Côte d'Ivoire dans une situation alarmante – Synthèse des résultats de l'inventaire forestier et faunique national. *Bois et Forêts des Tropiques* 355: 47–72. <https://doi.org/10.19182/bft2023.355.a36939>
- DING Y., ZANG R. 2021. Determinants of aboveground biomass in forests across three climatic zones in China. *Forest Ecology and Management* 482, 118805. <https://doi.org/10.1016/j.foreco.2020.118805>
- EGBE M.A., TABOT P.T., AMBO F.B. 2021. Tree Species Composition and Diversity in the Riparian Forest of Lake Barombi Kotto, Cameroon. *American Journal of Plant Sciences* 12(1): 127–145. <https://doi.org/10.4236/ajps.2021.121008>
- FAYOLLE A., RONDEUX J., DOUCET J.-L., ERNST G., BOUISSOU C., QUEVAUVILLERS S., BOURLAND N., FÉTÉKÉ R., LEJEUNE P. 2013. Réviser les tarifs de cubage pour mieux gérer les forêts du Cameroun. *Bois et Forêts des Tropiques* 317(3): 35–49. <http://hdl.handle.net/2268/160234>
- FEINSINGER P. 2001. Designing field studies for biodiversity conservation. Island Press, Washington, DC. 96 p.
- FRIIS I., HARRIS T. 2013. *Alchornea cordifolia* (Schumacher & Thonn.) Muell. Arg. (Euphorbiaceae), a disjunct Guineo-Congolian tree found in Ethiopia as dominant in riverine forest. *Webbia* 68(2): 147–154. <https://doi.org/10.1080/00837792.2013.857445>
- HAWTHORNE W.D., JONGKIND C.C.H. 2006. Woody Plants of Western African Forests. A Guide to the Forest Trees, Shrubs and Lianas from Senegal to Ghana. Royal Botanic Gardens, Kew. 1023 p.
- HITOSHI S., TOSHIKAZU T. 2008. Ecology of Riparian Forests in Japan: Disturbance, Life History and Regeneration. Springer. 339 p. <https://link.springer.com/book/10.1007/978-4-431-76737-4>
- HOLMGREN M., POOTER L., SIEPEL A., CHATELAIN C., GAUTIER L., HAWTHORNE W.D., HELMINK A.T.F., JONGKIND C.C.H., OS-BREIJER H.J., WIERINGA J.J., VANZOEEST

- A.R. 2004. Ecological profiles of rare and endemic species. In: Poorter L., Bongers F., Kouamé F.N., Hawthorne W.D. (Eds), Biodiversity of West African Forest: An ecological atlas of woody plants species. Wallingford, Royaume Uni, CABI Publishing: 101–389. doi: 10.1079/9780851997346.0041
- IRALU V., PAO N.T., UPADHAYA K. 2020. An assessment of population structure and regeneration status of *Magnolia punduana* Hk. f. & Th. (Magnoliaceae) in fragmented forests of northeast India. *Journal of Forestry Research* 31: 937–943. <https://doi.org/10.1007/s11676-019-00930-z>
- IUCN 2024. IUCN Red List of Threatened Species. <http://www.iucnredlist.org/>
- KAKAÏ R.G., BONOU W., LYKKE A.M. 2016. Approche méthodologique de construction et d'interprétation des structures en diamètre des arbres. *Annales des Sciences Agronomiques* 20 – spécial Projet Undesert-UE: 99–112.
- KONATE D., DIDI S.R., DJE K.B., DIEDHIOU A., KOUASSI K.L., KAMAGATE B., PATUREL J.-E., COULIBALY H.S.J.-P., KOUADIO C.A.K., COULIBALY T.J.H. 2023. Observed Changes in Rainfall and Characteristics of Extreme Events in Côte d'Ivoire (West Africa). *Hydrology* 10(5), 104. 15 p. <https://doi.org/10.3390/hydrology10050104>
- KONÉ Y., VROH B.T.A. 2021. Diversité de la régénération des ligneux dans les plantations forestières au centre de la Côte d'Ivoire. *Biotechnology, Agronomy and Society and Environment* 25(4): 253–266. doi: 10.25518/1780-4507.19355
- KOUAMÉ N.F., ZORO B.I.A. 2010. Nouveau découpage de la zone de forêt dense humide de la Côte d'Ivoire. *Sciences & Nature* 7(2): 177–194. doi: 10.4314/scinat.v7i2.59962
- KPOLITA A., DUBIEZ E., YONGO O., PELTIER R. 2022. First evaluation of the use of assisted natural regeneration by central african farmers to restore their landscapes. *Trees, Forests and People* 7, 100165. 14 p. <https://doi.org/10.1016/j.tfp.2021.100165>
- KURTZ B.C., VALENTIN J.L., SCARANO F.R. 2015. Are the neotropical swamp forests a distinguishable forest type? Patterns from southeast and Southern Brazil. *Edinburgh Journal of Botany* 72(2): 191–208. doi: 10.1017/S096042861400033X
- LANDROT N., DUFOUR S. 2015. Gestion durable de la faune et des ressources cynégétiques en Côte d'Ivoire. Rapport pour les États généraux de la forêt, de la faune et des ressources en eau. Ernst & Young Advisory. 100 p.
- LEDEC G. 1987. Effects of Kenya's Bura irrigation settlement project on biological diversity and other conservation concerns. *Conservation Biology* 1(3): 247–258. doi: 10.1111/j.1523-1739.1987.tb00039.x
- LEWIS S., SONKE B., SUNDERLAND T., BEGNE S., LOPEZ-GONZALEZ G., VAN DER HEIJDEN G., ET AL. 2013. Above-ground biomass and structure of 260 African tropical forests. *Philosophical Transactions of the Royal Society. Biological Sciences* 368(1625), 20120295. 14 p. <https://doi.org/10.1098/rstb.2012.0295>
- LIANG J., CROWTHER T.W., PICARD N., WISER S., ZHOU M., ALBERTI G., SCHULZE E.-D., MCGUIRE A.D., BOZZATO F., PRETZSCH H., DE-MIGUEL S., PAQUETTE A., HERAULT B., SCHERER-LORENZEN M., BARRETT C.B., GLICK H.B., HENGVELD G.M., NABUURS G.-J., PFAUTSCH S., ET AL. 2016. Positive biodiversity-productivity relationship predominant in global forests. *Science* 354(6309), aaf8957. 223 p. <https://doi.org/10.1126/science.aaf8957>
- MAGURRAN A.E., PHILLIP D.A.T. 2001. Implications of species loss in freshwater fish assemblages. *Ecography* 24(6): 645–650. <https://www.jstor.org/stable/3683766>
- MAINGI J.K., MARSH S.F. 2006. Composition, structure, and regeneration patterns in a gallery forest along the Tana River near Bura, Kenya. *Forest Ecology and Management* 236(2–3): 211–228. <https://doi.org/10.1016/j.foreco.2006.09.006>
- MALAN D.F., AKÉ ASSI L., TRA BI F.H., NEUBA D. 2007. Diversité floristique du parc national des îles Ehotilé (littoral est de la Côte d'Ivoire). *Bois et Forêt des Tropiques* 292(2): 49–58. <https://doi.org/10.19182/bft2007.292.a20348>
- MARCON E. 2025. Mesure de la biodiversité. Université de Guyane, AgroParitch. 293 p.

- <https://ericmarcon.github.io/MesuresBio-Div2/>
- MENINO G.C.O., NUNES Y.R.F., SANTOS R.M., FERNANDES G.W., FERNANDES L.A. 2012. Environmental heterogeneity and natural regeneration in riparian vegetation of the Brazilian semi-arid region. *Edinburgh Journal of Botany* 69(1): 29–51. doi: 10.1017/S0960428611000400
- OYEBANJI O.O., BOLARINWAK.A., OLOWOKUDEJO J.D. 2020. Diversity and distribution patterns of aquatic macrophytes in selected ecosystems of south western Nigeria. *African Journal of Ecology* 58(3): 468–480. <https://doi.org/10.1111/aje.12717>
- PAROLIN P., LUCAS C., PIEDADE M.T.F., WITTMANN F. 2010. Drought responses of flood-tolerant trees in Amazonian floodplains. *Annals of Botany* 105(1): 129–139. doi: 10.1093/aob/mcp258
- PASCAL J.-P. 2003. Notions sur les structures et dynamique des forêts tropicales humides. *Revue forestière française* 55(sp): 118–130. doi: 10.4267/2042/5765
- PIELOU E.C. 1966. The measurement of diversity in different types of biological collections. *Journal of Theoretical Biology* 13(C): 131–144. [https://doi.org/10.1016/0022-5193\(66\)90013-0](https://doi.org/10.1016/0022-5193(66)90013-0)
- POORTER L., BONGERS F., KOUAME F.N. 2004. Biodiversity of West African Forests: An Ecological Atlas of Woody Plant Species. CABI Publishing, Nederland, Pays-Bas. 521 p.
- POWO 2025. Plants of the World Online. Facilitated by the Royal Botanic Gardens, Kew. <https://powo.science.kew.org/> Retrieved 06 May 2025.
- R CORE TEAM 2023. R: A language and environment for statistical computing. R foundation for statistical computing, Vienna, Austria. Available at: <http://www.R-project.org/>
- RÉPUBLIQUE DE CÔTE D'IVOIRE 2019. Note technique sur la définition de forêt et le suivi de la déforestation dans la filière palmier à huile Contribution au processus d'interprétation nationale du standard RSPO en Côte d'Ivoire. Abidjan. 50 p.
- SAYER J.A., HARCOURT C.S., COLLINS N.M. (Eds) 1992. The conservation atlas of tropical forests: Africa. MacMillan, Basingstoke. 288 p. <https://portals.iucn.org/library/sites/library/files/documents/1992-063.pdf>
- SHANNON C.E. 1948. A mathematical theory of communication. *The Bell System Technical Journal* 27(3): 379–423, 623–656. <https://doi.org/10.1002/j.1538-7305.1948.tb01338.x>
- SINTAYEHU D.W., DALLE G., BOBASA A.F. 2020. Impacts of climate change on current and future invasion of *Prosopis juliflora* in Ethiopia: environmental and socio-economic implications. *Heliyon* 6(8), e04596. 7 p. <https://doi.org/10.1016/j.heliyon.2020.e04596>
- SULLIVAN M.J.P., TALBOT J., LEWIS S.L., PHILLIPS O.L., QIE L., BEGNE S.K., CHAVEJ., CUNI-SANCHEZ A., HUBAU W., LOPEZ-GONZALEZ G., MILES L., MONTEAGUDO-MENDOZA A., SONKE B., SUNDERLAND T., TER STEEGE H., WHITE L.J.T., AFFUM-BAFFOE K., AIBA S., DE ALMEIDA E.C., ET AL. 2017. Diversity and carbon storage across the tropical forest biome. *Scientific Reports* 7, 39102. 12 p. <https://doi.org/10.1038/srep39102>
- TCHOUTO G.P.M. 2004. Plant diversity in Central African rain forest: implication for biodiversity conservation in Cameroon. PhD thesis, Department of Plant Sciences, Biosystematic Group, Wageningen University. 208 p.
- VROH B.T.A., ADOU YAO C.Y., KOUAMÉ D., N'DA D.H., N'GUESSAN K.E. 2010. Diversités Floristique et Structurale sur le Site d'une Réserve Naturelle Volontaire à Azaguié, Sud-est de la Côte d'Ivoire. *European Journal of Scientific Research* 45(3): 411–421.
- WHITE F. 1983. The vegetation of Africa, a descriptive memoir to accompany the UNESCO/AETFAT/UNSO vegetation map of Africa. *Natural Resources Research* 20. 356 p.
- WILSEY B., STIRLING G. 2007. Species richness and evenness respond in a different manner to propagule density in developing prairie microcosm communities. *Plant Ecology* 190(2): 259–273. doi: 10.1007/s11258-006-9206-4

The influence of undergrowth species on the formation of forest litter and agrochemical soil properties in pine forest stands of Minor Polissya region in Ukraine

Taras Bondarenko¹, Andrii Sasyuk², Volodymyr Zaika³, Vasyl Pavlyuk⁴,
Yurii Olifir⁵, and Marek Trenčiansky⁶

¹Maria Curie-Sklodowska University in Lublin, pl. Marii Curie-Sklodowskiej 5, Lublin 20-031, Poland. E-mail: taras.bondarenko@mail.umcs.pl

²National Natural Park 'Small Polissya', 30300 Khmelnytsky region, Izyaslav, 32 Mykhelska Str., Ukraine. E-mail: malepolisja@ukr.net

³Department of Forestry and Agricultural Management, Vasyl Stefanyk Precarpathian National University of Ukraine, 76018 Ivano-Frankivsk, 57 Shevchenko Str., Ukraine.
E-mail: vkzaika@ukr.net

⁴Department of Forestry, National Forestry University of Ukraine, 79057 Lviv, 103 General Chupryny Str., Ukraine. E-mail: pww1960@i.ua

⁵Institute of Agriculture of Carpathian Region, National Academy of Agrarian Sciences of Ukraine, 5 Hrushevskoho Str., Obroshyne village, 81115 Lviv region, Ukraine.
E-mail: olifir.yura@gmail.com

⁶Department of Forest Economics and Policy, Faculty of Forestry, Technical University in Zvolen, 24 T. G. Masaryka, 96053 Zvolen, Slovakia. E-mail: treciansky@tuzvo.sk

Received: 18 February 2025 / Accepted: 03 June 2025 / Available online: 24 June 2025



Open Access: This work is distributed under the Creative Commons Attribution 4.0 License.

Abstract

The objective of the study was to assess the influence of undergrowth species on forest litter formation and agrochemical soil properties in pure Scots pine forest stands. Research was conducted in 56- to 90-year-old pine forest stands of Minor Polissya region (Ukraine). Based on the analysis of 14 forest stands with undergrowth species and 1 stand without undergrowth species (control), the dynamics, stock and decomposition of forest litter over one year was evaluated. The main part of the research was assessment of the impact of forest litter of undergrowth species on agrochemical soil indicators. From a dynamic point of view, the most forest litter was in the summer-autumn period. Total forest litter stocks in the stands with undergrowth species was significantly lower than in control one. Pine forest stands in Minor Polissya, characterised by variable density and species composition of underwood species, predominantly grow on highly acidic soils, exhibiting low levels of base saturation, exchangeable calcium and magnesium, moderate to high organic matter, and very low to low levels of mobile phosphorus and readily hydrolysable nitrogen. Based on the results of the cluster analysis, we can confirm that the influence of understorey litterfall on various agrochemical soil properties was heterogeneous. The positive impact of undergrowth species litter is significant in the case of nitrogen, pH and potassium.

Key words: forest undergrowth, humification, litter decomposition, litter stock, litterfall dynamics, soil quality.

Introduction

The subject of the study was the woody undergrowth of shrubs and small trees. The role of undergrowth vegetation in forest stands under varying site conditions has received limited research attention. A review of literature over the past 30 years reveals that in Ukraine, the role of undergrowth species in forest ecosystems was primarily studied by Bondarenko between 1998 and 2013. Together with co-authors, Bondarenko published a series of studies (Bondarenko 1998, 2013a, 2013b; Bondarenko and Muzika 2010a, 2010b; Kozlovskiy and Bondarenko 2013) analysing patterns of undergrowth formation in mixed hornbeam-oak forest stands of the Western Forest-Steppe region, emphasizing its relationship to silvicultural and taxonomic factors. Optimal conditions for undergrowth development were observed in stands aged 20–30 and over 70 years (Bondarenko 1998, 2013a; Bondarenko and Muzika 2010a, 2010b). Undergrowth vegetation was also found to improve the physico-chemical properties of soils and to support the proliferation of soil nematodes (Bondarenko 2013a, Kozlovskiy and Bondarenko 2013).

Forest litter plays an important role in determining nutrient cycling, balance and maintaining ecosystem function of forest ecosystems (Ge et al. 2013). It influences the biotic cycle of mineral elements, the intensity of mineralisation of dead organic residues and the composition of mineralisation products (Fisher and Binkley 2000, Bodnar 2007, Lukac and Godbold 2011). In our view, the role of undergrowth species becomes significantly pronounced in pure coniferous forest stands, where thick forest litter is predominantly composed of needles. Such litter layer generates acidic conditions, which are generally unfavour-

able for saprotrophic microorganisms, directly impacting on litter humification and mineralisation processes. Substantial research in this area was conducted by Pohrebniak (1993), who studied the pH responses of filtrates from the litter of 101 tree and shrub species across different growth stages. Based on his results, he classified species into three groups: acidifiers, alkalizers, and neutralizers (Pohrebniak 1993).

The objective of this study is to assess the influence of undergrowth species on forest litter formation and agrochemical soil properties in pure Scots pine (*Pinus sylvestris* L., hereinafter SP) forest stands. The mineralisation of SP litter releases compounds that, along with root exudates, acidify the soil, negatively impacting on the availability of essential nutrients to roots. Based on the results of previous research, we have verified the following hypotheses:

- H1: The amount of forest litter is greater in stands with undergrowth species;
- H2: Forest litter in pine stands is uneven in terms of dynamics, or seasonally influenced;
- H3: Undergrowth species in pine stands accelerates mineralisation and humification of forest soil;
- H4: Undergrowth species in pine stands improves agrochemical parameters of forest soil.

Object and Methods

This study was conducted across 15 sites within 56- to 90-year-old pine SP forest stands situated in the fresh and moist sandy loam soils of the north-eastern Minor Polissya region (Table 1, Fig. 1). All sites are on the same type of soil which, at the

same altitude which is and have the same forest type and similar habitat conditions. Undergrowth species are present in 14 sites. The control was an 81-year-old pure pine stand with oak and birch admixtures but lacking undergrowth (site 15).

SP in the analysed stands generally grew at quality classes I–I a. The absolute stocking density ($29.8\text{--}38.6\text{ m}^3\cdot\text{ha}^{-1}$) and timber volume ($326\text{--}481\text{ m}^3\cdot\text{ha}^{-1}$) of these stands were predominantly high.

The primary species in these experimental stands is *Pinus sylvestris* L., constituting 90–100 % of the tree-species composition. Stands contained up to 10 % of other tree species, mainly *Quercus robur* L. or *Betula pendula* Roth., with a minority representation of the species: *Acer platanoides* L., *Acer negundo* L., *Ulmus*

scabra Mill., *Fraxinus excelsior* L., *Picea abies* (L.) Karst., *Tilia cordata* Mill., and *Alnus glutinosa* (L.) Gaertn. Research plots measuring $50 \times 50\text{ m}$ were established, where we examined silvicultural and taxonomic characteristics of the forest stands, distribution and formation of undergrowth species, litterfall, forest litter, and soil agrochemical properties.

We identified 10 undergrowth species beneath the canopy, with *Sorbus aucuparia* L. found across all sites, *Frangula alnus* Mill. on 92.9 % of sites, and *Corylus avellana* L. on 78.6 % of sites. Besides these undergrowth dominants, *Prunus spinosa* L., *Viburnum opulus* L., *Berberis vulgaris* L., *Prunus spinosa* Ehrh., *Sambucus racemosa* L., *Euonymus europaeus* L., and *Crataegus monogyna* L. were

Table 1. Sampling sites of the study.

No of plot	Age, years	Undergrowth quantity, thousand spicemen·ha ⁻¹	Undergrowth species	Coordinates	
1	65	73.03	SA, FA, CA	N 50.1928457	E 26.7419412
2	65	29.67	EE, SR, SM, SA, CA	N 50.2619430	E 26.8275806
3	75	44.83	SA, FA, CA	N 50.2123810	E 26.8350820
4	71	45.86	EE, SR, SA, FA, CA	N 50.1601690	E 27.3681270
5	63	69.67	BV, SR, SA, CM, VO, FA, CA	N 50.1707340	E 26.8217830
6	58	39.33	BV, SR, SA, CM, FA, CA	N 50.1853660	E 26.8262120
7	73	18.67	BV, SA, VO, FA, PS	N 50.1797891	E 26.8145545
8	80	22.34	SA, FA	N 50.2012414	E 26.8117602
9	68	76.67	EE, CM, SA, FA, CA, PA	N 50.1927022	E 26.7438151
10	59	68.33	EE, SR, SA, FA, CA	N 50.2334096	E 26.5994901
11	81	13.67	SA, FA	N 50.2283540	E 26.8354790
12	56	63.67	SA, FA, PA	N 50.2677687	E 26.5930122
13	63	50.00	SA, FA, CA	N 50.2428034	E 26.5749633
14	90	35.00	SR, SA, FA, PA	N 50.3100558	E 26.7744801
15	81	-	-	N 50.2368077	E 26.8007269

Note: BV – *Berberis vulgaris*, CA – *Corylus avellane*, CM – *Crataegus monogyna*, EE – *Euonymus europaeus*, FA – *Frangula alnus*, PA – *Padus avium*, PS – *Prunus spinosa*, SA – *Sorbus aucuparia*, SR – *Sambucus racemosa*, VO – *Viburnum opulus*.

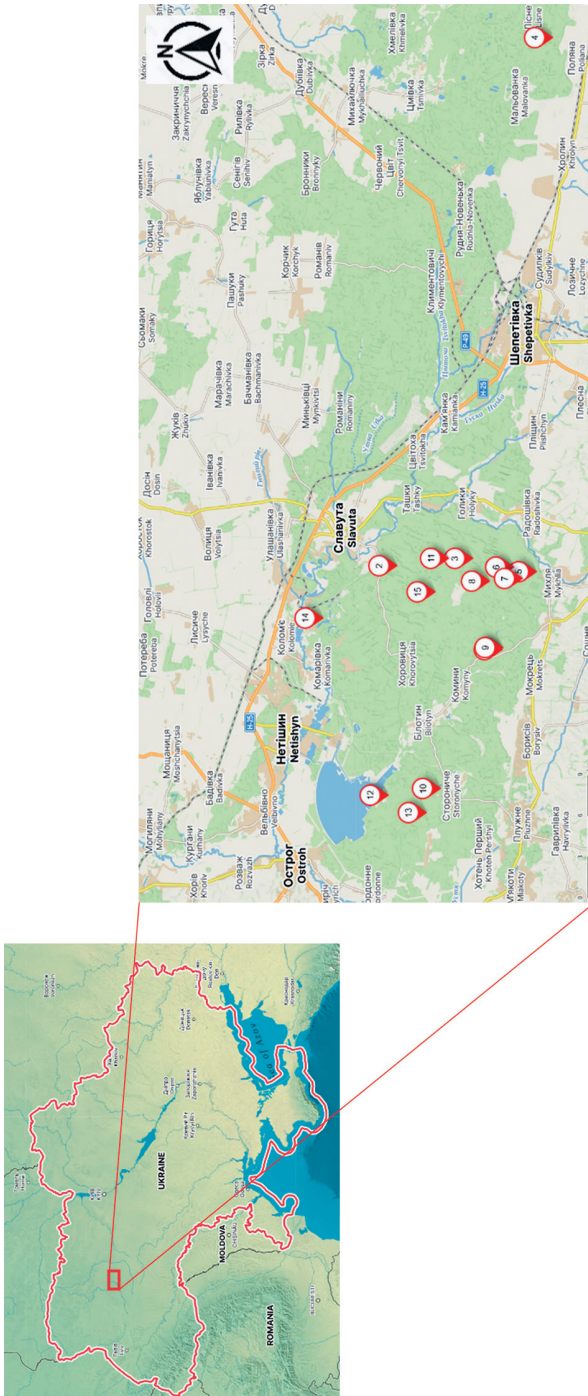


Fig. 1. Study area with sampling sites.

also present. The number of undergrowth species per site ranged from two to seven (Table 1). These species were mostly distributed singly throughout the stand, with a few instances of clustered formations.

Litterfall dynamics were assessed on 8 plots (No. 1, 3, 4, 5, 6, 7, 14, 15) for one year, from September 30, 2021 to September 30, 2022. Each plot was equipped with five litter traps of 1.0×1.0 m area. Samples were collected at the end of November, May, and September, being separated into fractions such as leaves, needles, and other components such as shoots, bark, and fruits, which were dried at 105°C to a constant weight.

Forest litter for assessing the stock and its decomposition was sampled from five 50×50 cm spots per plot. These samples were taken from all 15 plots and were categorised into two fractions: undecomposed material and partially or fully decomposed material. Samples were dried to a constant weight.

Soil samples were collected below the litter sample spots, amounting 1000 cm^3 ($10 \times 10 \times 10$ cm). These samples were combined per plot, thoroughly mixed, and a 1 kg composite sample was extracted. Samples were sieved, dried to their constant weights, and prepared for physico-chemical and agrochemical analyses according to harmonised Ukrainian standards with the international standard DSTU ISO 11464-2001 (2001):

- Soil pH – according to DSTU ISO 10390:2007 (2007);

- Humus – oxidation of soil organic matter by chromium mixture (DSTU 4289:2004 2005);

- Hydrolytic acidity – Kappen method (DSTU 7537:2014 2014);

- Sum of absorbed bases (Ca+Mg) – Kappen-Gilkovitz method (DSTU 7537:2014 2014);

- Nitrogen – Kornfield method (DSTU 7863:2015 2016);

- Mobile phosphorus (P_2O_5) and exchangeable potassium (K_2O) – Chirik method (DSTU 4115-2002 2002).

Data were statistically processed using Microsoft Excel and Statistica 6.0. Results in tables and figures are presented as the arithmetic mean with standard deviation ($\bar{x} \pm SD$). Given the differential impact of undergrowth species on soil agrochemical indicators in various pine stands, a cluster analysis of the plots based on soil agrochemical characteristics was conducted.

Results and Discussion

Litterfall dynamics

The litterfall dynamics were observed over a year (Table 2). From September 30 to November 25, 2021 the total mass of litterfall (in absolute dry weight) on the study sites ranged from 116.7 to 283.3 g·m⁻², which is 12.0–71.9 % higher than the control site. During this period, the sampled litterfall was 19.6–45.2 % leaves, 44.3–73.5 % needles, and 6.9–10.5 % other components (bark, shoots, fruits, etc.). This increased litterfall mass in undergrowth-inclusive stands compared to the control confirms hypothesis H1. The greater amount of litter is a significant contribution of deciduous un-

dergrowth species. The litter, particularly leaves, likely plays a role in enhancing nutrient dynamics and improving forest floor conditions by diversifying the organic input beyond the predominant needle fall. This diversity of litter composition is essential as it can influence decomposition rates and soil properties, including pH and nutrient availability, supporting better soil health and tree growth. It has been confirmed that the amount and especially the quality of litter, on which the rate of its decomposition depends, significantly affect nutrient cycling and thus indirectly affect the stability of forest ecosystems (Kodrík 1999).

During the winter-spring period (December–May), a decrease in litterfall mass was observed (Table 2). Over this period, the total litterfall mass in the studied forest stands ranged from 51.7 to 122.4 g·m⁻², which is 30.9 to 109.6 % higher than the control. Leaf content within this litterfall comprised 0.4–1.3 %, needles 28.8–32.6 %, and other components 65.5–70.1 %. During the summer period (June–September), litterfall mass increased sharply, reaching 285.3–719.9 g·m⁻² across the study plots. Here, needles predominated (42.7–72.8 %), followed by other components (10.0–49.9 %). Annually, the total litterfall mass in the studied forest stands was 505.9–1125.6 g·m⁻². Krynytska et al. (2017) reports that in Lviv Roztoche region the annual dynamics of litter-fall mass in the hornbeam-oak-pine stands, two peaks can be observed: the highest one in October (mainly due to the falling of leaves and pine needles cast) and in May (mainly due to the falling of cones, twigs, pine needles, damaged young leaves of associate species). The results confirm hypothesis H2. In stands, the dynamics of litter are strongly influenced by seasonality. The

Table 2. Dynamics of litterfall formation in forest stands from 30.09.2021 to 30.09.2022 (absolute dry mass).

Plot No	Leaves		Needles		Other components		Total g·m ⁻²
	g·m ⁻²	%	g·m ⁻²	%	g·m ⁻²	%	
30.09 – 25.11.2021							
1	35.7 ±4.9	22.9	110.3 ±9.6	70.0	11.3 ±1.5	7.1	157.3 ±11.3
3	22.8 ±2.0	19.6	85.7 ±6.1	73.5	8.2 ±2.3	6.9	116.7 ±8.6
4	128.3 ±8.1	45.2	125.8 ±9.0	44.3	29.9 ±2.8	10.5	283.3 ±12.8
5	40.0 ±1.4	27.9	126.1 ±9.2	68.4	17.8 ±0.7	9.7	183.9 ±12.3
6	62.7 ±8.5	33.4	108.8 ±7.8	57.5	17.2 ±3.2	9.1	188.7 ±2.8
7	39.8 ±3.9	24.3	110.6 ±4.3	67.7	13.4 ±2.2	8.1	163.8 ±7.0
14	84.3 ±9.4	36.4	124.3 ±2.9	54.4	21.6 ±5.2	9.2	232.1 ±12.1
15	7.3 ±1.5	7.3	84.9 ±7.1	81.2	12.0 ±0.6	11.5	104.2 ±5.8
26.11.2021 – 27.05.2022							
1	0.2 ±0.0	0.4	18.5 ±0.7	29.5	44.5 ±3.5	70.1	63.2 ±4.2
3	0.2 ±0.0	0.5	15.4 ±1.4	30.3	36.1 ±5.5	69.2	51.7 ±6.9
4	3.4 ±0.1	2.7	38.9 ±1.2	31.8	80.1 ±1.8	65.5	122.4 ±0.7
5	0.4 ±0.0	0.7	19.2 ±1.1	30.8	42.8 ±2.2	68.5	62.4 ±3.2
6	1.0 ±0.0	1.0	33.9 ±1.0	32.6	71.7 ±8.8	66.5	106.6 ±8.8
7	0.5 ±0.0	0.6	23.9 ±1.7	31.9	54.0 ±8.3	67.6	78.4 ±8.8
14	1.2 ±0.0	1.3	25.9 ±1.0	28.8	62.9 ±0.7	69.9	90.0 ±1.1
15	0.4 ±0.0	1.1	11.0 ±2.0	36.7	28.9 ±6.8	70.0	39.6 ±8.6
28.05 – 30.09.2022							
1	46.0 ±6.4	15.9	196.0 ±13.2	69.1	43.3 ±7.3	15.0	285.3 ±15.6
3	94.8 ±3.8	23.9	246.7 ±12.3	60.7	63.2 ±5.2	15.4	404.7 ±22.3
4	124.1 ±8.6	17.2	524.1 ±19.9	72.8	71.7 ±6.9	10.0	719.9 ±23.5
5	62.6 ±4.9	20.7	197.5 ±18.6	61.7	54.7 ±5.6	17.6	314.8 ±20.9
6	59.7 ±5.0	13.7	328.9 ±22.7	73.3	58.1 ±3.7	13.0	446.6 ±24.1
7	87.3 ±8.3	13.2	391.4 ±22.1	60.2	171.7 ±5.0	26.9	650.4 ±31.6
14	32.2 ±5.6	7.4	193.7 ±9.0	42.7	231.5 ±10.6	49.9	457.4 ±11.3
15	43.0 ±4.4	7.2	480.7 ±10.3	80.0	77.4 ±3.0	12.8	601.0 ±12.8

amount of new litter is highly variable, influenced mainly by the tree species composition and age of the stand, silvicultural interventions, habitat quality (soil, climate) and many other factors (Kodrík 1993). The seasonal and interannual dynamics of litter are confirmed by the results of analyses in beech stands (Lebret et al. 2001, Kodrík 2002), oak stands (Novák et al. 2014), and spruce stands (Kavvadias et al. 2001).

Forest litter stock and its decomposition

The total forest litter stock under the canopy of the forest stands by the end of September was 1.69–3.47 kg·m⁻² of absolute dry mass (Table 3). Within this composition, the portion of the undecomposed fraction was 12.7–52.3 %, while the semi-decomposed and fully decomposed fractions made up 47.7–87.3 %. The un-

Table 3. Forest litter stock in pine forest stands as of 30.09.2021 (absolute dry mass, kg·m⁻²).

Plot No	Fractions of forest litter							
	Undecomposed Fraction			Semi-decomposed and fully decomposed fraction			Total	
	<i>M</i> ± <i>m</i>	CV, %	%	<i>M</i> ± <i>m</i>	CV, %	%	<i>M</i> ± <i>m</i>	CV, %
1	0.88 ± 0.13	32.6	12.7	2.07 ± 0.65	24.0	87.3	2.95 ± 0.75	24.0
2	0.88 ± 0.07	17.6	35.8	1.58 ± 0.25	34.8	64.2	2.46 ± 0.30	27.1
3	0.67 ± 0.12	36.2	40.0	1.01 ± 0.30	60.3	60.0	1.69 ± 0.36	43.3
4	1.21 ± 0.18	30.4	36.2	2.13 ± 0.41	38.9	63.8	3.34 ± 0.58	34.9
5	0.94 ± 0.12	28.9	52.3	0.86 ± 0.14	36.7	47.7	1.80 ± 0.25	31.7
6	0.89 ± 0.10	22.0	35.9	1.59 ± 0.40	49.5	64.1	2.48 ± 0.46	36.8
7	0.73 ± 0.12	35.2	28.9	1.81 ± 0.40	49.5	71.1	2.54 ± 0.46	40.7
8	0.42 ± 0.04	17.3	23.3	1.38 ± 0.28	40.0	76.7	1.80 ± 0.30	33.4
9	0.77 ± 0.10	31.1	29.7	1.83 ± 0.39	47.3	70.3	2.60 ± 0.48	41.4
10	0.81 ± 0.14	35.0	29.6	1.93 ± 0.42	43.8	70.4	2.74 ± 0.55	39.9
11	0.74 ± 0.11	35.2	27.3	1.98 ± 0.35	39.2	72.7	2.72 ± 0.46	37.4
12	0.90 ± 0.17	35.6	25.8	2.57 ± 0.35	30.1	74.2	3.47 ± 0.51	32.7
13	0.68 ± 0.11	35.6	24.6	2.08 ± 0.40	43.1	75.4	2.76 ± 0.49	39.7
14	0.83 ± 0.07	17.9	44.8	1.02 ± 0.19	36.7	55.2	1.85 ± 0.23	25.2
15	1.01 ± 0.11	8.7	22.7	3.43 ± 0.81	47.3	77.3	4.44 ± 0.85	38.4

Note: *M* is mean value, *m* is error of the mean value, CV is coefficient of variation.

dergrowth species accelerate humification and mineralisation processes of forest litter. Our data indicate that, despite a substantial increase in litterfall mass in the study plots compared to the control, the total forest litter stock was found to be 21.8–71.9 % lower, which confirms hypothesis H3. Similar results were in the study by Prietzel et. al. (2006). In pine forest stands on poor soils in Germany showed a statistically significant decrease of the forest floor C/N ratio, and a considerable, significant accumulation of organic carbon (210 and 400 kg·ha⁻¹·yr⁻¹) and nitrogen (13 and 18 kg·ha⁻¹·yr⁻¹). In addition, the mineral topsoil has acidified significantly.

Within the studied forest stands, there is variability in the humified litter reserves, with the coefficient of variation typically ranging from 20 % to 50 %. The least variability is observed in the undecomposed

litter fraction (CV = 17.3–36.2 %), while the coefficient of variation increases substantially to 24.0–60.3 % for the semi-decomposed and fully decomposed fractions. This variation is influenced by the spatial structure of the forest stands and the distribution of undergrowth species, especially in areas where undergrowth plants form clusters and intensify humification processes.

The impact of undergrowth on agrochemical soil parameters

Forest litter plays a significant role in influencing the agrochemical characteristics of the soil. As it decomposes and microorganisms function within it, various organic and inorganic compounds, including acids, accumulate in the soil. The needle litter from coniferous trees particularly pro-

motes the buildup of organic and inorganic acids. Our research indicates that the sod-podzolic soils supporting the studied pine stands are highly acidic (Table 4), with a salt-extracted pH of less than 4, ranging from 3.01 to 3.75.

Hydrolytic acidity values in the soil across the study plots vary substantially, ranging from 4.10 to 9.98 mg-eq.100·g⁻¹ soil, with highly acidic soils predominating. Only plot 2 shows moderately acidic soils, whereas plots 7, 9, and 14 are classified as strongly acidic.

Pine forest stands, regardless of undergrowth species distribution, predominantly grow on highly acidic soils, where conditions for root nutrition are suboptimal and toxic compounds tend to accumulate. These soils are characterised by very low levels of base saturation (2.8–4.9 mg-eq.100·g⁻¹soil). Soil variability across the plots is relatively low for exchangeable forms of calcium, magnesium, and hu-

mus content. Exchangeable calcium is generally very low to low (1.88–2.98 mg-eq.100·g⁻¹), and exchangeable magnesium remains low (0.60–0.82 mg-eq.100·g⁻¹). Humus content is moderate (2.10–2.88 %) in some plots and elevated (3.13–3.74 %) in others.

The soils of the pine stands demonstrate significant variability in levels of easily hydrolysable nitrogen, and especially in mobile phosphorus content. Approximately 72 % of pine stands grow on soils with very low levels of easily hydrolysable nitrogen (71.6–96.6 mg·kg⁻¹ soil), with the remaining plots containing low levels (102.2–112.9 mg·kg⁻¹ soil). In the study region, soils with very low mobile phosphorus content (2.7–25.0 mg·kg⁻¹ soil) dominate in pine stands, accounting for about 79 % of the study area. The soils of the remaining pine stands exhibit low levels of mobile phosphorus (26.6–40.7 mg·kg⁻¹ soil). Exchangeable potassium content is

Table 4. Agrochemical indicators of the upper 10 cm soil layer.

Plot No	pH (salt)	Hu-mus, %	Hydrolytic acidity	Sum of absorbed bases	Exchangeable		Nitrogen (easily hydrolyz-able)	Phos-phorus (P ₂ O ₅)	Exchange-able potassium (K ₂ O)
					Calci-um	Mag-ne-sium			
mg-eq.100 g ⁻¹ soil					mg·kg ⁻¹ of soil				
1	3.01	2.18	9.98	2.8	1.88	0.60	96.6	4.1	39.7
2	3.64	2.10	4.81	3.7	1.92	0.80	88.2	40.7	33.9
3	3.38	3.13	7.70	3.5	1.78	0.64	102.2	8.6	28.1
4	3.37	3.14	7.18	3.6	1.98	0.66	105.7	20.5	42.1
5	3.49	3.74	7.44	3.2	2.48	0.68	112.9	26.6	58.4
6	3.49	2.73	6.30	3.3	2.24	0.69	86.8	16.8	35.1
7	3.47	2.64	5.95	3.2	2.14	0.65	93.8	10.2	35.0
8	3.31	2.50	6.74	2.9	1.92	0.60	79.8	33.0	25.7
9	3.75	2.10	4.10	4.9	2.60	0.82	79.1	2.7	39.7
10	3.48	3.19	7.35	4.0	2.98	0.65	103.6	20.2	21.0
11	3.32	2.88	6.48	3.3	1.94	0.60	86.1	1.7	29.2
12	3.29	2.66	6.91	4.3	2.16	0.63	91.0	3.9	29.2
13	3.37	2.72	6.56	3.4	2.04	0.65	81.2	10.7	23.4
14	3.65	2.37	4.38	4.8	2.68	0.78	75.6	25.0	30.4
15	3.14	2.34	5.78	3.3	1.92	0.60	71.6	14.8	18.7

very low (21.0–39.7 mg·kg⁻¹ soil) in 86 % of the study plots, with only 14 % of plots showing low levels (42.1–58.4 mg·kg⁻¹ soil).

The impact of undergrowth species litterfall on various soil agrochemical indicators is variable. The most notable influence is on the accumulation of easily hydrolysable nitrogen and exchangeable potassium in the upper soil layer. Levels of easily hydrolysable nitrogen in all pine stand soils exceed control by 5.6–57.7 %, and exchangeable potassium levels are elevated by 12.3–212.3 %. Based on the above, we can also partially confirm hypothesis H4: Undergrowth species in pine stands improve some agrochemical parameters of forest soil, especially: nitrogen and potassium. Hypothesis H4 was not confirmed for all agrochemical parameters in each stand. Undergrowth species also significantly reduce soil acidity, increasing humus and exchangeable

magnesium content. In 93 % of the plots, pH increased from 3.14 to 3.29 - 3.75 (exception: site 1), while hydrolytic acidity and exchangeable magnesium content in 79 % of the plots increased by 2.9–33.2 % and 5.0–36.7 %, respectively. Not all broadleaved trees and shrub species act as soil alkalizers. According to Pohrebniak (1993), *Sambucus nigra* L., *Euonymus europaeus*, *Euonymus verrucosus* Scop., and *Crataegus oxyacantha* are among the understory species that contribute to soil alkalisation.

The influence of undergrowth species on total base saturation, exchangeable calcium, and mobile phosphorus content is less pronounced, with 64–71 % of the study plots showing an increase in these indicators.

The pine stands grouped into clusters within which the influence of undergrowth species on soil agrochemical parameters was of a similar nature (Fig. 2). For exam-

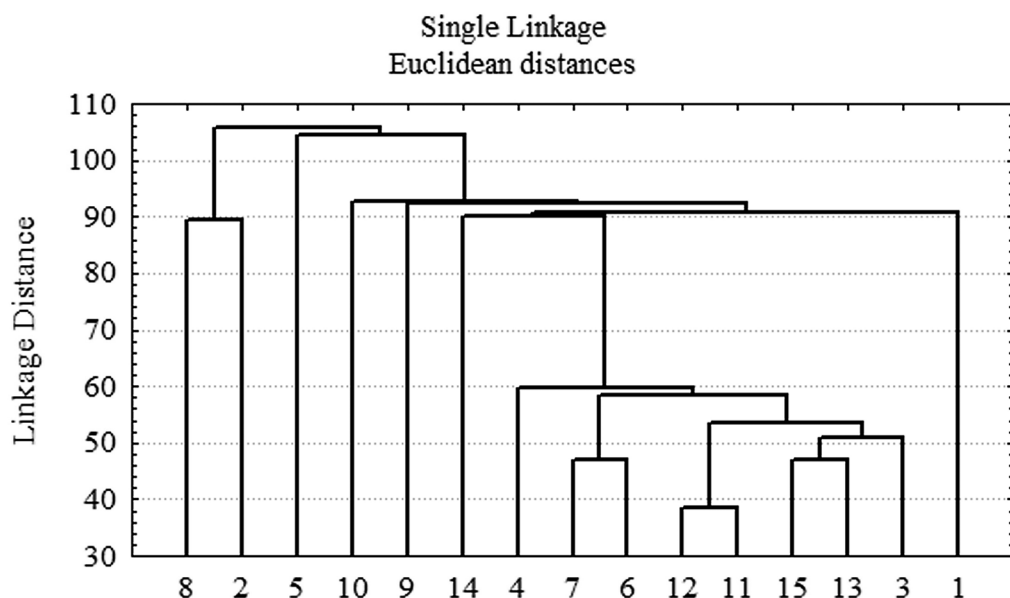


Fig. 2. Dendrogram illustrating the relationships among pine stands based on soil agrochemical parameters: 1–14 – sample plots, 15 – control.

ple, in plots 2, 5, 8, 9, 10, and 14, undergrowth litterfall exerts a significant impact on soil. These plots demonstrate substantial improvement in soil conditions beneficial to pine stand growth. In contrast, other plots (3, 4, 6, 7, 11, 12, 13) exhibited a weaker influence of undergrowth litter on soil agrochemical parameters. These stands showed soil properties similar to those of the control stand in plot 15.

The observed clustering of pine stands by soil agrochemical parameters is largely influenced by the species composition of their undergrowth. Needle litter predominates in the composition of litterfall in pine stands. The proportion of leaves from undergrowth species varies, influencing the rate of forest floor mineralisation and the resulting effect on soil.

Conclusions

The study investigated the influence of undergrowth species on forest litter formation and agrochemical soil properties in pure pine stands. The research confirmed some, but not all, of the initial hypotheses. Based on the research carried out, we can establish the following conclusions:

1. As hypothesized (H1), stands with undergrowth species exhibited a greater amount of forest litter compared to the control stand. The total litter mass at all study sites was 12.0–71.9 % higher than at the control site during the year.

2. The study also confirmed the seasonal influence on litterfall dynamics (H2), with distinct peaks observed in autumn and summer, primarily driven by leaf and needle fall. The total litterfall mass in the studied pine stands was 505.9–1125.6 g·m⁻² annually. The majority occurred between

June and September, a smaller part in the period from October to November and the smallest share in winter and spring.

3. The presence of undergrowth species accelerated the mineralisation and humification of forest litter, leading to a lower overall litter stock despite increased litterfall, thus supporting H3. The total forest litter stock in the studied research plots were 21.8–71.9 % lower than in the control plot without undergrowth.

4. While undergrowth species did improve some agrochemical parameters, notably nitrogen and potassium levels (partially supporting H4), the improvements were not universal across all parameters or stands. Soil acidity was reduced and humus and exchangeable magnesium content increased in most plots, but the effects on total base saturation, exchangeable calcium, and mobile phosphorus were less consistent. Cluster analysis revealed that the influence of undergrowth species on soil properties varied across stands, likely due to differences in undergrowth species composition.

The significance of the work is that the influence of undergrowth species on humification and mineralisation processes in pine stands was quantitatively determined and confirmed. At the same time, the positive influence of undergrowth on selected agrochemical indicators of forest soil was quantified. The study highlights the complex interplay between undergrowth vegetation, litter dynamics, and soil properties in pine forests, emphasizing the importance of considering undergrowth composition in forest management practices. From a practical point of view, it is important to support undergrowth species in pine stand management in order to reduce acidification and increase the overall quality of forest soil.

Acknowledgments

The authors would like to thank the Scientific Grand Agency of the Ministry of Education, Research, Development and Youth of the Slovak Republic and the Slovak Academy of Sciences. This paper was elaborated within the framework of Grant project 'VEGA 1/306/24: The quantification and development of Payment for water protection ecosystem services from forest'. The paper was supported by the Slovak Research and Development Agency under research projects 'APVV-23-0116: Opportunities and risks of the green economy concept in Slovak forestry'.

References

- BONDARENKO T.V. 1998. Some features of underwood formation in oak forests of the Forest-Steppe zone [Nekotorye osobennosti formirovaniia podleska v dubravakh Lesostepy]. In: Sbornik nauchnih trudov Instituta lesa NAN Belarusi. Homel 48: 110–112 (in Russian).
- BONDARENKO T.V., MUZIKA T.M. 2010a. The presence of *Cornus mas* in the forest stands of the Medobory Nature Reserve [Svyidina v lisovykh kulturakh pryrodnoho zapovidnyka 'Medobory']. In: Naukovi visnyk NLTU Ukrainy: zbirnyk nauko-vo-tekhnichnykh prats. Lviv: RVV NLTU Ukrainy 20.16: 128–131 (in Ukrainian).
- BONDARENKO T.V., MUZIKA T.M. 2010b. The species composition and condition of the underwood in the oak forests of the 'Medobory' Nature Reserve [Vydivyi sklad ta stan pidlisku dibrov pryrodnoho zapovidnyka 'Medobory']. In: Pryrodno-zapovidnyi fond Ukrainy – myne, sihodennia, maibutnie: materialu Mizhnarodnoji nauko-vo-praktychnoi konferencii prysviachenoj 20-richchuu zapovidnyka 'Medobory' (26–28 April 2010, Hrymaiv). Ternopil, 'Pidruchnyky i posibnyky': 247–250 (in Ukrainian).
- BONDARENKO T.V. 2013a. The silvicultural and ecological role of underwood in hornbeam-oak forests stands of the Western Forest-Steppe zone [Lisivnycho-ekolohichna rol pidlisku v hrabovykh dibrovakh Zakhidnoho Lesostepu]. PhD thesis: 06.03.03. Lviv. 20 p. (in Ukrainian).
- BONDARENKO T.V. 2013b. Phytomass of underwood shrubs as a resource for energy-saving fuel technologies [Fitomasa pidliskovykh chaharnykyv yak resurs dlia enerhooshchadnykh palivnykh tekhnolohii]. In: Naukovi visnyk NLTU Ukrainy: zbirnyk nauko-vo-tekhnichnykh prats. Lviv: RVV NLTU Ukrainy 21.16: 343–346 (in Ukrainian).
- BODNAR I.P. 2007. The biogeochemical circulation of mineral elements and the regulation of their fluxes in pine forest ecosystems of Central Polissya of Ukraine [Biotichnij krugobig mineral'nych elementiv ta shljachi jogo reguljuvannja v sosnovich derevostanach Central'nogo Polissja Ukraini]. NLTU, Publishing house, Lviv. 20 p. (in Ukrainian).
- DSTU ISO 11464-2001 2001. State Standard of Ukraine. Soil quality: Preliminary preparation of samples for physical-chemical analysis. 13 p. (in Ukrainian).
- DSTU 4115-2002 2002. State Standard of Ukraine. Soils: Determination of the mobile forms of phosphorus and potassium using the modified Chyrykov method [Grundy. Vyznachannia rukhomykh spoluk fosforu i kaliuu za modifikuvalnym metodom Chyrykova]. Chynnyi vid 2003-01-01. Vydavnytvo ofitsijnyj Kyiv, Derzhspozhyvstandart Ukrainy. 12 p. (in Ukrainian).
- DSTU 4289:2004 2005. State Standard of Ukraine. Soil Quality: Methods for determining organic matter content [Yakist gruntu. Metody vyznachannia orhanichnoi rechovyny]. Chynnyi vid 2005-07-01. Vydavnytvo ofitsijnyj Kyiv, Derzhspozhyvstandart Ukrainy. 17 p. (in Ukrainian).
- DSTU 7537:2014 2014. State Standard of Ukraine. Soil Quality: Determination of hydrolytic acidity [Yakist gruntu. Vyznachen-nia gidrolitichnoi kyslotnosti]. Chynnyi vid 2015-04-01. Vydavnytvo ofitsijnyj Kyiv, Derzhspozhyvstandart Ukrainy. 12 p. (in Ukrainian).
- DSTU 7863:2015 2016. State Standard of

- Ukraine. Soil quality: Determination of easily hydrolysable nitrogen by the Kornfield method [Yakist gruntu. Vyznachennia lehkohidroliznoho azotu metodom Kornfil'da]. Chynnyi vid 2016-07-01. Vydavnytvo ofitsijnyj Kyiv, Derzhspozhyvstandart Ukrainy. 9 p. (in Ukrainian).
- DSTU ISO 10390:2007 2007. State Standard of Ukraine. Soil quality: Determination of pH [Yakist gruntu. Vyznachennia pH]. ISO 10390:2005, IDT., Chynnyi vid 2009-10-01. Vydavnytvo ofitsijnyj Kyiv, Derzhspozhyvstandart Ukrainy. 8 p. (in Ukrainian).
- FISHER R.F., BINKLEY D. 2000. Ecology and management of forest soils. John Wiley & Sons, New York. 489 p.
- GE X., ZENG L., XIAO W., HUANG Z., GENG X., TAN B. 2013. Effect of litter substrate quality and soil nutrients on forest litter decomposition: A review. *Acta Ecologica Sinica* 33(2): 102–108. <https://doi.org/10.1016/j.chnaes.2013.01.006>
- KAVVADIAS V.A., ALIFRAGIS D., TSIONTSIS A., BROFAS G., STAMATELOS G. 2001. Litterfall, litter accumulation and litter decomposition rates in four forest ecosystems in northern Greece. *Forest Ecology and Management* 144(1–3): 113–127. [https://doi.org/10.1016/S0378-1127\(00\)00365-0](https://doi.org/10.1016/S0378-1127(00)00365-0)
- KODRÍK M. 1993. Quantitative changes in litter fall caused by different beech stand stocking [Kvantitatívne zmeny opadanky, vyvolané rôznym zakmenením bukového porastu]. *Forestry Journal [Lesnícky časopis]* 39: 371–376 (in Slovak).
- KODRÍK M. 1999. Total litter and some of its quantitative fractions analysis in the beech forest stand with different tree density. *Folia Oecologica* 26: 71–79.
- KODRÍK M. 2002. Annual litter fall dynamics of a beech forest ten years after regeneration intervention. *Ekológia (Bratislava)* 21(2): 110–116.
- Kozlovskiy M.P., Bondarenko T.V. 2013. The influence of the underwood in oak-hornbeam forests stands on the formation of soil nematode communities [Vplyv pidlisku u hrabovkykh dibrovakh na formuvannia uhrupovan' gruntovykh nematodiv]. In: *Naukovi visnyk NLTU Ukrainy: zbirnyk nauko-vo-tekhnichnykh prats. Lviv, RVV NLTU Ukrainy* 23.2: 15–23 (in Ukrainian).
- LEBRET M., NYS C., FORGEARD F. 2001. Litter production in an Atlantic beech (*Fagus sylvatica* L.) time sequence. *Annals of forest science* 58(7): 755–768. <https://doi.org/10.1051/forest:2001161>
- LUKAC M., GODBOLD D.L. 2011. *Soil Ecology in Northern Forests: A Belowground View of a Changing World*. Cambridge University press, New York. 256 p. <https://doi.org/10.1017/CBO9780511976100>
- NOVÁK K., DUŠEK D., SLODIČÁK M. 2014. Quantity and quality of litterfall in young oak stands. *Journal of Forest Science* 60(6): 219–225. <https://doi.org/10.17221/2/2014-JFS>
- POHREBNIÁK P.S. 1993. Regarding the question of the origin of forest underwood reactions. *Forest ecology and typology of forests* [Do pytannia pro pokhodzhennia reaktsii lisovoi pidstylky. Lisova ekolohiia i typolohiia lisiv]. In: *Vybrani pratsi, Kyiv, Naukova dumka*: 334–335 (in Ukrainian).
- PRIETZEL J., STETTER U., KLEMMT H.J., REHFUESS K.E. 2006. Recent carbon and nitrogen accumulation and acidification in soils of two Scots pine ecosystems in Southern Germany. *Plant and Soil* 289: 153–170. <https://doi.org/10.1007/s11104-006-9120-5>

Diversity and distribution of mega-trees in the vegetation of Azagny National Park, Southern Côte d'Ivoire

Bakayoko Hillihase^{1,2*} , N'Gouan Emmanuel-Joël Abrou¹ ,
Venance-Pâques Gniayou Kouadio³ , Adjo Estelle Genevieve Adiko¹ ,
and Constant Yves Adou Yao^{1,2,4} 

¹Natural Environments and Biodiversity Conservation Laboratory, UFR Biosciences, Felix Houphouët-Boigny University, Abidjan, Côte d'Ivoire. E-mails: hillihase@gmail.com* (BH)

²Biology, Environment, Health doctoral school, Félix Houphouët-Boigny University, Abidjan, Côte d'Ivoire. E-mail: edbes@ed-bio-env-sante.edu.ci (BH)

³Department of Plant Biology, UFR Biological Sciences, Péléforo Gon Coulibaly University, Korhogo, Côte d'Ivoire. E-mail: info@upgc.edu.ci (V-PGK)

⁴Swiss Center for Scientific Research in Côte d'Ivoire (CSRS), Abidjan, Côte d'Ivoire. E-mail: communication.csrs@csrs.ci (CYAY)

Received: 29 April 2025 / Accepted: 19 June 2025 / Available online: 15 July 2025



Open Access: This work is distributed under the Creative Commons Attribution 4.0 License.

Abstract

Mega-trees, although representing a small proportion of the flora of forest ecosystems, provide the bulk of ecosystem services. However, their degradation, accentuated by strong and changing climatic and ecological constraints, is intensifying under the action of anthropogenic activities. To assess the diversity, biomass and conservation value of these mega-trees in natural forests, this study was carried out in three vegetation types: old-growth forests, secondary forests and crop/fallow mosaics, in Azagny National Park, in Côte d'Ivoire. Inventories were undertaken in 71 plots of 2500 m² each. Within these plots, the diameter at breast height (DBH $\geq$ 70 cm) and the height of each tree were recorded to estimate total plant biomass. The study identified 49 mega-tree species, of which two are endemic to the Upper Guinea forest block and eight are listed as vulnerable or near threatened on IUCN Red List. Furthermore, old-growth forests were found to be the most productive in terms of biomass, reaching an average of 125.79 ± 76.29 t·ha⁻¹, well above the other two vegetation types mentioned above. This underlines their excellent biomass storage capacity in the protected area. In addition, the density and basal area of mega-trees in these old-growth forests are higher than in the other forest types.

Key words: carbon storage, mega-trees diversity, protected areas, spatial distribution.

Introduction

Forest ecosystems in the humid tropics are rich in biodiversity, with diverse structures and plant species composition (Slik

et al. 2013). They contain more than half of all living species (Puig 2001). This plant biodiversity is a source of genetic wealth and is fundamental to humanity (Amara 2010).

Despite their importance, tropical forest ecosystems are subject to enormous and multifaceted pressures, leading to functional imbalance and impoverishment of the biodiversity they contain (Abrou et al. 2019, Lapola et al. 2023). As a result, in Côte d'Ivoire, 30 million hectares of forest disappeared between 1970 and 2000, as reported by Nusbaumer et al. (2004). The main causes of this loss were extensive agriculture, logging and urbanisation (Adou Yao 2005). In 2020, Côte d'Ivoire's forest cover was estimated at around 9.2 % of the country's total land area, with an average annual deforestation rate of 2.8 % since 1986 (Cuny et al. 2023). In response to the decline in forest cover, Côte d'Ivoire has set out to preserve its forests and their biodiversity by creating national parks and nature reserves (World Wildlife Fund 2020). Among these protected areas, the Azagny National Park, created in 1981, stands out for its special character as a coastal park where old growth forests on dry land, swamp forests, secondary forests (SF) and crop-fallow mosaics co-exist.

In this park, very few studies have been carried out on forest diversity. Indeed, studies of very large trees with a diameter (DBH) of more than 70 cm (Clark and Clark 1996) have never been carried out. Yet these trees represent a tiny, irreplaceable part of ecosystems and are associated with major benefits in terms of ecosystem services (Slik et al. 2013, Pinho et al. 2020). They contribute most of the effects on biogeochemical cycles and ecosystem processes, the water cycle and nutrient dynamics (Bastin et al. 2018). They also account for almost half of total forest biomass (Clark and Clark 1996).

Therefore, it appears necessary to have more scientific data on mega-trees in West African forests. To this end, the

present study was initiated to analyse the diversity, biomass and distribution of these mega-trees in Azagny National Park. It seeks to answer the following questions: i) what is the diversity of the mega-trees found in the main vegetation types of Azagny National Park? ii) what is their contribution to the total biomass and to the carbon stock of the trees in Azagny forest? iii) how are the mega-trees distributed according to the main vegetation types of Azagny National Park?

Materials and Methods

Study site

Azagny National Park is located in the south of Côte d'Ivoire, in the coastal zone 120 km west of the city of Abidjan (Fig. 1). It lies between 5°14' and 5°31' latitude north and 4°76' and 5°01' longitude west (Lauginie 2017). Due to its position on the coast and the activities that took place there in the past, Azagny National Park contains several types of rainforests (both on uplands and wetlands): old-growth forests; secondary forests; crop-fallow mosaics (resulting from former peasant occupations) (Gnagbo et al. 2016).

Data collection

A surface inventory was conducted following the method described by Senterre (2005), using 71 square plots of 0.25 ha (50 × 50 m) randomly established in different forest types of the park: 17 in old growth forests (OGF), 40 in secondary forests and 14 in crop/fallow mosaics (Fig. 2). The uneven distribution of plots was due to site inaccessibility, particularly in areas with extensive marshland. In

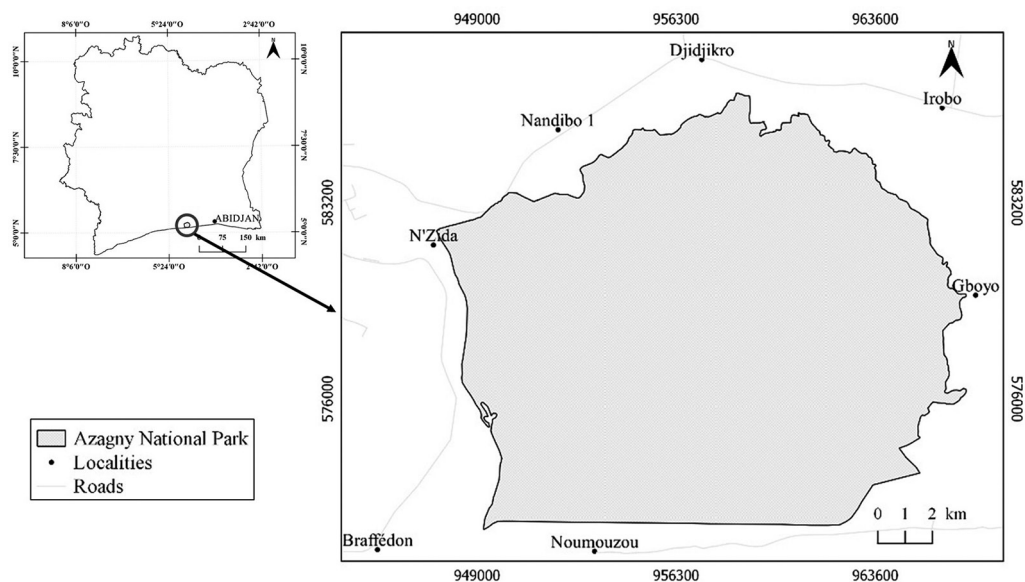


Fig. 1. Location of Azagny National Park in south Côte d'Ivoire.

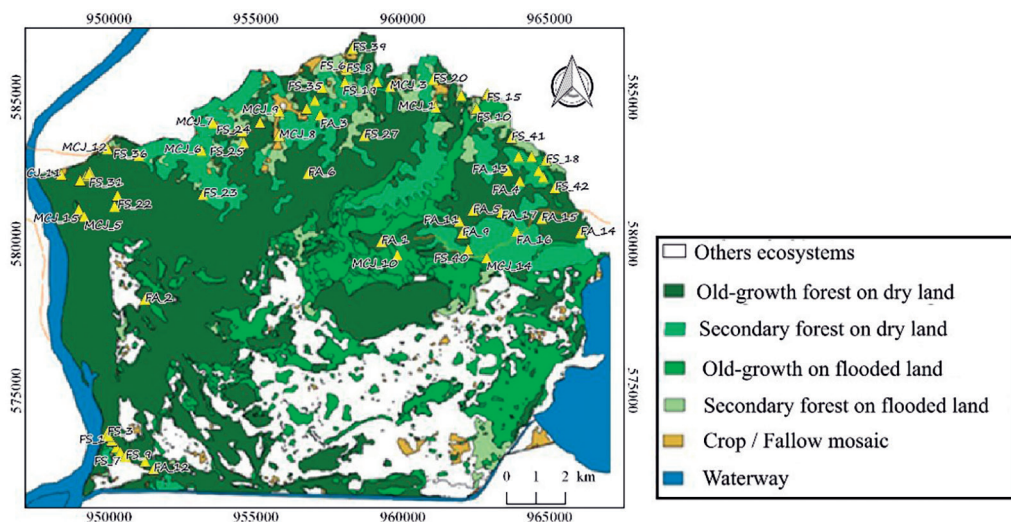


Fig. 2. Distribution of survey plots on Azagny National Park map.

each plot, trees with a diameter at breast height greater than or equal to 70 cm ($DBH \geq 70$ cm) were identified, geolocated using GPS and the heights measured using a rangefinder.

Diversity analysis

The diversity of large trees was estimated, on the one hand, by species richness and composition – number of species, num-

ber of genera, species endemic to Upper Guinea and threatened and rare species on IUCN Red List (2023). Secondly, diversity was assessed using Shannon's diversity index (1948), Simpson's index (1949), and Pielou's equitability index (1966), calculated using formulas (1), (2) and (3), respectively.

$$H' = -\sum \left(\frac{N_i}{N} \right) \cdot \ln \left(\frac{N_i}{N} \right), \quad (1)$$

$$DS = \frac{\sum [N_i \cdot (N_i - 1)]}{N \cdot (N - 1)}, \quad (2)$$

$$E = \frac{N'}{\ln S}, \quad (3)$$

where: N_i is the number of individuals of species i , N represents the total number of individuals of all species, H' denotes Shannon index; DS is Simpson's index, S refers to species richness, and E represents the Pielou's equitability index (1986).

To compare diversity within the different ecosystems of Azagny National Park, taking into account both species richness and abundance, the diversity profile was assessed using Rényi's diversity profile (Kindt et al. 2006), as shown in formula (4).

$$H_\alpha = \frac{1}{1-\alpha} \log_2 \left[\sum_i p_i(\alpha) \right], \quad (4)$$

where: H_α is the Rényi diversity value, p_i represents the relative abundance of species, and α is the diversity parameter scale ($\alpha = 0, 1, \infty$).

Diversity profiles of five vegetation plot categories were generated using Rényi's diversity (H_α). The scale parameter (α) gives the order of Rényi's diversity; as α increases, the index becomes more sensitive to the most abundant species.

The symmetrical Venn diagram (Venn 1880) was produced using the genomics and evolution bioinformatics tool (Bioinformatics & Evolutionary Genomics 2025). This diagram was also used to illustrate

the floristic similarities among old-growth forests, secondary forests and crop-fallow mosaics.

Calculation of mega-tree biomass

The above-ground biomass (AGB) of mega-trees was estimated using the allometric equation (5) of Chave et al. (2014), based on dense evergreen forest individuals.

$$AGB = 0.0673 \cdot (\rho \cdot DBH \cdot H)^{0.976} \quad (5)$$

where: AGB denotes the above-ground biomass of the tree, t; DBH is the trunk diameter at 1.30 m above ground, cm; ρ represents the species-specific gravity, H : the height.

The Global Wood density database (Zanne et al. 2009) was used to determine tree wood density. For species without a match in the database, $0.58 \text{ g} \cdot \text{cm}^{-3}$ was used as the default value. Carbon stock was estimated as 50 % of the total plant biomass, following the guidelines of GIEC (2006).

The basal area of the stand in each vegetation type was calculated using the formula (6).

$$G = \sum \frac{\pi \cdot D_i^2}{4}, \quad (6)$$

where: G is the basal area, m^2 ; D_i is DBH, m of individual i .

Distribution analysis

An existing topographic map of Azagny National Park was georeferenced and the mega-trees were projected onto it. Data collected in the field, such as geographical coordinates of each plant and their diameter, were saved in an Excel file and converted to a CSV format for their use in QGIS 3.22. The imported data was then labelled and classified based on individual trees basal area values and species

names, enabling the distribution of mega-tree species to be visualised with the space they occupy.

Inverse Distance Weighting (IDW) interpolation is a method used to estimate unmeasured values from known data points, by assigning more weight to nearby points than to distant ones. It calculates a weighted average of the values of neighbouring points, with a weighting that decreases with distance, using a formula where distance is raised to a negative power. The choice of exponent, often between 2 and 3, influences the speed of this decrease. IDW is simple to implement and is particularly effective for space applications where the data varies continuously.

Statistical analysis

Analysis of Variance (ANOVA) was used to compare the data and the diversity indices calculated for the different vegetation type studied. In cases where the assumptions required for ANOVA were not met such as

data independence, normality and homogeneity of variances, the non-parametric Kruskal-Wallis test was used.

Results

Species richness, composition and diversity

A total of 49 species belonging to 42 genera and 26 botanical families were recorded in all three ecosystems. Species richness varied according to forest type, ranging from an average of 1.5 ± 0.52 species per plot in crop-fallow mosaic (CFM) to 2.29 ± 1.2 species per plot in OGF, as shown in Table 1.

Among the 49 species identified, ten have a special conservation status, including two species endemic to the Upper Guinea (UG) forest block, five vulnerable species on the IUCN Red List (2023) and four mega-tree species listed as 'near-threatened' category (Table 2).

Table 1. Summary of the average number of mega-tree species per vegetation type.

Ecosystem	Number of plots	Number of species	Average species richness	Test statistics
OGF	17	18	2.29 ± 1.2^a	$p\text{-value} = 0.19$
SF	40	39	2.05 ± 1.15^a	
CFM	14	15	1.5 ± 0.52^a	

Note: Values within the same column that share the same letter are not significantly different from each other ($p > 0.05$).

The Venn diagram revealed that four species are common to all three ecosystem types, while only one species is common to both OGF and CFM. SF contain 21 species that are unique to them (Fig. 3).

The Shannon index does not vary significantly between the three forest types (Table 3). The situation is similar for the

Simpson and Pielou diversity indices. These indices show that no type of vegetation is significantly more diverse than another.

On the diversity profile, the SF curve lies above those of the other two for $\alpha < 2$ (Fig. 4). Above this value, the CFM curve is higher, and all three curves run parallel.

Table 2. List of mega-trees species with special conservation status recorded in the study area.

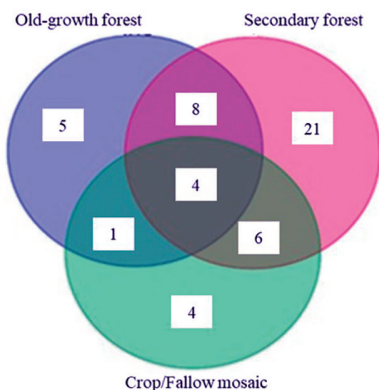
Species	Family	Ende- mism	IUCN status	OGF	SF	CFM
				Individuals number		
<i>Albizia ferruginea</i> (Guill. & Perr.) Benth	Fabaceae	-	NT	-	-	1
<i>Anopyxis klaineana</i> (Pierre) Engl.	Rhizophoraceae	-	VU	-	1	2
<i>Dialium aubrevillei</i> F.Pellegrin.	Fabaceae	UG		-	1	-
<i>Entandrophragma angolense</i> (Welw.) C. DC.	Meliaceae	-	NT	2	2	2
<i>Entandrophragma utile</i> (Dawe & Sprague) Sprague	Meliaceae	-	VU	-	1	-
<i>Irvingia gabonensis</i> Aubry Lecomte	Irvingiaceae	-	NT	-	1	-
<i>Lophira alata</i> Banks ex C.F.Gaertn (Ambé)	Ochnaceae	-	VU	3	6	2
<i>Milicia excelsa</i> (Welw.) C.C. Berg	Moraceae	-	NT	-	2	-
<i>Milicia regia</i> (A. Chev.) C.C. Berg	Moraceae	UG	VU	1	-	-
<i>Sterculia oblonga</i> Mast (Eyong)	Malvaceae	-	VU	-	2	1

Note: NT is Near Threatened, VU is vulnerable species.

Table 3. Average diversity index values.

Ecosystem	Shannon index	Simpson index	Pielou's index
Old-growth forest	0.75 ±0.38 ^a	0.48 ±0.23 ^a	0.83 ±0.37 ^a
Secondary forests	0.63 ±0.47 ^a	0.40 ±0.27 ^a	0.67 ±0.44 ^a
Crop-fallow mosaic	0.39 ±0.78 ^a	0.23 ±0.34 ^a	0.37 ±0.51 ^a
<i>p</i> -value	0.22	0.28	0.36

Note: Values within the same column sharing the same letter are not significantly different ($p > 0.05$).

**Fig. 3. Species similarity among the three ecosystems.**

Note: The figure shows the number of species of trees with DBH > 0.70 m.

AGP biomass and carbon stock in mega-trees

These indicators of mega-trees in OGF are significantly higher than those in SF and CFM (Table 4). The latter two ecosystem types are similar in terms of these calculated parameters.

Spatial distribution of mega-trees in Azagny National Park

The 154 georeferenced mega-trees and their basal areas were projected onto a map of the ANP (Fig. 5). OGF were found to have highest tree density (bas-

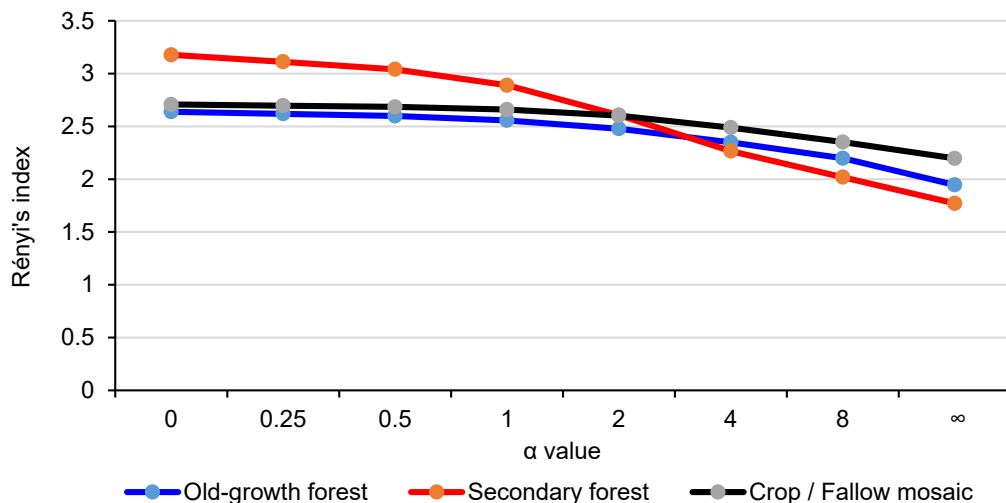


Fig. 4. Comparison of ecosystems using Rényi's diversity profile.

Table 4. Average values for total biomass and average carbon stock for the ecosystems studied.

Ecosystem	Number of individuals per ha	Density, m ² ·ha	Average total biomass, t·ha ⁻¹	Average carbon stock, tC·ha ⁻¹
OGF	10	11.20	125.79 ±76.29 ^b	15.72 ±9.53 ^b
SF	9	8.31	65.90 ±59.69 ^a	8.23 ±7.46 ^a
CFM	6	6.8	63.47 ±57.57 ^a	7.93 ±7.18 ^a
<i>p</i> -value			0.007	0.007

Note: Values within the same column sharing the same letter are not significantly different ($p > 0.05$).

al area $G = 11.20 \text{ m}^2 \cdot \text{ha}^{-1}$). Mosaics had 42 mega-trees recorded, followed by SF ($G = 8.61 \text{ m}^2 \cdot \text{ha}^{-1}$) with 91 individuals recorded. The CFM were the least dense, with 21 mega-trees for a basal area of $6.8 \text{ m}^2 \cdot \text{ha}^{-1}$. It should be noted that the distribution of mega-trees in the three types of vegetation (figs 6, 7 and 8) highlights the importance of taking into account both the density and the diameter of trees when assessing the structure of a forest (Table 4).

Prediction of mega-trees using IDW interpolation

The results of the predictive map of the distribution of mega-trees obtained by IDW show a high probability of the presence of large-diameter individuals ($> 125 \text{ cm}$) in the central-northern and north-western parts of the park. In contrast, mega-trees with a DBH between 70 and 98 cm is high in the eastern, northern and south-western parts of the park. Furthermore, IDW predicts a

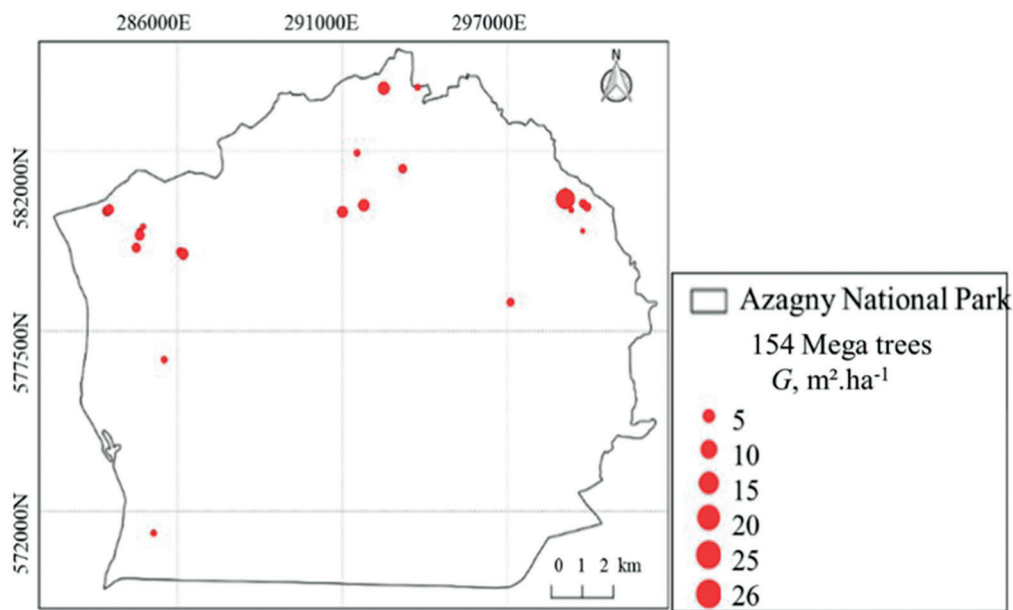


Fig. 5. Representation of mega-trees across land areas in Azagny National Park.

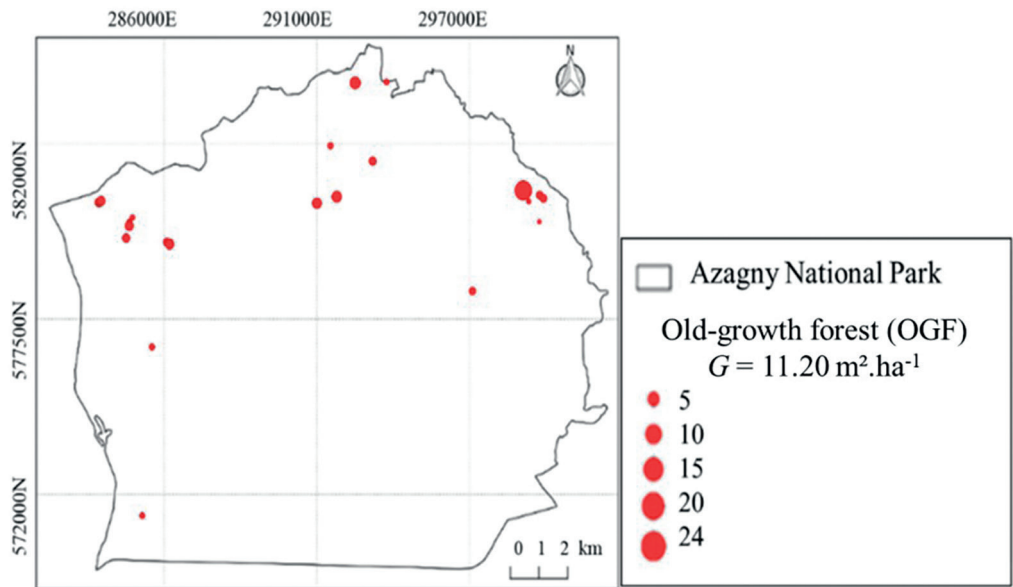


Fig. 6. Distribution of mega-trees in the old-growth forest.

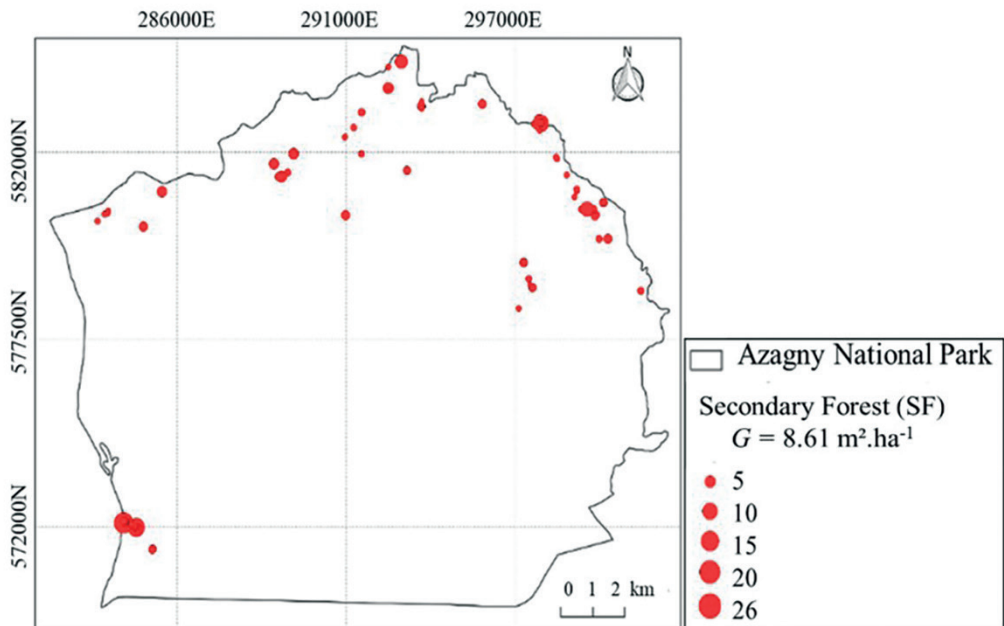


Fig. 7. Distribution of mega-trees in the secondary forest.

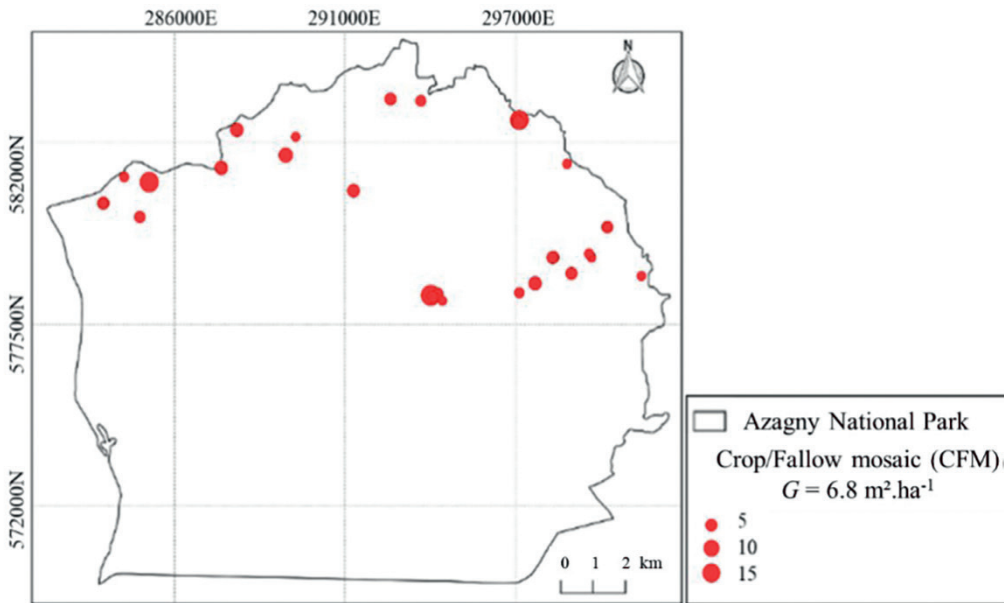


Fig. 8. Distribution of mega-trees in the crop-fallow mosaic.

wider distribution of mega-trees with DBH between 98 and 125 cm in the southern and central parts of the park. Overlaying the land cover map with the IDW results reveals a high probability that large-diam-

eter individuals (> 125 cm) will be found mainly in OGF. Conversely, mega-trees with a DBH of between 70 and 98 cm occur mainly in SF, CFM, and other ecosystems dominated by savannah? (Fig. 9).

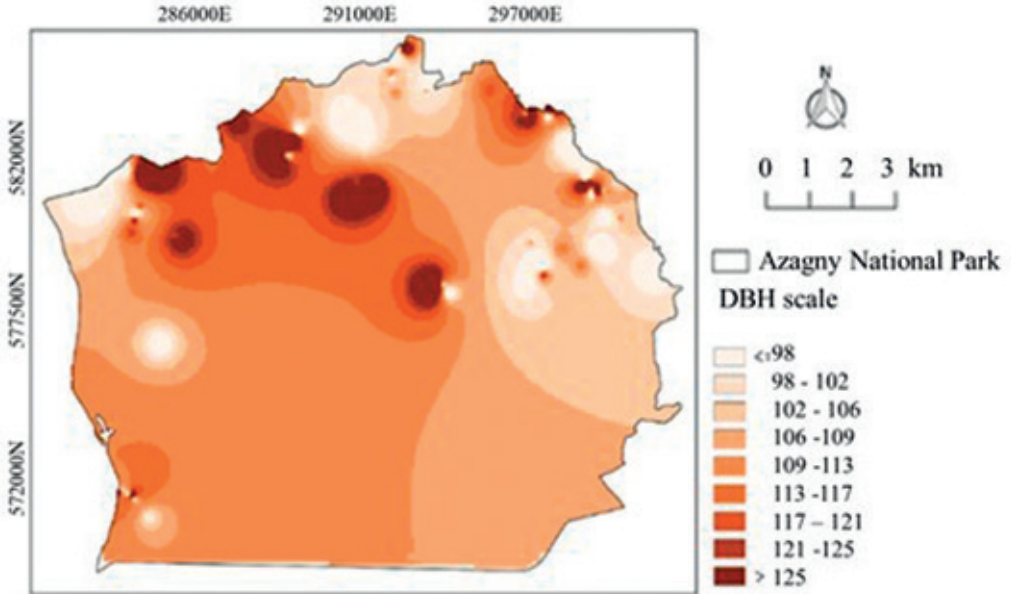


Fig. 9. Distribution map of mega-tree zones according to tree diameter classes.

Discussion

Diversity of mega-trees

This study identified 49 species with a high diversity in OGF compared with the other two types of vegetation. The low floristic diversity of mega-trees in SF can be explained by the existence of many pioneer species (Adou Yao 2005) thus causing strong competition for light because it is considered the main source of competition (Grime 1979). Competition will thus lead to growth in height at the expense of diameter, hence the low diversity of mega-trees in this biotope. Fallow lands, composed of a succession of trees and abandoned oil palm, cocoa and cof-

fee plantations, exhibit moderate diversity, as some trees were preserved during the occupation period for their uses, their economic and social values (Adou Yao and N'Guessan 2006). However, these differences are not significant, unlike the work of de Vroh (Vroh et al. 2017), whose research results showed that species diversity was significantly higher in OGF. This could be explained by the fact that mega-trees represent only 3 % of the population of a plant formation, as shown by the work of Slik et al. (2013).

The low floristic similarity of mega-trees across the different vegetation types in Azagny National Park can be explained by several factors. OGF, as mentioned by van Gernerden (2004) in Central African

tropical forest, like in the Guinean forests of West Africa hotspot a rich diversity of species adapted to specific ecological conditions established over long periods without disturbance. In contrast, secondary forests, which arise following disturbance, show increasing biodiversity with age, but generally include species and fewer mega-trees. CFM, often influenced by agricultural practices, have a less varied flora, dominated by cultivated species. These differences in plant succession and historical adaptations help to explain the low floristic similarity observed between these types of vegetation. In addition to the above explanations, other local conditions may therefore be more important in the variation in species diversity. For example, topography and soil quality.

As far as special-status species are concerned, their presence, number and diversity underline the importance of the role played by the protected area studied in the conservation of biodiversity, as indicated by the work of Adou Yao and Rousset (2007). These authors emphasise that such a presence is one of the important elements to be taken into account when qualifying an area as a 'West African Guinean forest hotspot'. Indeed, of the 49 species recorded, five are considered vulnerable according to IUCN Red List (2023).

Mega-trees and total plant biomass

The AGB of mega-trees in the various ecosystems of Azagny National Park is estimated at $319.06 \text{ t}\cdot\text{ha}^{-1}$, i.e. $159.53 \text{ tC}\cdot\text{ha}^{-1}$ of stored carbon. These results represent over 90 % of the average carbon stock of forests in Côte d'Ivoire estimated at $177 \text{ tC}\cdot\text{ha}^{-1}$ (World Health Organization 2011) and almost half of those obtained in Banco National Park ($\text{AGB} = 742.76 \text{ t}\cdot\text{ha}^{-1}$ and $\text{Stk C} = 371.38 \text{ tC}\cdot\text{ha}^{-1}$) during the

study conducted by Bakayoko (2013). This difference in the results of the current study and the latter can be explained by variations in the evaluation criteria. Indeed, the present study focused on a relatively restricted category of trees (mega-trees $\text{DBH} \geq 70 \text{ cm}$), which represents a tiny part of the flora of Azagny National Park. By contrast, the previous study carried out in the Banco National Park broadened its scope of analysis to include all woody individuals with a DBH of at least 25 cm. In other words, mega-trees, although representing a small proportion of the trees in a forest, store more than half of the biomass of those forests and, by extension, the carbon sequestered by them.

From OGF to mosaics of crops and fallow lands, there was a noticeable decline in the AGB from mega-trees. This can be explained by the fact that OGF contain mature trees that have had decades, even centuries, to grow in size and mass. The older a tree is, the more carbon it stores in its wood, roots and leaves. Due to their complexity, maturity and ecological balance, OGF represent greater reservoirs of biodiversity and carbon than fallow and secondary forests. The strong increase in carbon storage with increasing tree diameter testifies to the importance of preserving large, mature and old trees to keep this stored carbon in the forest ecosystem where it remains for centuries (Law and Deng 2018, Lutz et al. 2018). Once trees reach a large size, each additional increment of DBH leads to a significant increase in the total carbon stocks in the tree, whereas small diameter trees do not lead to significant carbon gains. These observations are consistent with those of Dubé and Sénécal (2006), who claim that the high AGB obtained in OGF is linked to DBH and the specific density of the wood in the trees. According to these authors,

the larger the diameter of a tree is, the higher is its carbon sequestration capacity.

Conclusion

This paper studied the diversity and biomass of mega-trees in three types of vegetation (OGF, SF and CFM) of Azagny National Park. Across all the sampled vegetation types, 49 species of mega-tree were identified. Of these, 10 species have a special conservation status, including two that are endemic to the Upper Guinea forest block and eight that are listed as vulnerable or Near Threatened in IUCN Red List. The old-growth forests, generally located at the extremities of the park, are the most diverse and the richest in species. The secondary forests and the mosaics of crops and fallow land, although relatively stable, are less favourable for the establishment of most mega-tree species. This study also highlights the remarkable carbon sequestration capacity of this protected area through the high level of carbon stored by mega-trees in old-growth forests. In addition, the spatial distribution of mega-trees, with a prevalence of large-diameter individuals in most old-growth forests, enriches our understanding of forest structure. This highlights the importance of incorporating both tree density and diameter into ecological assessments. These results suggest that Azagny National Park not only fulfils a crucial role in biodiversity conservation, but also has significant potential to mitigate the effects of climate change through its capacity to store carbon via mega-trees.

Acknowledgements

The authors would like to express their gratitude to the Ivoirian Office of Parks and reserves for data collection, to the

Swiss Centre for Scientific Research for support, to the Foundation of Parks and Reserves for their financing, to the Doctoral School Environment Biology Health and BioValSE members for their assistance, and to the local communities of the Azagny National Park who contributed to the data collection and analysis process.

Disclosure statement

No potential conflicts of interest have been reported by the authors.

Financing

This work was financed by the Foundation of Parks and Reserves through the Endowment Fund set up to finance the activities of Azagny National Park.

Authors' contributions

Conceptualisation: HB, AYC; Data collection: HB, KV, AD, NKE; Data analysis: AN, KV; Writing – preparation of the original version: HB, AYC, ANEJ, KV; Writing – revision and modification: HB, AYC, ANEJ; Acquisition of funding: FPRCI; All authors have read and approved the final version of the manuscript.

Declaration on data availability

To protect the confidentiality of respondents, data is available on request from the corresponding author.

References

- ABROU J.E.N.G., KOUAMÉ D., YAO C.Y.A. 2019. Floristic diversity of plant communities in the Forêt des Marais Tanoé-Ehy (FMTE) area, south-eastern Côte d'Ivoire.

- ire. *International Journal of Biological and Chemical Sciences* 13(6): 2874–2887. <https://doi.org/10.4314/ijbcs.v13i6.35>
- ADOU YAO C.Y. 2005. Farming practices and biodiversity dynamics in the Monogaga classified forest (Côte d'Ivoire). PhD thesis, Département Homme Nature et Société, MNHN University, Paris, France. 233 p.
- ADOU YAO C.Y., N'GUESSAN K.E. 2006. Diversité floristique spontanée des plantations de Cacao et de Café dans la forêt classée de Monogaga (Côte d'Ivoire). *Agris* 157: 31–36. doi: 10.3188/szf.2006.0031
- ADOU YAO C.Y., ROUSSEL B. 2007. Forest management, farmers' practices and biodiversity conservation in the Monogaga protected coastal forest in Southwest Cote d'Ivoire. *Africa* 77(1): 63–85. <https://doi.org/10.3366/afr.2007.77.1.63>
- AMARA R. 2010. Impact of human activities on biodiversity and the functioning of marine ecosystems. Example of the Channel-North Sea. *VertigO – la revue électronique en sciences de l'environnement, Hors-série* 8. 13 p. <https://doi.org/10.4000/vertigo.10129>
- BAKAYOKO O. 2013. Etude d'estimation du stock de carbone et du potentiel de sequestration du Parc National du Banco. OIPR-PNUE. 70 p.
- BASTIN J.-F., RUTISHAUSER E.J.R., SAATCHI S., PÉLESSIER R., HÉRAULT B. 2018. Pan tropical prediction of forest structure from the largest trees. *Global Ecology and Biogeography* 27(11): 1366–1383. <https://doi.org/10.1111/geb.12803>
- BIOINFORMATICS & EVOLUTIONARY GENOMICS 2025. Calculate and draw custom Venn diagrams. VIB / UGent Bioinformatics & Evolutionary Genomics. Available at: <http://bioinformatics.psb.ugent.be/webtools/Venn/>
- CHAVE J., RÉJOU-MÉCHAIN M., BÚRQUEZ A., CHIDUMAYO E., COLGAN M.S., DELITTI W.B., VIEILLEDENT G. 2014. Improved allometric models to estimate the aboveground biomass of tropical trees. *Global Change Biology* 20(10): 3177–3190. <https://doi.org/10.1111/gcb.12629>
- CLARK D.B., CLARK D.A. 1996. Abundance, growth and mortality of very large trees in Neotropical lowland rain forest. *Forest Ecology and Management* 80(1–3): 235–244. [https://doi.org/10.1016/0378-1127\(95\)03607-5](https://doi.org/10.1016/0378-1127(95)03607-5)
- CUNY P., PLANCHERON F., ABRAHAM B.I.O., KOUAKOU E., MORNEAU F. 2023. La forêt et la faune de Côte d'Ivoire dans une situation alarmante-Synthèse des résultats de l'Inventaire forestier et faunique national. *Bois & Forêts des Tropiques* 355: 47–72. <https://doi.org/10.19182/bft2023.355.a36939>
- DUBÉ A.D.S.L., SÉNÉCAL G. 2006. Penser le renouvellement des politiques de conservation de la forêt urbaine à l'ère du réchauffement climatique. Institut National de Recherche Scientifique-Urbanisation, culture et société. 51 p.
- GIEC 2006. Guide pour l'inventaire national des gaz à effet de serre; agriculture, foresterie et autre usage des terres. Institute for Global Environmental Stratégies, vol. 4: 46–52.
- GNAGBO A., KOUAMÉ D., ADOU YAO C.Y. 2016. Diversity of vascular epiphytes in the lower stratum of plant formations in Azagny National Park (Southern Côte d'Ivoire). *Journal of Animal and Plant Sciences* 28(1): 4366–4386.
- GRIME J.P. 1979. Stratégie des plantes et processus de végétation. John Wiley & Sons Ltd. 222 p.
- IUCN 2023. IUCN Red List of Threatened Species. Available at: www.iucnredlist.org
- KINDT R., VAN DAMME P., SIMON A.J. 2006. Tree diversity in western Kenya: Using profiles to characterize richness and evenness. *Biodiversity and Conservation* 15(2006): 1253–1270. <https://doi.org/10.1007/s10531-005-0772-x>
- LAPOLA D.M., PINHO P., BARLOW J., ARAGÃO L.E., BERENGUER E., CARMENTA R., ET AL. 2023. The drivers and impacts of Amazon forest degradation. *Science* 379(6630), eabp8622. doi: 10.1126/science.abp8622
- LAUGINIE F. 2017. Nature conservation and protected areas in Côte d'Ivoire. CE-DA-NEI, Abidjan (Côte d'Ivoire). 668 p.
- LAW H., DENG J. 2018. CornerNet: Detecting objects as paired keypoints. In: Proceedings of the European conference on computer vision (ECCV): 734–750. https://doi.org/10.1007/978-3-04-583486-8_47

- org/10.48550/arXiv.1808.01244
- LUTZ W., STILIANAKIS N., STONAWSKI M., GOUJON A., SAMIR K.C. (Eds) 2018. Demographic and human capital scenarios for the 21st century: 2018 assessment for 201 countries. Publications Office of the European Union. 594 p. <https://data.europa.eu/doi/10.2760/835878>
- NUSBAUMER L., GAUTIER L., CHATELAIN C., SPICHTER R. 2004. Structure et composition floristique de la Forêt Classée du Scio (Côte d'Ivoire): Étude descriptive et comparative. *Candollea* 60(2): 393–443.
- PIELOU E.C. 1986. Assessing the diversity and composition of restored vegetation. *Canadian Journal of Botany* 64(7): 1344–1348. <https://doi.org/10.1139/b86-185>
- PINHO B.X., CARLOS A. PERES C.A., LEAL I.R., TABARELLI M. 2020. Critical role and collapse of tropical mega-trees: A key global resource. Chapter in *Advances in Ecological Research* 62: 253–294. <https://doi.org/10.1016/bs.aecr.2020.01.009>
- PUIG H. 2001. The tropical rainforest. Editions Belin, Paris. 448 p.
- SENTERRE B. 2005. Recherches méthodologiques pour la typologie de la végétation et la phytogéographie des forêts denses d'Afrique tropicale. PhD thesis, Université libre de Bruxelles, Belgium. 343 p.
- SHANNON C.E. 1948. A mathematical theory of communication. *The Bell System Technical Journal* 27(3): 379–423. <https://doi.org/10.1002/j.1538-7305.1948.tb01338.x>
- SIMPSON E.H. 1949. Measurement of Diversity. *Nature* 163, 688. <https://doi.org/10.1038/163688a0>
- SLIK J.W.F., PAOLI G., MCGUIRE K.L., AMARAL I.L., BARROSO J., BASTIAN M., BLANC L., BONGERS F., BOUNDJA P., CLARK C.J., ET AL. 2013. Large trees drive forest aboveground biomass variation in moist lowland forests across the tropics. *Global Ecology and Biogeography* 22(11): 1261–1271. <https://doi.org/10.1111/geb.12092>
- THAMMANU S., MAROD D., HAN H., BHUSAL N., ASANOK L. 2021. The influence of environmental factors on species composition and distribution in a community forest in Northern Thailand. *Journal of Forestry Research* 32(3): 649–662. <https://doi.org/10.1007/s11676-020-01239-y>
- VAN GEMERDEN B.S. 2004. Disturbance, Diversity and Distributions in Central African Rainforest. PhD thesis, Wageningen: Wageningen University. 174 p. <https://doi.org/10.18174/121504>
- VENN J. 1880. On the diagrammatic and mechanical representation of propositions and reasonings. *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science* 10(59): 1–18. <https://doi.org/10.1080/14786448008626877>
- VERMEULEN C., DUBIEZ É., PROCES P., MUKUMARY S.D., YAMBA T.Y., MUTAMBWE S., PELTIER R., MARIEN J.-N., DOUCET J.-L. 2011. Land issues, exploitation of natural resources and local community forests on the outskirts of Kinshasa, DRC. *Biotechnology, Agronomy, Society and Environment* 15(4): 535–544.
- VROH B.T.A., N'GUESSAN K.E., ADOU YAO C.Y. 2017. Tree species diversity in perennial crops around Yapo protected forest, Côte d'Ivoire. *Journal of Horticulture and Forestry* 9(11): 98–108. <https://doi.org/10.5897/JHF2017.0507>
- WORLD HEALTH ORGANIZATION 2011. FAO/OIE/WHO joint scientific consultation on influenza and other emerging zoonotic diseases at the human-animal interface, 27–29 April 2010, Verona, Italy: consultation summary 2010. World Health Organization. 53 p. <https://iris.who.int/handle/10665/44591>
- WORLD WILDLIFE FUND 2020. Living Planet Report 2020 – Bending the curve of biodiversity loss. 164 p.
- ZANNE A.E., LOPEZ-GONZALEZ G., COOMES D.A., ILIC J., JANSEN S., LEWIS S., MILLER R.B., SWENSON N.G., WIEMANN M.C., CHAVE J. 2009. Global wood density database. Dryad Digital Repository. <http://hdl.handle.net/10255/dryad.235>

A study of adaptive potential and aesthetic impact of Floribunda and Grandiflora rose cultivars in urban landscape in Suhareka, Kosovo: An investigation of vegetative growth and remontant flowering

Nexhat Balaj^{ib}, Vezir Januzi^{ib}, and Hyzer Rizani^{ib}

Faculty of Agriculture and Environment Engineering, University for Business and Technology (UBT), 56 Rexhep Krasniqi Str., 56 Prishtina, Kosovo. E-mail: vezir.januzi@ubt-uni.net

Received: 25 April 2025 / Accepted: 02 July 2025 / Available online: 15 July 2025



Open Access: This work is distributed under the Creative Commons Attribution 4.0 License.

Abstract

The rose species and cultivars are considered one of the most valued ornamental shrubs in urban landscape design due to its aesthetic role, positive impact on biodiversity enhancement, high adaptability to various climatic and environmental conditions. The aim of this study is to evaluate the vegetative growth and flowering stage of selected Floribunda and Grandiflora rose cultivars and to assess their adaptive potential and aesthetic impact within urban environments in Suhareka, Kosovo. Ten rose cultivars – eight Floribunda ('Angel Face', 'Sunsprite', 'Amber Queen', 'Bonica 82', 'English Miss', 'Scentimental', 'Betty Boop' and 'Iceberg') and two Grandiflora ('Queen Elizabeth' and 'Love's Promise') – were analysed under the climatic conditions of Kosovo. The most intensive flowering stage occurred in June, with the 'Queen Elizabeth' cultivar producing an average of 35 flowers per plant, followed by the 'Love's Promise' cultivar with 34 flowers per plant. The lowest number of flowers was recorded in the 'Angel Face' cultivar, with 22 flowers per plant, and in the 'Bonica 82' cultivar, with 23 flowers per plant. The cultivars 'Queen Elizabeth' and 'Sunsprite' demonstrated best performance under climatic and environmental conditions of Kosovo. The Grandiflora group of roses blooms more abundantly, which is proven by the effect of additional hybridizations that have been made between hybrid tea roses and the Floribunda group.

Key words: flowering period, growth characteristics, modern roses, urban environments.

Introduction

The use of roses in urban green spaces is primarily guided by their quality and growth characteristics, including flower colour, stem length and diameter, and the continuity of flowering throughout the summer (Godin et al. 1999). A well-designed land-

scape with rose plants contributes to an extended flowering period (reblooming) throughout the summer, accompanied by the continuous development of flower stalks (Crespel et al. 2014). The diversity of flower forms, prolonged and remontant blooming, as well as the wide range of colours and scent, which vary not only

among cultivars but also during different flowering stages, make roses a key ornamental element in the design of parks, flower gardens, and urban environments (Dinga 1998).

The rose is one of the most popular plants among ornamental species in Kosovo, widely used for decorating gardens, parks and vases, as well as for flowers in bouquets (Balaj et al. 2022). Among the most commonly cultivated rose varieties in public green spaces in Kosovo are the following cultivars: 'Double Delight', 'Cristofor Colombo', 'Vaj Vecend', 'Princesse de Monaco', 'Norita', 'Charles de Gaulle', 'Maria Callas', and 'Eiffel Tower'.

Rose flowers can appear singly on a flower stalk or in clusters of 3–25 flowers. The plant blooms once in summer or repeats flowering throughout the summer-reblooming, which is a key feature of modern roses.

Roses are generally classified into two main categories: ancient (or antique) roses, which include varieties cultivated before 1867, and modern roses, which comprise those developed after that year. Modern roses are the result of crossbreeding among European, Chinese, Tea, and Mediterranean rose species, as well as the natural variability observed among rose types during the 18th and 19th centuries. Particularly valued by humans is their ability to bloom continuously or repeatedly throughout the summer (remontant flowering) and their resistance to adverse environmental conditions (American Rose Society 2014).

Floribunda roses are a type of modern garden roses, known for their exceptional adaptability, extended flowering season, and aesthetic appeal, making them an excellent choice for enhancing the beauty and ecological value of urban green spaces. Their flowers may appear singly

or in clusters, exhibiting a wide range of colours and a strong, fine fragrance.

Grandiflora roses are relatively new hybrids resulting from the crossbreeding of hybrid tea roses and Floribunda roses and belong to the group of modern garden roses, known for their ease of cultivation and extended flowering period, characterized by repeated blooming throughout the summer (Cervelli and Paoli 2003). These roses typically initiate blooming with a single flower, followed by successive blooms that create a visually striking effect in green spaces (Blechert and Debenner 2005). The first cultivar of this group, 'Queen Elizabeth', was a pink rose with a notable fragrance.

Today, Grandiflora and Floribunda roses are commonly found in urban parks in diverse colours, with many retaining the characteristic fragrance inherited from their Hybrid Tea parentage (Van de Pol and Pierik 1995).

According to Zieslin (1992), roses are capable of blooming independently on each stem once it reaches a specific length. Research also shows that plant architecture significantly affects both number of flowers per plant and duration of flowering stage (Shimelis and Shiringani 2010). Numerous studies indicate that the performance of roses in landscape design varies according to the cultivar, environmental conditions, and climatic factors (Nadeem et al. 2011). Furthermore, flower production and quality are influenced by the choice of cultivar, cultivation practices, and the type of rootstock used (Cabrera 2002).

The purpose of this study is to evaluate the vegetative growth and flowering stage of selected Floribunda and Grandiflora rose cultivars and to assess their adaptive potential and aesthetic impact within urban environments in Suhareka, Kosovo.

Materials and Methods

The study was conducted in the urban green space 'City Park', located in Suhareka, Republic of Kosovo, over two growing seasons from May 2023 to October 2024, on area of 2500 m² (Fig. 1).

Kosovo is located in the central part of the Balkans. It lies between 41°50'58" and 43°51'42" of northern geographic latitude and between 20°01'3" and 21°48'02" of longitude.

The average monthly temperature during the growing period was in April (13.1 °C), May (16.3 °C), June (20.7 °C), July (24.1 °C), August (22.3 °C) and in September the average temperature was 17.3 °C. The precipitation amount during the growing period was 26.4 mm in April, 79.0 mm in May, 81.0 mm in June, 71.0 mm in July, 55.2 mm in August and in September the average of precipitation was 21.3 mm (HMIK 2023).

In this study, eight Floribunda rose

cultivars – 'Angel Face', 'Sunsprite', 'Amber Queen', 'Bonica 82', 'English Miss', 'Scentimental', 'Betty Boop', and 'Iceberg' – along with two Grandiflora rose cultivars – 'Queen Elizabeth' and 'Love's Promise' – were analysed under the climatic conditions of Kosovo.

The seedlings were produced using the budding method with T-bud grafts, which was performed in August 2021 on rootstock of *Rosa canina* var. Laxa.

The age of the planted plants at the beginning of the experiment was two years. The plants were planted in green spaces with a spacing of 40 cm between individual plants and 100 cm between rows. The experiment was 'Randomized block' type with four replications and 150 plants for each cultivar.

The plants were planted in sandy soil and irrigated during the growth period by drip irrigation system.

During the spring season, field-grown roses were managed using an integrat-

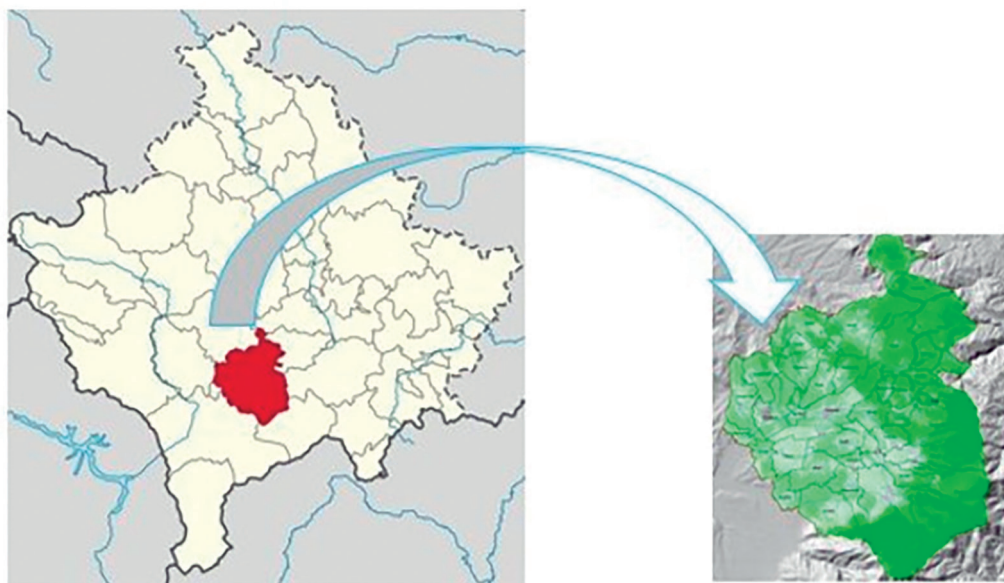


Fig 1. Location of study, Suhareka, Kosovo.

ed fertilization strategy, comprising both organic and mineral fertilizers, applied in accordance with the physiological requirements of the plant at each developmental stage.

In March, well-decomposed organic manure was applied at a rate of 2–3 kg per plant, aiming to improve soil structure, enhance water-holding capacity, and support microbiological activity in the rhizosphere. During the vegetative growth stage (April), ammonium nitrate was applied at a dose of 20–25 g per plant as a source of nitrogen in both ammonium and nitrate forms.

During the flowering stage (May), two key mineral fertilizers were applied: single superphosphate at a dose of 30 g per plant, served as a soluble source of phosphorus to support root development and stimulate flowering.

Potassium sulphate at a dose of 20 g per plant was applied to improve nutrient translocation, enhance the visual and aromatic qualities of flowers, and strengthen plants' resilience against both biotic and abiotic stressors. At the end of June, the spring fertilisation cycle for roses was concluded, having met the plants' nutritional requirements during the key stages of phenological development.

During the growing season, the following parameters were measured: dynamics of the flowering stages, remontant flowering, development stages of rose flowers, diameter of fully opened flowers, number of petals per flower, colour and fragrance, number of flower stalks 50 cm above ground level, diameter of flower stalks, number of leaves per shoots, and density of thorns in 15 cm length per shoot.

For all data, an analysis of variance (ANOVA) was applied using the statistical package, Systat, Genstat, further analysed using rang test with a critical level (P -val-

ue) of 5 % (Gomez and Gomez 1984).

Results and Discussion

Flowering stage of Floribunda and Grandiflora rose cultivars

The results indicate that the flowering stage begins in mid-May, with 1.5 to 2.5 flowers per plant, depending on the cultivar. The most intensive flowering stage occurred in June, with 35 flowers per plant in the 'Queen Elizabeth' cultivar, followed by the 'Loves Promise' cultivar with 34 flowers per plant. The lowest number of flowers was recorded in the 'Angel Face' cultivar with 22 flowers per plant. The other cultivars in the study had the following flower numbers: 'Amber Queen' with 31 flowers per plant, 'Iceberg' with 27 flowers per plant, 'English Miss' with 25 flowers per plant, and 'Betty Boop' with 26 flowers per plant (Fig. 2).

The standard error of the mean ($\pm$ SE) for the number of flowers per plant in the rose cultivars evaluated in this study is as follows: the mean number of flowers per plant was 28.6, with a standard deviation (SD) of 4.74 and a standard error of the mean ($\pm$ SE) of 1.5 flowers. These results indicate that the average number of flowers produced per plant during the growing season (May to October) is associated with a standard error of ± 1.5 flowers.

In July, the highest flower count was observed in the 'Sunsprite' cultivar with 34 flowers per plant, followed by 'Queen Elizabeth' with 25. The lowest number of flowers per plant was recorded in the 'Bonica 82' cultivar with 12, followed by 'Angel Face' with 19, and 'Betty Boop' with 20. During August, the 'Amber Queen' cultivar had the highest flower count, with 20 flowers per plant, followed by 'Sunsprite'

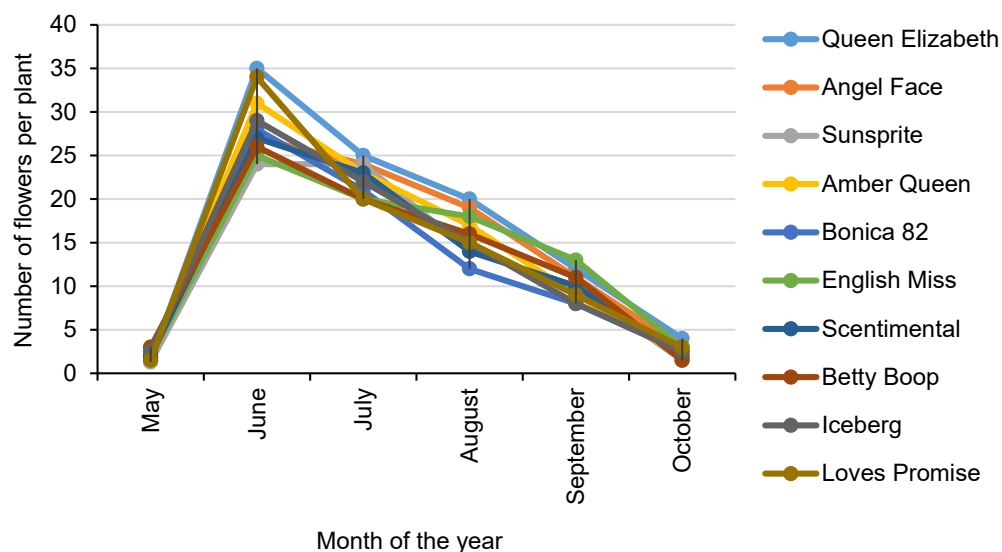


Fig. 2. Flowering stage of Floribunda and Grandiflora rose cultivars.

with 14. The lowest counts were observed in the 'Bonica 82' cultivar with 10 flowers, 'Loves Promise' with 15, and 'Scentimental' with 14 flowers per plant. The lowest number was recorded in the 'Iceberg' cultivar with 8 flowers, while the highest was observed in the 'Scentimental' cultivar with 15 flowers per plant. This decreasing trend continued in October and varied by cultivar. The lowest flower count was found in the 'Betty Boop' cultivar with 1.5 flowers per plant, followed by 'Amber Queen' with 2, and 'Queen Elizabeth' with 4 flowers per plant.

Similar results concerning the number of flowers per plant were reported by Pes-sala (1977), Parkinson (2003), and Crespel et al. (2014). Regarding the flowering stage in Grandiflora rose cultivars, similar findings were reported by Manjula (2005).

Remontant flowering of Floribunda and Grandiflora rose cultivars

The analysis revealed that, during spring, the flowering period is longer, ranging

from 24 to 30 days, depending on the cultivar. In this period, flowers exhibit more vibrant colours and a higher number of blooms per plant. In contrast, during summer, the duration of the flowering succession is shorter between 10 and 16 days and the flower colours tend to be lighter. In autumn, the flowering phase lasts from 19 to 24 days, depending on the cultivar.

These seasonal differences are mainly attributed to variations in temperature, daylight duration, and plant water availability, which significantly influence the physiological processes of flowering (Fig.3).

The results of the study on the repeat flowering of rose cultivars are consistent with the findings of other authors Varies and Dubois (1990), Zieslin (1992), Kool and Van de Pol (1993). Similar results were reported by Dubois and Varies (1993) regarding the flowering stage and the influence of climatic factors in roses cultivars.

The statistical results for the two-year period (2023–2024) are presented in Table

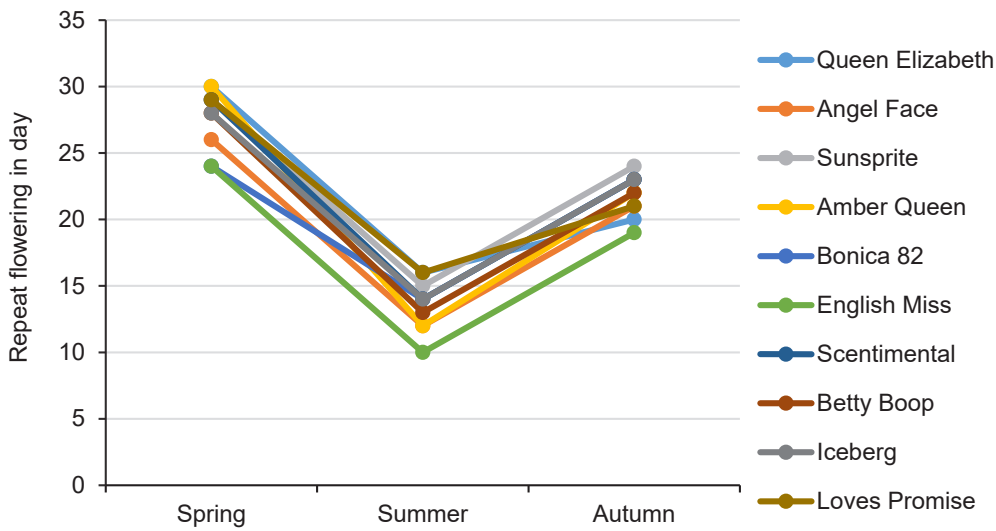


Fig. 3. Remontant flowering in Floribunda and Grandiflora rose cultivars.

1. The analysis of variance indicates that there are statistically significant differences among the Floribunda and Grandiflora rose cultivars in terms of repeat flowering and the diameter of fully opened flowers.

The statistical results for the two years

(2023–2024) are presented in Table 2. The analysis of variance confirms that there are statistically significant differences regarding the flower diameter and the number of flowers per plant of Floribunda and Grandiflora rose cultivars.

Table 1. Analysis of variance for remontant flowering and diameter of fully opened flowers in Floribunda and Grandiflora rose cultivars.

Source of variation	Flowering succession		Diameter of fully opened flower	
	F-value	p-value	F-value	p-value
Year of study	2843.21	0.001	1121.46	0.001
Cultivar	375.67	0.001	1545.24	0.001
Cultivar × Year	12.23	0.001	34.26	0.001

Table 2. Analysis of variance for flower diameter and number of flowers per plant in Floribunda and Grandiflora rose cultivars.

Source of variation	Flower diameter		Number of flowers per plant	
	F-value	p-value	F-value	p-value
Year of study	0.25	0.001	0.31	0.001
Cultivar	208.21	0.001	301.56	0.001
Cultivar × Year	5.21	0.001	4.65	0.001

Developmental stages of flowers in Floribunda and Grandiflora rose cultivars

Seven developmental stages of rose flowers were identified, presented in Figure 4: F1 – unopened bud stage, F2 – semi opened stage, F3 – fully opened stage, F4 – initial bloom stage, F5 – full bloom stage, F6 – bloomed stage, F7 – senescent stage.

These stages are important for evaluating the aesthetic and agronomic performance of the cultivars under urban conditions, as well as for the optimal maintenance planning of green spaces.

Diameter of fully opened flowers of Floribunda and Grandiflora rose cultivars

The maximum diameter of fully opened flowers was recorded in the 'Amber Queen' cultivar, with 12.5 cm, followed by 'Loves Promise' with 11.5 cm. The minimum diameter was recorded in the 'Betty Boop' cultivar, with 5.5 cm (Fig. 5).

The standard error of the mean ($\pm$ SE) for the diameter of fully opened flowers in the rose cultivars included in this study is as follows: the mean flower diameter was 9.4 cm, with a standard deviation (SD) of 1.5 cm and a standard error of the mean

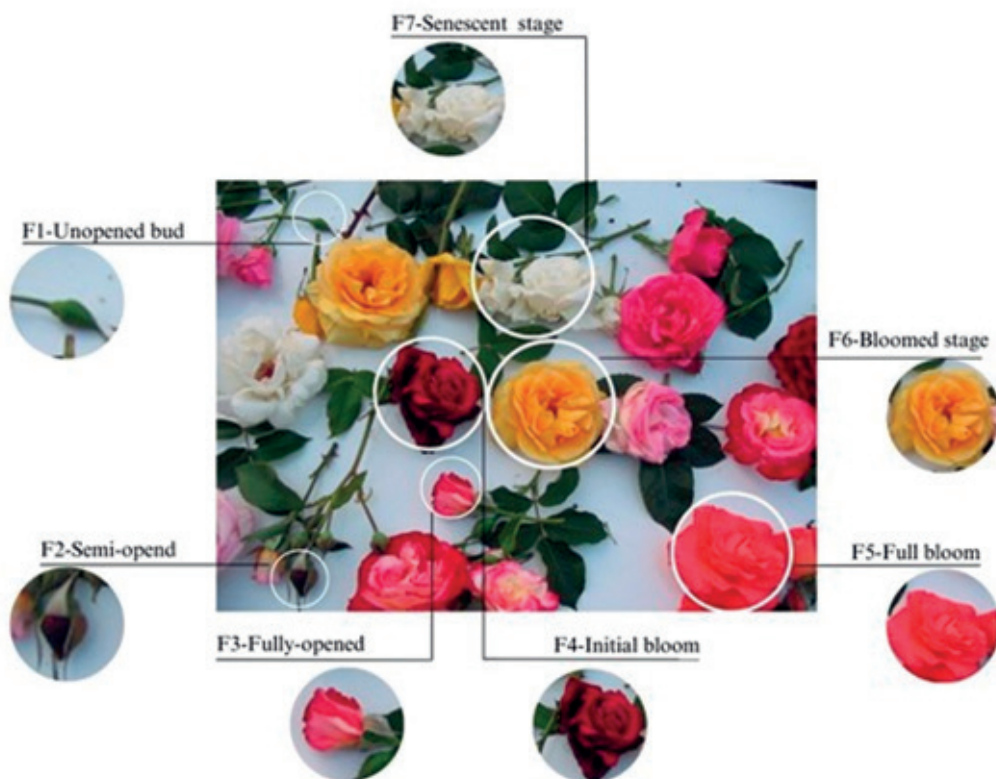
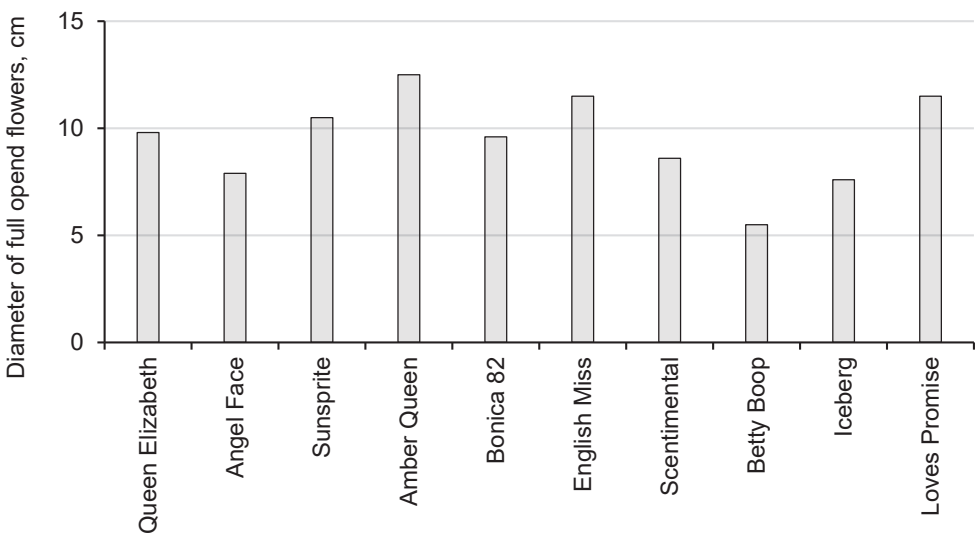


Fig. 4. Seven developmental stages of flowers in Floribunda and Grandiflora rose cultivars.



Floribunda and Grandiflora rose cultivars

Fig. 5. Diameter of fully opened flowers of Floribunda and Grandiflora rose cultivars.

($\pm$ SE) of 0.5 cm. These results indicate that the average diameter of fully opened flowers is associated with a standard error of $\pm$ 0.5 cm.

Number of petals per flower, flower colour, and fragrance of Floribunda and Grandiflora rose cultivars

Table 3 presents the number of petals per flower, flower colour, and fragrance

level of the Floribunda and Grandiflora rose cultivars. The highest number of petals was observed in the ‘Bonica 82’ cultivar (35.55), followed by ‘Amber Queen’ (34.35), whereas the lowest number was recorded in ‘Betty Boop’ (10.21). The flower colours among the cultivars ranged from white, yellow, and red to pink and pink-white, contributing to the visual appeal of landscape and park settings. Cultivars exhibiting a strong fragrance included

Table 3. Number of petals per flower, flower colour, and fragrance level in Floribunda and Grandiflora rose cultivars.

Cultivars of <i>Rosa hybrida</i> L.	Number of petals per flower	Flower colour	Fragrance level
Queen Elizabeth	33.15	Clear pink	Light fragrance
Angel Face	30.21	Pink	Very fragrance
Sunsprite	33.23	Yellow	Very fragrance
Amber Queen	34.35	Amber	Mild fragrance
Bonica 82	35.55	Pink	Neutral fragrance
English Miss	30.21	Light pink	Moderate
Scentimental	29.23	Pink	Sweet fragrance
Betty Boop	10.21	Red	Strong fragrance
Iceberg	28.23	White	Little fragrance
Loves Promise	29.23	White	Strong fragrance

'Queen Elizabeth', 'Angel Face', 'Amber Queen', 'Bonica 82', 'English Miss', 'Sentimental', 'Betty Boop', and 'Vaj Vicend'.

Growth in length of flower stalks in Floribunda and Grandiflora rose cultivars

The growth of the flower stalks follows a dynamic pattern, characterized by vigorous elongation during the early stages until the end of June, when the main shoot terminates in a flower. Following the initial bloom, branching begins, with the development of secondary and tertiary shoots, each also ending in flowers. The study confirmed significant differences among the cultivars. The longest flower stalk was recorded in the 'Amber Queen' cultivar (117 cm), followed by 'Queen Elizabeth' (114 cm), while the shortest was observed in the 'English Miss' cultivar (98 cm). Plant height is a cultivar-specific trait and varies between different rose cultivars (Fig. 6).

The results of the study on the growth in length of the flower stalks of rose cultivars are also consistent with studies by other authors (Zieslin and Mor 1990).

The standard error of the mean ($\pm$ SE) for the length of the flower stalks, based on the rose cultivars included in this study, is as follows: the mean flower stalk length was 93.1 cm, with a standard deviation (SD) 8.5 cm and a standard error of the mean ($\pm$ SE) 2.3 cm. These results indicate that the average length of 93.1 cm is associated with a standard error of ± 2.3 cm.

Number of flower stalks per plant, flower stalk diameter, number of leaves per shoot, and thorn density

Table 4 presents the number of flower stalks per plant, stalk diameter, number of leaves per shoot, and thorn density in 15 cm length of shoot for the Floribunda and Grandiflora rose cultivars. The highest number of flower stalks per plant was

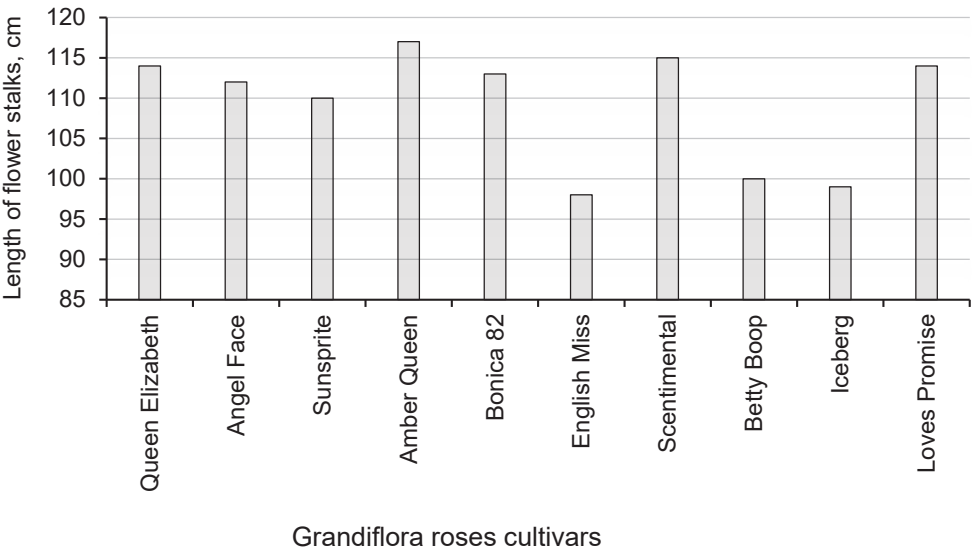


Fig. 6. Growth in length of flower stalks in Floribunda and Grandiflora rose cultivars.

recorded in the ‘Iceberg’ cultivar (8.11), followed by ‘Betty Boop’ (7.88), while the lowest was observed in ‘Scentimental’ (5.11). Regarding stalk diameter, the highest values were recorded in ‘Angel Face’ (9.82 mm), followed by ‘English Miss’ (9.72 mm), whereas the lowest value was observed in ‘Iceberg’ (9.5 mm). The highest number of leaves per shoot was recorded in ‘Queen Elizabeth’ (81.32), followed by ‘English Miss’ (77.45), while ‘Scentimental’ showed the lowest number (55.32). As for thorn density per 15 cm of shoot, the greatest number of thorns was found in ‘Angel Face’ (25.32), followed by

‘Bonica 82’ (23.11), whereas ‘Betty Boop’ recorded the lowest density (13.67).

The statistical results for the two-year period (2023–2024), presented in Table 5, show significant statistical differences regarding the length and diameter of flower stalks of Floribunda and Grandiflora rose cultivars, as confirmed by the analysis of variance. These differences highlight the genetic variability among cultivars in urban environments and landscape projects, where roses that can easily adapt and contribute to the visual beauty and sustainability of green spaces are essential.

Table 4. Average number of flower stalks per plant, flower diameter, number of leaves, and thorn density.

Cultivars of <i>Rosa hybrida</i> L.	Number of flower stalks per plant	Flower stalk diameter, mm	Number of leaves per shoot	Thorn density, per 15 cm of shoots
Queen Elizabeth	6.67	9.45	81.32	24.21
Angel Face	7.33	9.82	66.21	25.32
Sunsprite	6.31	8.81	71.21	20.26
Amber Queen	5.83	8.94	62.32	20.34
Bonica 82	6.54	8.63	68.21	23.11
English Miss	5.56	9.72	77.45	18.23
Scentimental	5.12	7.76	55.32	17.76
Betty Boop	7.88	8.73	70.21	13.67
Iceberg	8.11	9.58	77.29	19.87
Loves Promise	6.56	9.23	75.23	20.34

Table 5. Analysis of variance for flower stalk length and diameter in Floribunda and Grandiflora rose cultivars.

Source of variation	Length of flower stalk		Diameter of flower stalk	
	F-value	p-value	F-value	p-value
Year of study	0.29	0.000	0.42	0.000
Cultivar	221.41	0.000	331.26	0.000
Cultivar x Year	6.44	0.000	4.22	0.000

Conclusions

The long flowering period and significant aesthetic value Floribunda and Grandiflora roses make them ideal for use in urban

green spaces in Kosovo. Their ability to continuously bloom throughout the growing season, accompanied by a wide range of colours, forms, and strong fragrances, makes them perfect for enhancing the vi-

sual and ecological quality of urban environments. Each flower stalk develops and blooms independently once it reaches a certain length, allowing for staggered and continuous flowering. Significant variations were observed among cultivars in relation to succession flowering, fully opened flower diameter, petal count, colour intensity, fragrance, and the number of flower stalks. During spring and autumn, the flowering phase is longer, with brighter colours and a higher number of flowers per plant.

The 'Queen Elizabeth' and 'Sunsprite' cultivars demonstrated the best performance under the climatic and environmental conditions of Kosovo. Given their high ornamental and ecological value, these Floribunda and Grandiflora cultivars are recommended for incorporation into the planning, planting and development of urban green spaces in Kosovo. Their inclusion would not only improve the visual quality of both public and private spaces but also contribute to enriching urban ecosystems, increasing biodiversity, and promoting the overall ecological sustainability of urban environments in Kosovo.

Acknowledgments

We wish to express our sincere gratitude to Prof. Dr. Ljazar Haxhinasto and Prof. Dr. Adem Salillari for their valuable support and guidance throughout the duration of this study.

References

- AMERICAN ROSE SOCIETY 2014. Handbook for Selecting Roses. New York. Published by American Rose Society: 35–35.
BALAJ N., RIZANI H., KAMBERI N., HAXHINASTO

- L. 2022. The effect of rootstock on vegetative development and flower production on modern roses (*Rosa canina* L.). Bulgarian Journal of Agriculture Science 28(3): 395–400.
BLECHERT O., DEBENER T. 2005. Morphological characterization of interaction between *Diplocarpon rosae* and various rose species. Plant Pathology 54(1): 82–90. doi: 10.1111/j.1365-3059.2005.01118.x
CABRERA R.I. 2002. Rose yield, dry matter partitioning and nutrient status response to rootstock selection. Scientia Horticulturae 95(1–2): 75–83. [https://doi.org/10.1016/S0304-4238\(02\)00020-1](https://doi.org/10.1016/S0304-4238(02)00020-1)
CERVELLI C., PAOLI G. 2003. Roses for landscape use: selection criteria and performance. Acta Horticulturae 620: 251–256.
CRESPEL L., LE BRAS C., RELION D., MOREL P. 2014. Genotype × year interaction and broad-sense herability of architectural charactersitics of rose bush. Plant Breeding 133(3): 412–418. <https://doi.org/10.1111/pbr.12157>
DINGA L. 1998. Ornamental plants of the field, Tirana. Albania. Geer: 67–68.
DUBOIS L.A.M., VARIES D.P. 1993. Rozenonderstammen in beweging. Prophyta 5: 117–119.
GODIN C., COSTES E., SINOQUET H. 1999. A method for describing plant architecture which integrates topology and geometry. Annals of Botany 84(3): 343–357. <https://doi.org/10.1006/anbo.1999.0923>
GOMEZ K., GOMEZ A.A. 1984. Statistical procedures for Agricultural Research. 2nd edition. John Wiley and Sons. New York. 680 p.
HMIK (HYDRO METEOROLOGICAL INSTITUTE OF Kosovo) 2023. Hydrometeorological Yearbook of Kosovo. Ministry of Environment and Spatial Planning, Prishtina, Kosovo. 34 p.
KOOL M.T.N., VAN DE POL P.A. 1993. Controlling the plant development of *R. hybrida* 'Motera'. Scientia Horticulturae 53(3): 239–248.
MANJULA G.M. 2005. Performance of rose cultivars under naturally ventilated polyhouse in hillzone. University of Agricultural Sciences, Dharwad, India: 100–101.

- NADEEM M., KHAN M.A., RIAZ A., AHMAD R. 2011. Evaluation of growth and flowering potential of *Rosa hybrida* cultivars under Faisalabad climatic conditions. Pakistan Journal of Agriculture and Sciences 48(4): 283–288.
- PARKINSON H. 2003. Landscaping with Native Plants of the Intermountain Region. Technical Reference No. 1730-3. USDI Bureau of Land Management, Boise, Idaho. 7 p. https://idahonativeplants.org/Guides/cover_p7.pdf
- PESSALA T. 1977. The effect of plant material and plant density on flowering in the 'Baccara' rose variety. Annales Agriculture Fenniae 16(1): 72–79.
- SHIMELIS H., SHIRINGANI R. 2010. Variance components and heritabilities of yield and agronomic traits among cowpea genotypes. Euphytica 176(3): 383–389. doi: 10.1007/s10681-010-0222-z
- VAN DE POL P.A., PIERIK R.L.M. 1995. Newest developments in rose (*Rosa hybrida* L.) propagation. Revista Chapingo 3: 15–22.
- VARIES D.P., DUBOIS L.A.M. 1990. Shoot production of 'Sonia', on hybrid tea rootstock clones of different vigour. Gartenabuwissenschaft 55: 268–271.
- ZIESLIN N. 1992. Regulation of flower formation in rose plants: a reappraisal. Scientia Horticulturae 49(3–4): 305–310. [https://doi.org/10.1016/0304-4238\(92\)90166-A](https://doi.org/10.1016/0304-4238(92)90166-A)
- ZIESLIN N., MOR Y. 1990. Light on roses. A review. Scientia Horticulturae 43(1–2): 1–14. [https://doi.org/10.1016/0304-4238\(90\)90031-9](https://doi.org/10.1016/0304-4238(90)90031-9)

Population dynamics and conservation status of *Salmo labrax* in the Strugarnitsa River, North-Western Bulgaria

Vasil Kolev* and Gradimir Gruychev

Department of Wildlife Management, University of Forestry, 10 St. Kl. Ohridski Blvd., 1797 Sofia, Bulgaria. E-mails: vassilie@abv.bg*, gradi.val@gmail.com

Received: 23 April 2025 / Accepted: 09 July 2025 / Available online: 17 July 2025



Open Access: This work is distributed under the Creative Commons Attribution 4.0 License.

Abstract

This study investigates the population dynamics of river trout (*Salmo labrax*) in the Strugarnitsa River, a protected tributary of the Ogosta River in North-Western Bulgaria. Utilising electrofishing across two transects in winter 2023 and summer 2024, the study assessed abundance, biomass, size structure, and age composition. The calculations were made using the Seber and Le Cren (1967) removal method based on two-pass electrofishing. The objective of the study is to quantify and evaluate the population dynamics of river trout in the Strugarnitsa River. The average trout density was 368 ind.·ha⁻¹, and the biomass was 15.2 kg·ha⁻¹, with a notable 50 % higher abundance in summer compared to the breeding season in November. The population consisted primarily of one- two three-year-old fish, with no zero-year-olds observed in the lower trout zone during summer, suggesting spatial segregation of juveniles. These values are among the lowest reported in Bulgaria, likely due to low summer water flow and water diversion. The absence of stocking and presence of natural reproduction indicate a self-sustaining population, albeit with limited fish production capacity. The findings provide baseline data for future management, recommending minimal exploitation and catch-and-release fishing to maintain population equilibrium.

Key words: population density, biomass, river trout.

Introduction

River trouts are globally valued for recreational fishing and their important role as indicators of mountain river ecosystem health, prompting extensive research to ensure their sustainable management.

Two species of local trout inhabiting mountain rivers were distinguished in

Bulgaria, in recent years. In the Danube and Black Sea catchment areas, both connected to the Black Sea, they are inhabited by *Salmo labrax* Pallas, 1814. In the rivers of the southern part of the country, in the Aegean catchment area, the native trout was assumed to be *Salmo macedonicus* Karaman, 1924 (Kottelat and Freihof 2007). However,

for decades, rivers in Bulgaria have also been stocked with non-native trout, primarily *Salmo trutta fario* Linnaeus, 1758. In the recent past, it was believed that this was the native species of trout in the country. In scientific studies, all trout in the inland rivers of Bulgaria were referred to as *Salmo trutta fario*. In Bulgaria, trout fish have been studied comprehensively to support sustainable management, balancing recreational use with the preservation of montane stream health. Early research by Dikov and Yankov (1985a) laid the foundation for understanding trout population dynamics in Bulgaria, reporting an average density of 192 ind. $\cdot$ ha $^{-1}$ and biomass of 34 kg $\cdot$ ha $^{-1}$ in the Iliina and Rilska rivers of the Rila Mountains. In a comprehensive study, Yankov (1988) expanded this work to survey trout stocks across Bulgaria's two major watersheds: the Danube catchment (Iskar and Vit rivers) and the Aegean catchment (Mesta, Vacha, Chaya, and Struma rivers). Across these systems, he reported a mean trout density of 1123 ind. $\cdot$ ha $^{-1}$ and biomass of 52.81 kg $\cdot$ ha $^{-1}$, alongside biological insights into growth rates and reproductive potential. The author also reported the average growth in length of trout for Bulgaria as follows: L_1 – 103 mm, L_2 – 157 mm, L_3 – 198 mm, L_4 – 251 mm, and L_5 – 271 mm. For the Vit River, from the Danube catchment area, Yankov (1988) provided the following data on trout growth: L_1 – 96 mm, L_2 – 137 mm, L_3 – 160 mm, L_4 – 180 mm, and L_5 – 220 mm.

This pioneering work, the most comprehensive of its time, surveyed trout stocks across Bulgaria's major watersheds, providing important baseline data for subsequent ecological and conservation studies.

Building on early studies, some

authors documented the growth rates of river trout in the Stara Ribaritsa River, a tributary of the Vit River, highlighting regional differences in trout biology (Dikov and Yankov 1985b). Further studies by Karapetkova et al. (2000) explored trout populations along the Bulgarian Black Sea coast, reporting an average density of 301 ind. $\cdot$ ha $^{-1}$ and biomass of 14.6 kg $\cdot$ ha $^{-1}$ in the Veleka, Mladezhka, and Aydere creeks, with notable variability across river sectors. Kolev (2010) investigated trout abundance and biomass in tributaries of the Maritsa River, identifying stark contrasts between the Sredna Gora Mountains rivers (Topolnitsa and Stryama, with 110 ind. $\cdot$ ha $^{-1}$ and 3.1 kg $\cdot$ ha $^{-1}$) and those in the Rhodope Mountains (Yadenitsa and Chepinska, with 526 ind. $\cdot$ ha $^{-1}$ and 23.3 kg $\cdot$ ha $^{-1}$). More recently, Raikova-Petrova et al. (2018) provided insights into growth rate, mortality, and survival of trout in the Iliina River. Despite this extensive research, data on trout populations in smaller, protected streams like the Strugarnitsa River in North-Western Bulgaria remain scarce, underscoring the need for targeted studies to inform conservation and management strategies in these unique ecosystems.

This study focuses on the river trout (*Salmo labrax*) population in the Strugarnitsa River; the trout being an important species for informing future conservation and management strategies in Bulgaria's montane ecosystems. Currently, no data exist on this river's trout population dynamics, highlighting the need for targeted research to support effective species management.

This study aims to assess the quantitative characteristics and seasonal dynamics of the river trout population in the Strugarnitsa River.

Materials and Methods

Study area

The study area is North-Western Bulgaria and the extreme north-western parts of the Stara Planina Mountains. This part of the territory of Bulgaria is drained mainly by four watercourses – the rivers: Vidbol, Lom, Tsibritsa and Ogosta, right tributaries of the Danube River. These rivers are characterised by snow-rain feeding, with a spring maximum of the flow and a minimum in autumn (Dimitrov 1973). The largest and most significant watercourse in this region is the Ogosta River. The Ogosta River is one of longest rivers in Bulgaria, with length 144.1 km (Hristova 2012). In the bed of the Ogosta River, in the immediate vicinity of the town of Montana, one of the biggest Dams in Bulgaria has been built – Ogosta Dam. Ogosta River has numerous tributaries. The Burzia River is one of its tributaries, and the Stru-

garnitsa River flows into it (Fig. 1). Two zones are distinguished in the Burzia River – high mountain, so-called trout zone and mid-mountain, so-called barbel zone (Dimitrov 1973). Strugarnitsa is a small stream that falls into a special purpose area. This is a hunting enclosure built in the last century with a view to sustainable game management. Fishing is prohibited here. According to forestry officials, no stocking material has been introduced into the stream from outside in recent years.

Equipment, methods and layout

The studied transects were located in the protected area. The river's width there was no more than 3.5–4 m. The depth of the water only in the pools reached 1.5 m.

The material was collected by moving upstream by two participants in the electrofishing, i.e. one cap-anode and one cap behind the operator with the unit. The river was surveyed completely from one bank

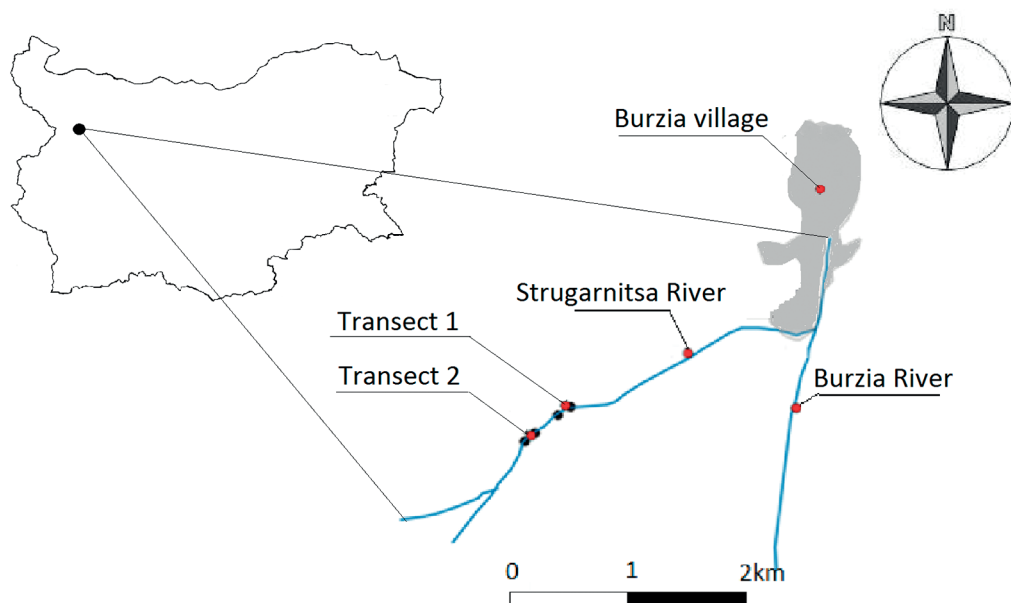


Fig. 1. Location of studied stream.

to the other. Two transects with a length of more than 100 m were used. Each transect was searched twice in succession (Table 1). The study was conducted in two stages, in the winter of 2023 and in the summer of 2024. A total of 48 individuals of river trout were caught. Electrofishing was performed using direct current with a backpack electrofisher (Samus 25G), delivering DC impulses at frequencies ranging from 5 to 100 Hz and durations between 0.03 and 3 ms. The device operated with a maximum power output of 650 W and a load current ranging from 5 to 65 A. The fish total length was measured

by a ruler with an accuracy of 1 mm and the total weight – with an electronic portable scale with an accuracy of 1 g. Using the average growth rate of the species in length in the Vit River (Yankov 1988) and the measured lengths of the fish in the Strugarnitsa River, we determined the age groups in the sample.

The length of the transect was calculated from the coordinates detected with a portable GPS 'Garmin-Oregon' 600. The average width was obtained as the arithmetic mean of the 3 measured transect widths. The measurement was made with a meter.

Table 1. Transects in the Strugarnitsa River.

Transect	Coordinates		Altitude	Transect length, m	Transect area, m ²
	N	E			
I	43°11'026"	23°07'970"	680m	174	522
	43°10'984"	23° 07'879"	735m		
II	43°11'890"	23°07'730"	774m	203	772
	43°10'847"	23° 07'661"	777m		

The estimation of fish abundance was made according to Seber and Le Cren (1967) formulas for two catching passes. The theoretical number of fish (N_e) is determined by formula (1).

$$N_e = \frac{c_1^2}{c_2 - c_1}, \quad (1)$$

where: C_1 and C_2 are, respectively, the number of fishes from the first and from the second catch passes.

The theoretical biomass B_e calculates according to Mahon et al. (1979) by formula (2).

$$B_e = \frac{B \cdot N_e}{N}, \quad (2)$$

where: B_e – theoretical biomass, g; B – biomass of caught individuals, g; N – number of caught individuals.

Theoretical abundance and biomass were calculated by using MS-Exel 2010.

Results

Despite the relatively low altitude of 700 m, the large slopes and the cold climate are the reason why the studied section of the Strugarnitsa River represents the trout zone. In winter, the water temperature was 1.7°C, pH 6.2, and dissolved oxygen varied between 8.9 and 9.0 mg·L⁻¹. These living conditions in the Strugarnitsa River meet the requirements of the river trout there.

River trout were the only fish we found in the stream. The largest specimen had a total length of 22 cm and a total weight of 63 g. The smallest one was 9.7 cm long and weighed 3.8 g. Fish with a length of 130 to 200 mm predominated in the sampling areas (figs 2 and 3).

One, two and three-years-old fish represented the sample. In the summer,

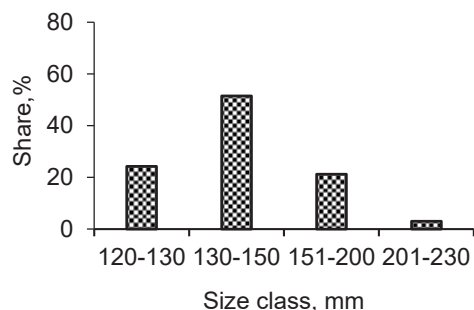


Fig. 2. Size composition of the catch in winter of 2023.

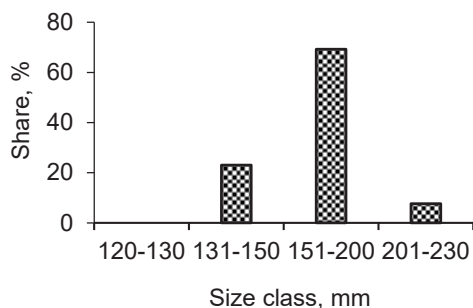


Fig. 3. Size composition of the catch in summer of 2024.

yearlings were not found in the sampling area. It is likely that they stayed upstream during this period (figs 4 and 5).

Some differences were observed in the results of the summer and winter studies. In the summer, the number of fishes was about 50 % higher than in November, when

is the breeding season for river trout. In addition, more large individuals are observed in the study area during the summer.

The average density and biomass values of river trout in the studied river were 368 ind. $\cdot$ ha $^{-1}$ and biomass 15.2 kg $\cdot$ ha $^{-1}$, respectively (Table 2).

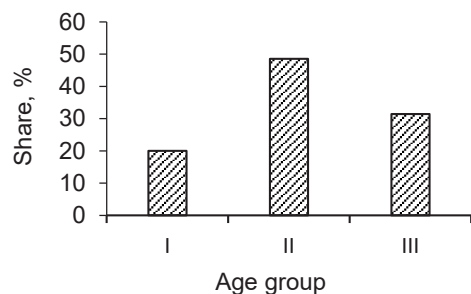


Fig. 4. Age groups of the catch in winter of 2023.

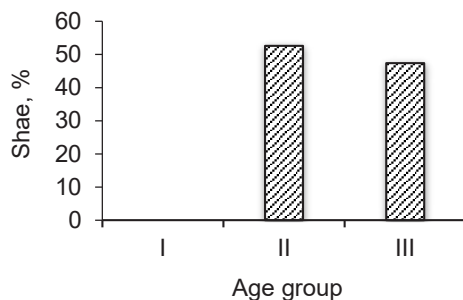


Fig. 5. Age groups of the catch in summer of 2024.

Table 2. Mean calculated density (N_e) and biomass (B_e) of the river trout in the streams Strugarnitsa.

Year	Month	Transect	N_e , ind. $\cdot$ ha $^{-1}$	N_e , ind. $\cdot$ km	B_e , kg $\cdot$ ha $^{-1}$	B_e , kg $\cdot$ km
2023	November	I	310	93	12.9	6.7
2023	November	II	331	126	9.9	7.7
2024	July	I	462	138	22,7	11,9
Average			368	119	15.2	8.8

Discussion

Despite the connection between the Strugarnitsa River and the Burzia River, the large stone steps, along with increasing slope and current velocity, probably prevent other fish species, such as *Barbus petenyi* Heckel, 1852 and *Squalius cephalus* Linnaeus, 1758, from moving upstream.

When surveying the river in summer and late autumn, we found a difference in the density of fish populations in the two seasons. The number of trout found in summer was about 50 % higher than in November. Probably one third of the trout left the study area in November. It is possible that these were sexually mature individuals migrating to the breeding grounds.

During the summer, only two- and three-year-old fish were present in the study area. It is likely that the younger fish still inhabited the upper reaches and have not reached the study area, which falls in the lower part of the trout zone. The lack of older specimens in the river is perhaps related to downstream migration.

According to the classification of Szczerbowski (1981), the Strugarnitsa River was characterised by low overall trout abundance (Table 3). The abundance and biomass of river trout in this river are

close to the lowest values established for Bulgaria (in the Iskar River – 270 ind.·ha⁻¹ and 9.48 kg·ha⁻¹, Yankov 1988). These indicators are significantly below the national average values of 1123 ind.·ha⁻¹ and 52.8 kg·ha⁻¹, respectively, established by Yankov (1988). The quantity of trout in the Strugarnitsa River is significantly lower than that found in major European rivers such as the Lima and the Garonne's tributaries – the Pique and the Ger (Lim et al. 1993, Maia and Valente 1999). However, similar low trout densities are observed in most other Bulgarian rivers. This is likely due to a combination of factors. One of them is the low water level, a result of the withdrawal of water from the Strugarnitsa River. Another important factor is the substantial annual stocking observed in rivers such as the Garonne's tributaries in France (Lim et al. 1993). In comparison to certain rivers in Turkey (Korkmaz 2005, Tanir and Fakioğlu 2017), the Strugarnitsa River actually supports a higher river trout population. Nonetheless, despite the relatively high abundance, the trout biomass in this river remains low (Table 3). This may indirectly indicate a limited food supply and possibly a shorter life cycle for trout in the Strugarnitsa River.

The reason for the low mass growth and modest trout density is most likely the low runoff in the summer and its diversion

Table 3. Mean calculated density (N_e) and biomass (B_e) of the river trout in some water courses.

River	Country	N_e , ind.·ha ⁻¹	B_e , kg·ha ⁻¹	Source
Pique and Ger	France	1000–2469	125–278	Lim et al. (1993)
Gallo	Spain	1163–3135	67.26–208.22	Almodóvar and Nikola (1998)
Lima	Portugal	1000–2000	23.04–27.04	Maia and Valente (1999)
Kadincik	Turkey	28	26.77	Korkmaz (2005)
Cagliari	Italy	2580	100.15	Zanetti et al. (2010)
Goruh	Turkey	106–167	4.76–10.64	Tanir and Fakioğlu (2017)
Strugarnitsa	Bulgaria	368	15.2	Present data (2025)

for drinking purposes. However, the fact that no stocking material has been introduced into the Strugarnitsa River for years (information from the employees of the state) allows us to assume that the population has enough adult fish, as well as natural reproduction and replenishment. This contributes to the formation of a certain stock of river trout in the Strugarnitsa River and to its reproduction and survival.

Conclusions

The study of river trout in the Strugarnitsa River reveals a stable population density of $368 \text{ ind.} \cdot \text{ha}^{-1}$, accompanied by a relatively low biomass of $15.2 \text{ kg} \cdot \text{ha}^{-1}$. Seasonal variations were observed, with higher abundance and larger individuals recorded in summer.

Given the Strugarnitsa River's limited water flow and fish production capacity, coupled with its protected status, careful management is essential to preserve its river trout population. Recreational fishing should be restricted to catch-and-release practices, enforced rigorously within the protected area to minimize disturbance to the trout's natural reproduction cycles. Additionally, limiting water diversions for drinking purposes is of primary importance to maintain the river's natural flow regime, which supports the ecological conditions of the trout zone. To ensure the population's resilience against stressors such as climate change or reduced water flow, a biennial monitoring program should be implemented to track changes in trout abundance, age structure, and habitat quality. These strategies collectively safeguard the Strugarnitsa River's trout population, ensuring its long-term viability as a self-sustaining ecosystem within Bulgaria's montane landscapes.

References

- ALMODÓVAR A., NIKOLA G.G. 1998. Assessment of a brown trout *Salmo trutta* population in the River Gallo (central Spain): Angling effects and management implications (Salmonidae). Italian Journal of Zoology 65(1): 539–543. doi: 10.1080/11250009809386881
- DIKOV Ts., YANKOV Y. 1985a. Growth rate of the river trout in four rivers in the Rila Mountains. International symposium 'The game and environment', Sofia: 517–526.
- DIKOV Ts., YANKOV Y. 1985b. Dynamics of the river reserves along River Vit. I. Age composition and rate of increase of the River Trout (*Salmo trutta fario* L.) in Stara Ribaritsa River. Bulgarian academy of sciences. Hydrobiology 25: 51–61 (in Bulgarian with English summary).
- DIMITROV D. 1973. Climatology. Atlas of the People's Republic of Bulgaria. Main Department of Geodesy and Cartography. 63 p. (in Bulgarian).
- HRISTOVA N. 2012. River waters of Bulgaria. Top Press Publishing House. 538 p. (in Bulgarian).
- KARAPETKOVA M., YOCHEV S., DIKOV Ts. 2000. The state of fish abundance in Veleka rivers and its tributaries. Report to the Ministry of environment and waters. 43 p.
- KORKMAZ A.Ş. 2005. Density and biomass of fish in Kadincik (Camliyayla-Mersin) Brook. Ankara University Journal of Agricultural Sciences 11(1): 91–97 (in Turkish with English abstract). https://doi.org/10.1501/Tarimbil_00000000493
- KOLEV V. 2010. Density and biomass of the river trout in some Bulgarian rivers. Forestry Ideas 16(2): 221–229.
- KOTTELAT M., FRAYHOF J. 2007. Handbook of European freshwater fishes. Edition Kottelat. 646 p.
- LIM P., SEGURA G., BELAUD A., SABATON C. 1993. Study of the habitat of Brown trout (*Salmo trutta fario*) role of artificial and natural covers on trout populations. Bulletin français de la pêche et de la pisciculture 331: 373–396 (in French with English abstract). <https://doi.org/10.1051/>

- kmae:1993004
- MAHON R., BALON E., NOAKES D. 1979. Distribution, community, structure and production of fishes in the upper Speed river, Ontario; a preimpoundment study. *Environment, Biology, Fishes* 4: 219–244. <https://doi.org/10.1007/BF00005480>
- MAIA C.F.Q., VALENTE A.C.N. 1999. The brown trout *Salmo trutta* L. population in the river Lima catchment. *Limnetica* 17(1): 119–126. doi: 10.23818/limn.17.12
- RAIKOVA-PETROVA G., ROZDINA D., VALKANOV R. 2018. Growth rate of the Bulgarian Brown trout (*Salmo trutta* Linnaeus, 1758) from the river Iliyana, Bulgaria. *International Journal of Aquaculture* 8(16): 121–126. doi: 10.5376/ija.2018.08.0016
- SEBER G., LE CREN E. 1967. Estimating population parameters from catches large relative to the population. *Journal of animal ecology* 36(3): 631–643. <https://www.jstor.org/stable/2818>
- SZCZERBOWSKI J. 1981. Criteria for estimating the rate of growth in fish. *Yearbook of the Institute of Agricultural Sciences (Roczniki Nauk Rolniczych) Seria H* 99(4): 123–136 (in Polish).
- TANIR O.Z., FAKIOĞLU O. 2017. Density and biomass and length-weight relationship of the brown trout (*Salmo trutta* Linnaeus, 1758) population in the Coruh River basin, North-Eastern Anatolia, Turkey. *Journal of Limnology and Freshwater Fisheries Research* 3(3): 129–136. doi: 10.17216/LimnoFish.313520
- YANKOV I. 1988. The dynamic of populations of river trout (*Salmo trutta fario* L.) in the major trout rivers in Bulgaria. PhD thesis. Bulgarian Academy of Sciences, Institute of Zoology. 157 p. (in Bulgarian).
- ZANETTI M., TURIN P., PICCOLO D., BELLIO M., FLORIS B., BUA R., COTTIGLIA C., LIGGI G. 2010. Distribution of fish fauna in the main hydrographic basins of the Province of Cagliari. *Studi Trentini di Scienze Naturali* 87 (2010): 269–271 (in Italian).

Assessing the impact of green open spaces on urban microclimate in Pinrang Regency, South Sulawesi, Indonesia

Hasniar Ulang Dari^{}, Mukrimin Mukrimin^{}, and Yusran^{}

Department of Forestry, Faculty of Forestry, Hasanuddin University, Tamalanrea Campus, Jalan Perintis Kemerdekaan Km. 10, Makassar 90245, Indonesia. E-mail: mukrimin@unhas.ac.id

Received: 29 April 2025 / Accepted: 12 July 2025 / Available online: 23 July 2025



Open Access: This work is distributed under the Creative Commons Attribution 4.0 License.

Abstract

Rapid urbanisation and global climate change have increased the Urban Heat Island (UHI) phenomenon, which impacts the quality of the urban environment. Green Open Space (GOS) has a strategic role in mitigating microclimate change. However, its availability in various regions, including Pinrang Regency, is still not optimal. This study aimed to determine the contribution of GOS to microclimate regulation in urban environments. This was achieved by comparing environmental parameters between areas inside and outside the GOS in Pinrang Regency – specifically, Pinrang Urban Forest, Lasinrang Park, Lasinrang Monument Park, and Bau Massepe Stadium Park. The study identified the main factors influencing variations in environmental conditions across these areas and explored the interrelationships among all measured environmental parameters using Principal Component Analysis (PCA). Measurements were conducted at four GOS locations using a Mastech MS6300 device. The Mann-Whitney U test results show significant difference in environmental parameters between areas inside and outside the GOS, where the temperature inside the GOS was 5–6 °C lower than outside, humidity increased by 15–20 %, light intensity decreased by 70 %, wind speed decreased due to vegetation barriers, and noise decreased by 10–15 dB. Identifying the causes of differences in environmental parameters showed that the main contributing factors were vegetation type and density, canopy structure, and surrounding environmental conditions such as exposure to direct sunlight intensity and human activities outside the GOS. In addition, vegetation density analysis using NDVI imagery shows significant differences between GOS. GOS with wide-canopy and high-density vegetation showed more significant microclimate moderating effects than areas with more open vegetation. PCA analysis revealed that temperature, humidity, and sunlight intensity were the dominant factors determining environmental quality in GOS. Therefore, empirical data-based planning and GOS management are essential to improve urban environmental quality optimally.

Key words: humidity, noise level, sunlight intensity, temperature, urban heat island, wind speed.

Introduction

The World Bank (2019) notes that Indonesia will experience significant demographic changes, with more than 70 % of its population expected to live in urban areas by 2045 (Roberts et al. 2019). Rapid urbanisation, coupled with climate change, is causing urban temperatures to rise, a scientific phenomenon known as the Urban Heat Island Effect (UHI) [Intergovernmental Panel on Climate Change (IPCC) 2023]. On an international scale, climate change trends indicate an increase in average global temperatures of more than 1.1°C since the pre-industrial era. According to the IPCC AR6 (2021) projections, the increase could exceed 2°C by the end of this century if no significant mitigation efforts are implemented (IPCC 2021). Accelerated urbanisation in many countries exacerbates the UHI effect, causing city temperatures to rise faster than in rural areas (Nowak et al. 2022). Globally, Green Open Spaces (GOS) are now recognised as one of the most effective Nature-based Solutions (NbS) for addressing the impacts of climate change in urban areas. GOS can absorb carbon, lower surface temperatures by 1.5–7 °C, depending on local conditions, and increase relative humidity, which is important for thermal comfort (Shi et al. 2022, Ziter et al. 2019). Additionally, GOS supports international targets, such as Sustainable Development Goals (SDGs) 11 and 13, which call for the provision of public green spaces to create climate-resilient cities and support global climate action.

GOS play an essential role in urban planning, helping to maintain ecosystem balance, improve environmental quality, and provide public spaces that are accessible to the community (Mukrimin et al. 2025, Setiowati et al. 2018). Pinrang Re-

gency, one of the regions in South Sulawesi, has experienced rapid development in recent years. Infrastructure growth and settlement expansion have significantly changed the landscape of this area (Statistics Indonesia (BPS) Pinrang Regency 2023). These changes have raised concerns about the urban environment, such as rising air temperatures, declining air quality, and reduced biodiversity. In this situation, research on the contribution of green space in maintaining the balance of the urban environment has become increasingly important and urgent (Wu and Liu 2023). Recent research in tropical cities has shown that it is not only the presence of green open spaces that is important, but also urban morphology, such as building density, street canyon proportions (the ratio of street height to street width), and vegetation layout, which greatly influence the urban microclimate. For example, a study in a densely populated residential area in Bandung Province, Indonesia, found that areas with very high building coverage (over 95%) experienced minimal daily temperature variations, indicating trapped heat and poor ventilation. Conversely, areas with lower building density have a wider daily temperature range, better air circulation, and a lower risk of heat stress (Paramita and Matzarakis 2019).

The Indonesian government, through the Regulation of the Minister of Agrarian and Spatial Planning/Head of the National Land Agency Number 14 of 2022, requires each region to provide a minimum of 30 % of its total area as Green Open Space, with details of 20 % for public GOS and 10 % for private GOS. However, implementing this policy in various regions, including the Pinrang Regency, has not been optimal. In 2023, the total area of GOS in the Pinrang Regency only reached

8233 ha out of a total area of 196,177 ha. Based on the provisions, the area of public GOS that should ideally be provided is 20 % of the total area, around 39,235 ha (KEMEN-ATR/BPN 2022). Thus, the current public GOS has only reached about 20.98 % of the target. This means there is still a shortfall of 31,002 ha, or around 79.02 % of the total public GOS requirement. This condition shows that Pinrang Regency has not yet fulfilled the obligation to provide public GOS according to the regulation.

Various studies confirm that GOS is essential for creating more comfortable and healthier urban environments. According to Kraemer and Kabisch (2022), GOS can reduce noise and improve air quality through enhanced air circulation and stabilised air pressure. Du et al. (2021) revealed that GOS with water bodies or aligned with prevailing winds are more effective in maintaining humidity and lowering temperatures compared to areas outside GOS. Ornelas et al. (2023) highlighted that tree canopies in GOS reduce temperatures and provide shade, enhancing thermal comfort. Additionally, a study in Indonesia by Syafitri et al. (2020) showed that non-built areas like parks, urban forests, and ponds have lower surface temperatures than built-up areas, emphasising the GOS's role in microclimate regulation.

Research on GOS in Indonesia has mainly focused on areas, distribution, disaster mitigation, spatial planning, and public space provision. However, studies comparing environmental parameters, such as air temperature, humidity, sunlight intensity, wind speed, and noise levels inside and outside GOS, remain scarce. This indicates a research gap that needs attention to support data-driven GOS planning and management. This study aims to evaluate

the contribution of GOS to urban microclimate regulation in Pinrang Regency. To achieve this, the study compares environmental parameters between areas inside and outside GOS, identifies the causes of observed differences, and explores patterns and relationships among these parameters using Principal Component Analysis (PCA), as a basis for adaptive and empirical GOS planning. This holistic approach is expected to offer a practical and empirical reference for GOS management that meets local needs and addresses global urban challenges.

Materials and Methods

Study area

The research locations included areas within GOS, namely Pinrang Urban Forest, Lasinrang Park, Lasinrang Monument Park, and Bau Massepe Stadium Park. These areas were selected based on several criteria: a minimum size of approximately 1 ha, significant tree cover (with moderate to high tree density), diversity of vegetation types (including shade-providing species), and their function as public urban parks with active community use. Areas with minimal vegetation cover, under 1 ha in size, or not actively used as public spaces were excluded from the sampling. For comparison, measurements were also taken in surrounding non-GOS areas characterised by dense urban activities and limited vegetation. The elevation in each GOS location is relatively uniform, ranging between 16 and 18 m a.s.l.: Pinrang Urban Forest is at 18 m, Lasinrang Park at 16 m, Lasinrang Monument Park at 17 m, and Bau Massepe Stadium Park at 17 m. The locations of the GOS areas are shown in Figure 1.

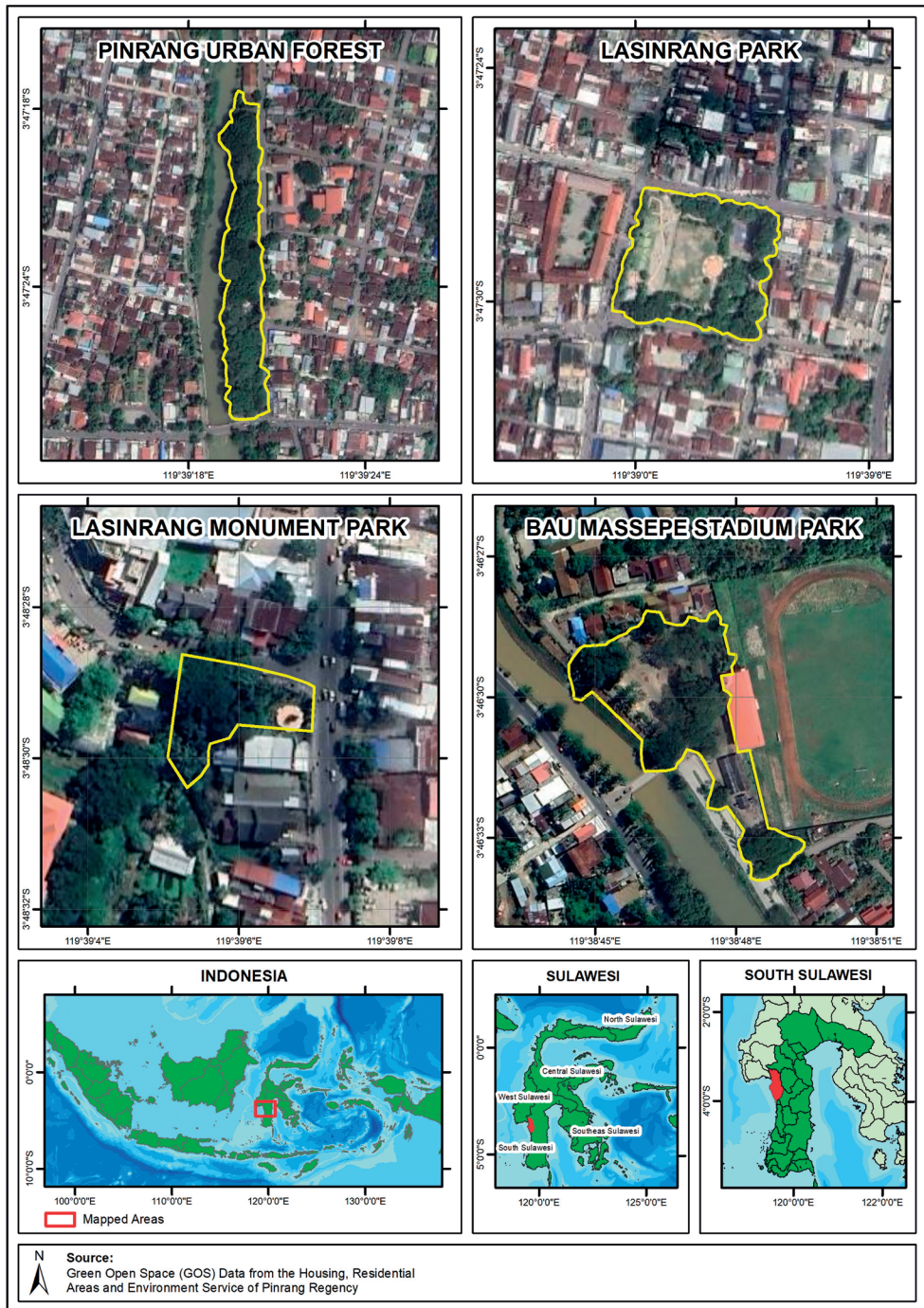


Fig. 1. Research locations of GOS in Pinrang Regency.

Vegetation density analysis

Vegetation density analysis on GOS in Pinrang Regency was conducted using Normalized Difference Vegetation Index (NDVI) analysis, a common and effective approach for assessing vegetation condition based on spectral reflectance from the Earth's surface. Data processing was conducted using Google Earth Engine (GEE) platform, which enables fast and efficient spatial data processing through cloud computing. The data used came from Sentinel-2 satellite imagery acquired in 2023, specifically the near-infrared (B8) and red (B4) channels. NDVI values close to +1 indicate high levels of vegetation (dense and healthy). In contrast, values close to 0 or negative indicate non-vegetative areas, such as water bodies, impermeable surfaces, or open land. The closer to +1, the higher the vegetation density (Kanjir et al. 2018, Wu et al. 2021). The classification of NDVI values is divided into five classes, namely: (1) -1 to -0.03 as water/bare soil, (2) -0.03 to 0.15 as no vegetation, (3) 0.15 to 0.25 as sparse vegetation, (4) 0.25 to 0.35 as moderate vegetation, and (5) 0.35 to 1 as dense/lush vegetation.

Measurement of microclimate parameters

This study used the Mastech MS6300 device, a multifunctional tool designed to support accurate and efficient data collection. It integrates five main functions: temperature (thermometer), relative humidity meter (hygrometer), sunlight intensity (luminometer), wind speed or airflow (anemometer), and sound level meter. Integrating these functions into a single device enables efficient data collection and reduces the risk of inter-tool mismatches. The use of the MS6300 also supports consistency and accuracy of results, as its

specifications are standardised for environmental research needs. Measurement points were set at two locations: under the shade inside the GOS and in an unshaded area outside the GOS. Measurements outside the GOS were taken at 100 m from the GOS boundary. This distance was chosen to ensure that the measurement area is in a zone not directly affected by the GOS vegetation but remains within a radius that reflects the residual or transitional influence of the GOS ecosystem on the surrounding environment. This approach is supported by previous research, such as the studies of Bowler et al. (2010), Colunga et al. (2015), which showed that the thermal and environmental effects of GOS are most significant within a radius of up to 100–500 m, depending on the scale and characteristics of the GOS. Measurements were taken at four different time intervals daily: 06:00–07:00, 09:00–10:00, 12:00–13:00, and 15:00–16:00. Data collection was conducted during the dry season to capture the microclimatic conditions typical of hot weather. Each monitoring site was evaluated repeatedly on multiple days within the same season to ensure consistency and temporal reliability. All measurements were conducted under clear weather conditions to minimise the influence of unpredictable weather factors on the research results. Detailed information on measurement accuracy is presented in Table 1.

Statistical analysis

This study used the Mann–Whitney U test to compare the environmental parameters inside and outside the GOS. This test was chosen because it is suitable for data that is not normally distributed ($p < 0.05$) and that violates the assumption of homogeneity of variance. As shown in Table 2,

Table 1. Mastech MS6300 accuracy specifications.

Parameter	Range measurement	Resolution	Accuracy
Temperature	-10 °C–60 °C	0.1 °C	±1.5 °C
Relative humidity	20–80 % RH	0.1 % RH	±3.0 % RH
	<20>80 %RH	0.1 % RH	±5.0 % RH
Sunlight intensity	0–2000 LUX	1 LUX	± (5.0 % +10)
	x10 (20000)	10 LUX	± (5.0 % +10)
	x100 (50000)	100 LUX	± (5.0 % +10)
Wind speed	0.5–20 m·s ⁻¹	0.1 m·s ⁻¹	± (3.0 % +10)
	1.8–72 km·h ⁻¹	0.1 km·h ⁻¹	± (3.0 % +10)
	96–3942 ft·min ⁻¹	1 ft·min ⁻¹	± (3.0 % +10)
	0.9–38.9 knots	0.1 knots	± (3.0 % +10)
Noise level	30–130 dB (A)	0.1 dB	±1.5 dB
	35–130 dB (C)	0.1 dB	±1.5 dB

Table 2. Results of the Shapiro–Wilk normality test (significance values).

Measurement locations	Temperature	Relative humidity	Sunlight intensity	Wind speed	Noise level
Inside Pinrang Urban Forest	0.012	0.008	0.049	0.973	0.316
Outside Pinrang Urban Forest	0.044	0.271	0.019	0.130	0.025
Inside Lasinrang Park	0.107	0.006	0.073	0.174	0.970
Outside Lasinrang Park	0.010	0.075	0.097	0.244	0.078
Inside Lasinrang Monument Park	0.084	0.008	0.038	0.883	0.184
Outside Lasinrang Monument Park	0.041	0.172	0.030	0.395	0.239
Inside Bau Massepe Stadium Park	0.085	0.003	0.039	0.091	0.248
Outside Bau Massepe Stadium Park	0.050	0.270	0.083	0.103	0.121

Note: Significance values below 0.05 indicate deviation from normal distribution.

the null hypothesis (H_0) states that there is no significant difference in environmental parameters between areas inside and outside the GOS, while the alternative hypothesis (H_1) suggests a significant difference exists. The conclusion is based on the significance value (p -value); if $p < 0.05$, H_0 is rejected, indicating a significant difference between the two areas, while if $p \geq 0.05$, H_0 cannot be rejected, indicating insufficient statistical evidence to support a significant difference.

In this study, Principal Component Analysis (PCA) was employed to investigate the relationships between environmental parameters, including temperature, humidity, sunlight intensity, wind

speed, and noise levels, at the four GOS locations. PCA was chosen not only for its ability to reduce dimensions but also for its effectiveness in identifying dominant patterns and linear relationships between variables (Jolliffe 2002), which aligns with the study's objective of understanding the interactions between parameters in the urban microclimate. This method enables clear visualisation through loading plots, which is important for communicating findings to multidisciplinary stakeholders, including urban planners and policymakers. Additionally, the use of PCA maintains consistency with previous research in the field of urban microclimate, which has widely applied this method to uncover

interrelationships among environmental factors before employing more complex predictive models. Given that the environmental data in this study exhibit moderate to strong linear correlations, PCA is considered a suitable and reliable tool for identifying underlying patterns while maintaining the interpretability essential for practical recommendations in GOS planning.

Results and Discussion

Vegetation density level

The analysis of vegetation density based on NDVI imagery, as shown in Figure 2, reveals an apparent variation in vegetation cover, both within and around the GOS area in Pinrang Regency. Pinrang Urban Forest has the densest vegetation,

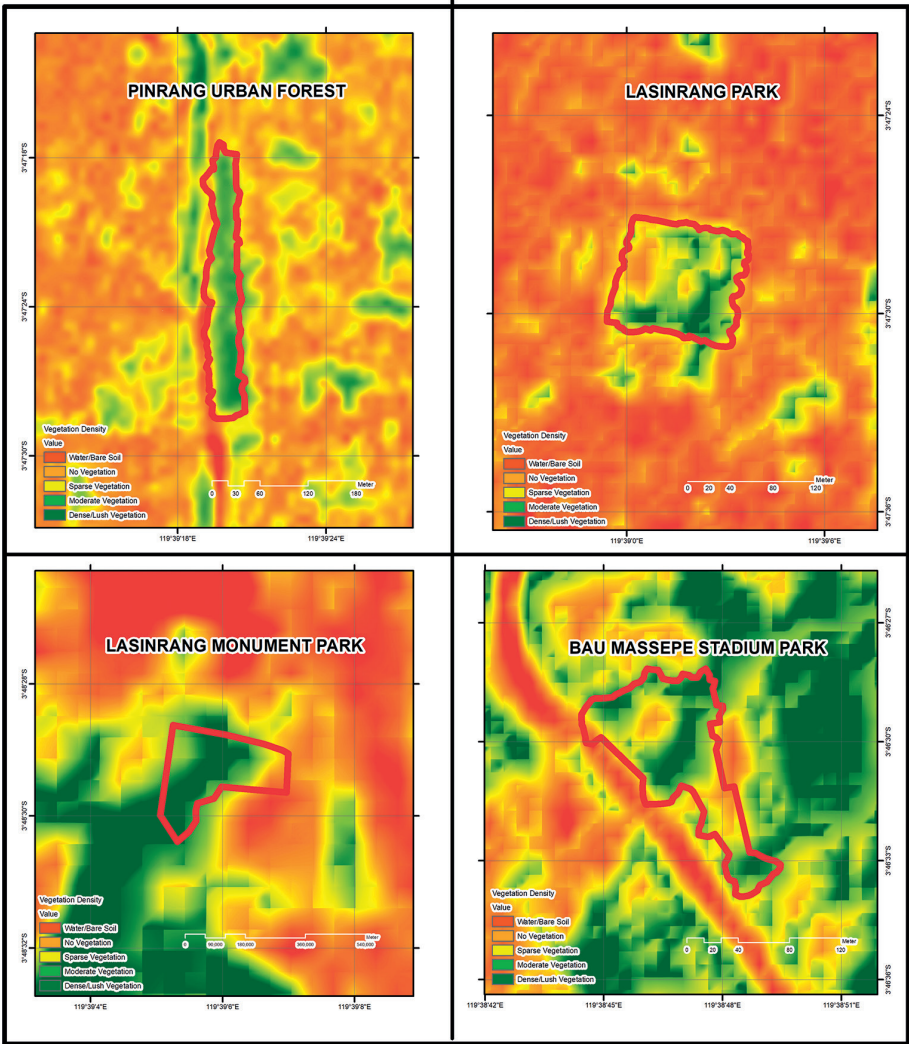


Fig. 2. Vegetation density level in Pinrang Regency.

characterised by the dominance of dark green regions that extend vertically. This dense vegetation is not only concentrated within the GOS area but also extends slightly into the surrounding area, which can increase the cooling effect on areas outside the park (Yan et al. 2021). In contrast, Lasinrang Park shows a limited distribution of dense vegetation, with vegetation cover dominated by a combination of sparse to medium vegetation. The NDVI map shows that dense vegetation is mainly concentrated in the centre of the park, while areas of lower vegetation density surround the edges. This pattern suggests that the park's ability to reduce temperature and increase humidity is localised, rather than evenly distributed throughout the park (Wu et al. 2021).

Lasinrang Monument Park shows a disjointed (uneven) vegetation pattern, where dense vegetation is concentrated in the southern part of the park area. The northern and eastern sections show minimal or sparse vegetation, indicating an imbalance in green space distribution. This uneven distribution can result in the park's effectiveness in reducing sunlight intensity, noise, and heat being reduced overall (Rahman and Hasan 2024). Bau Masepe Stadium Park shows a unique pattern with moderate to dense vegetation concentrated in the north and southeast of the park. Although the overall density of vegetation is higher than in Lasinrang Park and Lasinrang Monument Park, the distribution remains fragmented (not fully integrated). The design of this park appears to combine green and open areas, which can limit its ability to provide equitable microclimate benefits (Zhang et al. 2025). Thus, the NDVI analysis confirms that vegetation density varies greatly between green spaces in Pinrang, and this affects the ecological function of each GOS.

Comparison of environmental parameters inside and outside GOS

A comparison of environmental parameters between areas inside and outside the GOS in Pinrang Regency is summarised in Figure 3. This figure illustrates the variations in temperature, humidity, sunlight intensity, wind speed, and noise level observed at different times of the day across the sites studied.

Temperature

The temperature in Figure 3 shows a significant difference between areas inside and outside the GOS (p -value = 0.000, $p < 0.05$), confirming the importance of vegetation in reducing air temperature within the GOS compared to urban areas lacking vegetation. This statistical result not only indicates significance but also highlights the ecological relevance of vegetation in microclimate regulation. Evapotranspiration processes, the shading effect of the tree canopy, and increased surface albedo contribute to this temperature reduction. In contrast, areas outside the GOS directly exposed to sunlight and dominated by urban activities experience higher temperatures, indicating the presence of a UHI effect.

According to Livesley et al. (2016), Mukrimin et al. (2025), urban forests and green parks can act as thermal buffers through evapotranspiration and canopy shading. Evapotranspiration is the process of water vapour release by plants into the atmosphere, which absorbs heat and lowers local temperatures (Febrita et al. 2021). The tree canopy also reduces direct sunlight intensity, inhibiting the ground surface and the air below. The temperature measurements show that the average temperature inside the GOS is

consistently lower than outside the GOS at all-time intervals. The temperature inside the Pinrang Urban Forest (06:00–07:00) in the morning was in the range of 26.5–27.0 °C, while outside, the GOS reached 28.6–29.2 °C, with a difference of about 2 °C. The difference was even more striking during the day (12:00–13:00), with temperatures inside the GOS ranging from 31.2–31.6 °C, while temperatures outside the GOS reached 36.4–37.5 °C, indicating a difference of up to 5–6 °C. These results reinforce the findings of Varşak and Altay (2024) that densely vegetated areas can reduce temperatures by 4–7 °C compared to urban areas with minimal vegetation.

Humidity

The air humidity in Figure 3 shows a significant difference between areas inside and outside the GOS (p -value = 0.000, $p < 0.05$), confirming the critical role of vegetation in increasing air humidity. This statistically significant result highlights not only the numerical contrast but also the functional ecological role of vegetation in regulating humidity. Vegetation supports the process of evapotranspiration, where plants release water vapour into the atmosphere, increasing relative humidity locally. In addition, vegetation-covered soil surfaces retain moisture better than hard surfaces, such as asphalt and concrete, which are dominant outside GOS (Erlwein et al. 2021).

Vegetation density is positively correlated with air humidity levels. Pinrang Urban Forest, with dense vegetation, provides higher humidity than parks with more open vegetation. This finding aligns with the previous research by Gunawardena et al. (2017), Mbarep et al. (2021), highlighting that forested areas can create a comfortable microclimate by increasing humidity

while reducing temperature. Hwang et al. (2023) also confirmed that the denser the vegetation, the greater the contribution to increased humidity. Based on the data, the relative humidity inside the GOS is consistently higher than outside the GOS. At 06:00–07:00, the humidity inside Pinrang Urban Forest reached 79.7 %, higher than 66.6 % outside the GOS. This pattern continued until noon (12:00–13:00), where the humidity inside Pinrang Urban Forest was recorded at 66.0 % compared to 50.1 % outside the GOS. Similar differences were observed in other parks, such as Lasinrang Park, Lasinrang Monument Park, and Bau Massepe Stadium Park, although the values varied depending on the vegetation density. Research by Li et al. (2024) supports these results, showing that dense vegetation can increase air humidity by 15–20 % compared to urban areas without vegetation. Pinrang Urban Forest, with the densest vegetation, showed the highest humidity compared to other parks with lower vegetation density, such as Bau Massepe Stadium Park and Lasinrang Park. In contrast, the lower humidity outside the GOS reflects the direct impact of urbanisation, where hard surfaces increase the UHI effect, characterised by high temperature and low humidity (Rizwan et al. 2008).

Sunlight intensity

The sunlight intensity in Figure 3 shows a significant difference between the areas inside and outside the GOS (p -value = 0.000, $p < 0.05$), confirming that the GOS effectively reduces light intensity through the mechanism of vegetation canopy closure. This statistically significant result highlights not only the numerical contrast but also the ecological role of dense vegetation in modulating incoming sunlight

intensity and improving microclimate conditions. Dense vegetation creates a significant shading effect, absorbing and blocking direct sunlight intensity, thereby lowering ground surface temperature and the surrounding environment. Previous studies by Beute and de Kort (2018), Zhao et al. (2023) have shown that high sunlight intensity increases body heat load, especially in urban areas with minimal vegetation, causing thermal discomfort, particularly during the daytime.

Measurement data show consistently lower light intensity inside the GOS, for example, at 06:00–07:00, sunlight intensity in Pinrang Urban Forest was recorded at 552 lx, much lower than 5594 lx outside the GOS. At midday (12:00–13:00), the light intensity inside Pinrang Urban Forest reached 3987 lx, while outside the GOS reached 23,919 lx. This pattern was also observed in Lasinrang Park, Lasinrang Monument Park, and Bau Massepe Stadium Park, with differences directly proportional to vegetation density. The decrease in light intensity within the GOS also correlates with a higher increase in relative humidity. Dense vegetation supports microclimate moderation by lowering light intensity and increasing humidity, thereby reducing the impact of extreme heat. Research by Takebayashi et al. (2017) supports these results, where dense vegetation can reduce sunlight intensity by up to 70 % compared to areas without vegetation. In contrast, the high sunlight intensity outside the GOS reflects the lack of shade vegetation, exacerbating the UHI phenomenon through high temperature and low humidity.

Wind speed

The wind speed in Figure 3 shows a significant difference between the areas inside

and outside the GOS (p -value = 0.000, $p < 0.05$), indicating that the vegetation inside the GOS acts as an aerodynamic barrier that effectively reduces wind flow through physical resistance. The dense trees, shrubs, and complex vegetation structures within the GOS absorb and distribute wind energy, as found by Gunawardena et al. (2017), who stated that dense vegetation canopies create a more aerodynamically stable environment. Vegetation can break up wind turbulence, providing thermal protection to the surrounding environment. In contrast, areas outside the GOS, which lack vegetation, allow winds to flow more freely, increasing speed and turbulence, and exacerbating UHI effects due to higher moisture evaporation. Measurement data showed consistently lower wind speeds inside the GOS than outside, such as at 12:00–13:00, where wind speeds outside Pinrang Urban Forest reached $3.2 \text{ m}\cdot\text{s}^{-1}$ compared to $2.5 \text{ m}\cdot\text{s}^{-1}$ inside. Similar patterns were found in other parks, such as Lasinrang Monument Park, with differences suggesting vegetation is a natural barrier to reduce wind speed. This finding supports the view of Hui et al. (2024) that urban vegetation creates significant aerodynamic barriers while lowering the air temperature in the area.

Noise level

The noise levels in Figure 3 show significant difference between areas inside and outside the GOS (p -value = 0.000, $p < 0.05$), indicating that GOS is essential in reducing noise in urban environments. This statistically significant result highlights not only the contrast in numerical values but also the functional role of vegetation as a natural acoustic buffer. The dense vegetation inside the GOS, such as trees and shrubs, acts as natural acous-

tic barrier that absorbs and blocks sound waves, reducing the impact of noise from human and vehicular activities (Dzhambov and Dimitrova 2014). For example, at 06:00–07:00, the noise inside Pinrang Urban Forest was recorded at 49.5 dB, far below the noise level outside the GOS, which reached 70.0 dB. This noise reduction aligns with the findings of Margaritis and Kang (2017), and Rey-Gozalo et al. (2023), who reported that dense vegetation in GOS can reduce noise levels by 10–15 dB. The effect is reinforced by Gidlöf-Gunnarsson and Öhrström (2010) who explained that complex vegetation structures can increase sound absorption capacity through vegetation's leaves, stems, and soil.

The interaction between wind speed and noise further clarifies the contribution of the GOS in creating a comfortable acoustic environment. Lower wind speeds inside the GOS, for example, $1.2 \text{ m}\cdot\text{s}^{-1}$ in the morning to $2.5 \text{ m}\cdot\text{s}^{-1}$ in the afternoon, reduce the propagation of sound waves. Conversely, outside the GOS, stronger wind speeds can increase the propagation of sound waves. This is consistent with research by Zannin et al. (2013), which found that high-speed winds in urban areas can accelerate the spread of noise from the sound source to the surrounding area. High noise exposure, especially outside the GOS, has serious health consequences. Chronic noise above 65 dB increases the risk of hypertension, sleep disorders, and cardiovascular diseases, as revealed in the WHO (Environmental Noise Guidelines) (Clark and Paunovic 2018, Münzel et al. 2018). El Masri et al. (2024) also highlighted that chronic noise triggers psychological stress that can develop into anxiety and depression. In addition, the combination of noise with high wind speeds exacerbates the dispersion

of air pollutants, increasing the risk of respiratory diseases such as asthma.

Identify the causes of differences in environmental parameter values in GOS

The differences in environmental parameter values within the GOS in Pinrang Regency are presented in Figure 4. This figure shows variations in temperature, humidity, sunlight intensity, wind speed, and noise level recorded at various GOS locations, highlighting disparities in microclimatic conditions related to vegetation cover and surrounding urban characteristics. One of the leading causes is the lack of attention to vegetation distribution in some GOS, such as in Bau Massepe Stadium Park and Lasinrang Park, which show higher temperatures, lower humidity, and higher noise levels than greener areas, such as Pinrang Urban Forest. The lack of vegetation increases UHI effects that worsen thermal conditions and environmental comfort. In addition, development patterns that do not consider ecological aspects are also significant factors, as many GOS are dominated by artificial structures rather than natural elements that should be the central part of green spaces.

In addition, uncontrolled urbanisation and a lack of regulation in protecting GOS worsen urban microclimate conditions in some locations. Higher wind speeds in open areas without vegetation barriers, as seen in Lasinrang Monument Park and Bau Massepe Stadium Park, indicate that the design of GOS does not consider microclimatic aspects that should be able to create cooler and more comfortable environmental conditions. In addition, the high noise levels in some locations indicate that the GOS does not fully function as a

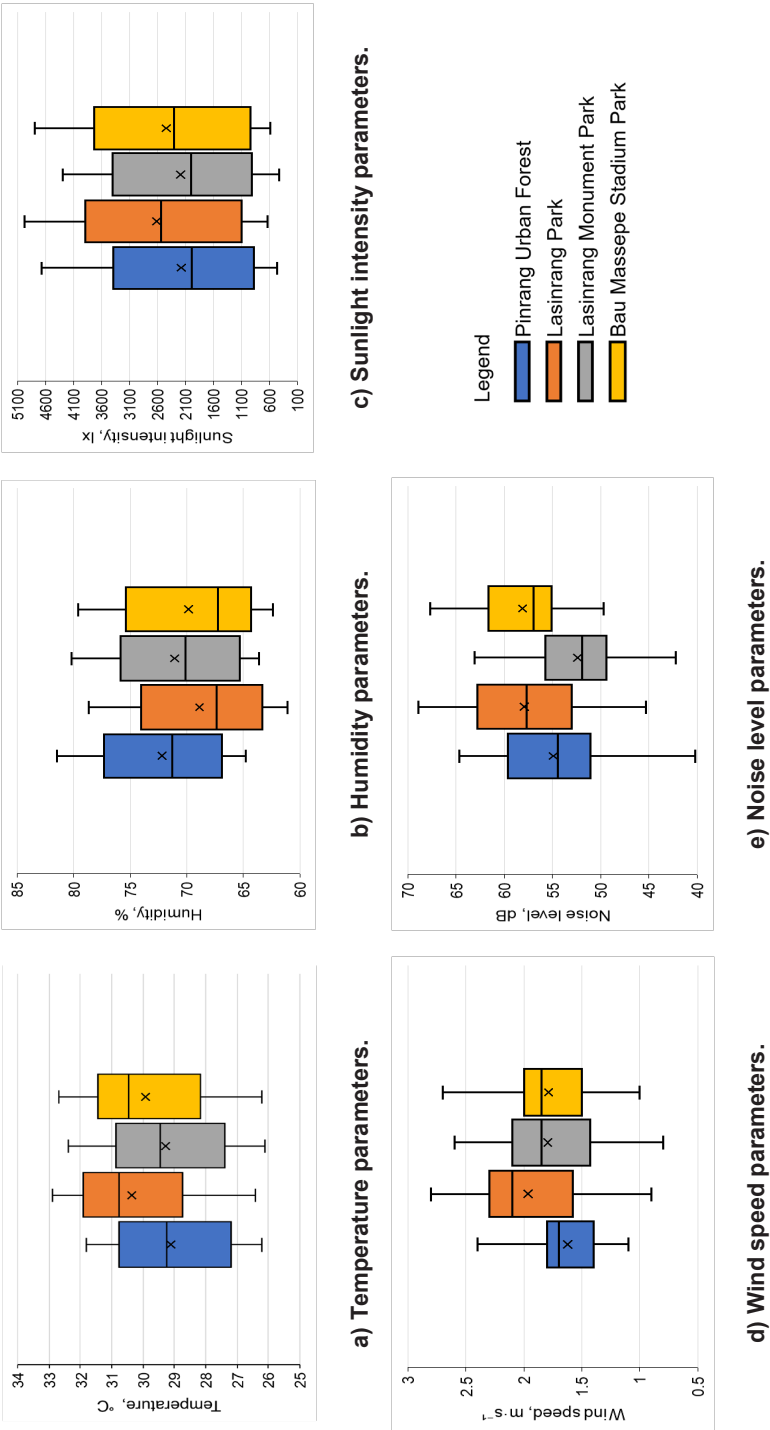


Fig. 4. Comparison of environmental parameters in GOS Pinrang Regency.

noise pollution mitigation area, especially in areas close to main roads and urban activity centres.

It is also considered that each tree species has a different influence on microclimate due to differences in morphology, crown density, transpiration rate, and other physical characteristics. In the urban forest, broad-canopy species, such as *Ficus benjamina* L., *Terminalia catappa* L., and *Samanea saman* (Jacq.) Merr. effectively reduce temperature and increase humidity because they can shade the area underneath and retain sunlight intensity. Other dense-leaved trees, such as *Swietenia macrophylla* King and *Pterocarpus indicus* Willd., also help absorb pollutants and reduce noise. In contrast, fast-growing *Neolamarckia cadamba* (Roxb.) Bosser and *Gmelina arborea* Roxb. can accelerate the restoration of open areas to a greener state (Aluyah and Rusdian- to 2019). Some fruiting species, such as *Mangifera indica* L., *Artocarpus heterophyllus* Lam., and *Dimocarpus longan* Lour., have medium to wide canopies and support biodiversity, but are generally not as shady as *F. benjamina* or *S. saman*.

In Lasinrang Park, tree species like *Casuarina junghuhniana* Miq. and *Ficus microcarpa* L.f. provide more limited shade due to their narrower canopy structure. At the same time, *Terminalia mantaly* H. Perrier, *Handroanthus chrysotrichus* (Mart. ex DC.) Mattos, and *Caryota mitis* Lour. (fish-tail palm) tend to function as ornamental trees with narrower canopies. This makes the garden area more open and makes it easier for sunlight to reach the land surface, which results in increased temperature and decreased humidity. In Monument Park, palms (e.g. *Ptychosperma elegans* (R.Br.) Blume, *Livistona chinensis* (Jacq.) R.Br. ex Mart., and *Roystonea regia* (Kunth) O.F.Cook) and some shrubs,

such as *Justicia gendarussa* Burm.f. and *Euphorbia* L., act more as aesthetic elements and do not provide as high thermal protection as trees with wide canopies. However, *S. macrophylla* and *T. mantaly* trees still help to reduce heat and noise around the park (Environmental Protection Agency 2012).

Meanwhile, in Stadion Park, large-canopy species, such as *S. saman*, *P. indicus*, and *T. catappa* help to shade specific areas, but poor organisation leads to uneven shade. Other species, such as *G. arborea*, *M. indica*, and *Leucaena leucocephala* (Lam.) de Wit, contribute to heat and moisture absorption, although their capacity varies depending on density and growing conditions (Rötzer et al. 2023). Thus, species with wide canopies compositions (e.g., *F. benjamina*, *S. saman*, *T. catappa*, and *S. macrophylla*) proved to be most effective in reducing temperatures and increasing thermal comfort. In contrast, narrow canopies or more ornamental species (such as various palms, cypresses, and shrubs) tended to produce more limited shading and heat absorption effects.

Variations in microclimate parameters among the four GOS locations were not only caused by internal factors, such as vegetation density through NDVI, but were also influenced by the characteristics of the surrounding urban environment. For example, Pinrang Urban Forest is surrounded by low-density residential areas, water bodies (rivers), main roads, government offices, and schools. The presence of water bodies and open spaces helps to enhance the cooling effect through evaporation and air circulation, thereby creating a more stable and comfortable microclimate (Deng et al. 2022, Febrita et al. 2021). Furthermore, Lasinrang Park is located in the city centre, surrounded

by shopping centres, major roads, high-rise buildings, and schools, which cause urban heat stress and high noise levels. This densely built-up environment also has the potential to obstruct airflow and increase heat reflection from hard surfaces (such as asphalt and concrete) (Amani-Beni et al. 2021, Sari 2021). Lasinrang Monument Park borders a main road and office buildings, resulting in moderate levels of heat exposure and urban noise, depending on traffic intensity (Amani-Beni et al. 2021, Sari 2021). Meanwhile, Bau Masepe Stadium Park is located on an inter-district road, in a relatively dense residential area, and near a body of water (river). This combination can have mixed effects: on the one hand, the presence of water and surrounding vegetation supports a cooling effect; on the other hand, high traffic volumes have the potential to increase temperature and noise levels (Deng et al., 2022). Differences in urban environmental contexts, such as proximity to highways, the type and density of buildings, the presence of water bodies, and the level of human activity, can influence the performance of each GOS in regulating the microclimate.

This disparity emphasizes the need for a thorough evaluation of the design and management of GOS in Pinrang Regency. Local governments and urban planners need to adopt an ecological and sustainability-based approach to GOS planning, ensuring that each site has sufficient vegetation, natural barriers to noise, and designs that support a balance between social and environmental aspects. Suppose there are no concrete steps to improve these conditions. In that case, the differences in urban microclimate in each GOS will become more pronounced, and the main functions of GOS as microclimate regulators, carbon sequestration, and im-

provement of air quality and thermal comfort will not be maximised.

Identification of environmental parameter patterns through PCA

The results of the principal component analysis, visualised through the loading plot in Figure 5 and supported by the eigenvectors in Table 3, show that two main factors dominate the variation of the data. The first component (PC1) is mainly influenced by temperature (0.486), sunlight intensity (0.483), wind speed (0.382), and noise level (0.375), which have high positive weights, while humidity (-0.488) has a negative weight. This indicates that high temperatures, vigorous sunlight intensity, and strong winds are associated with higher noise levels, while humidity tends to be lower. This phenomenon can be explained by increased human activity and changes in the physical properties of the environment due to hot and dry conditions. As shown in Table 4, the first two principal components (PC1 and PC2) collectively account for 84.3 % of the total variation in the dataset, indicating that they effectively represent the primary structure of the data.

The second component (PC2) is dominated by elevation (0.858), followed by wind speed (0.474), indicating that site elevation significantly affects wind speed, with data variability that PC1 cannot fully explain. Meteorological variables, such as temperature, humidity, and noise level have a small contribution to PC2, indicating that topographic factors play more of a role in distinguishing neighbourhood characteristics based on topographic aspects than weather conditions. The following components (PC3 to PC6) have relatively small loading patterns on the total data variation, so their contribution to the total

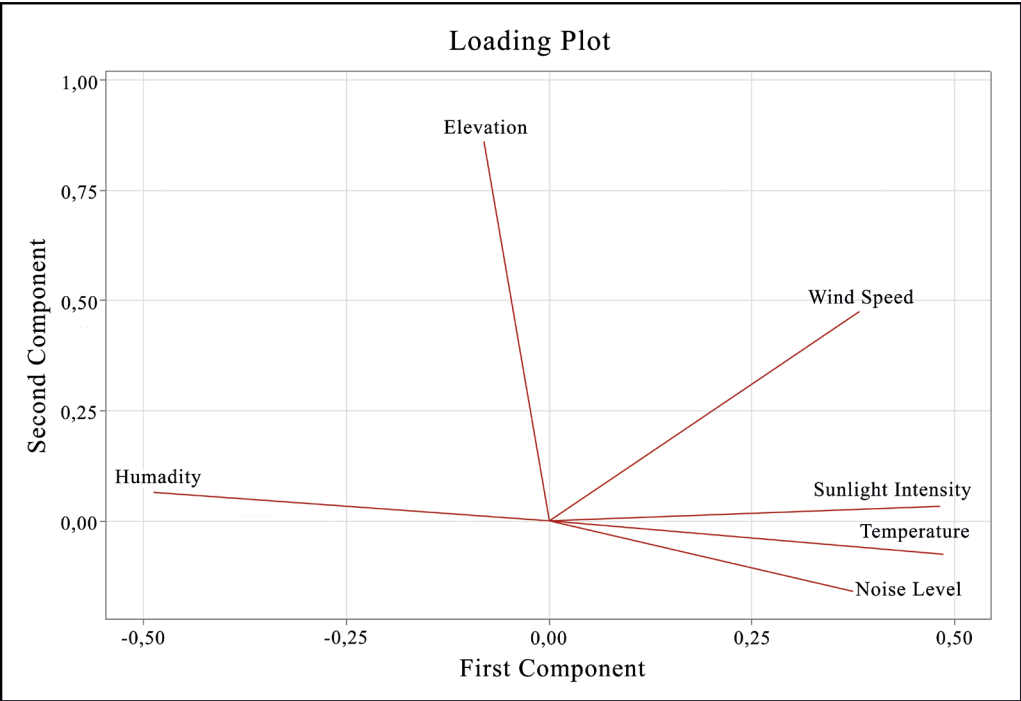


Fig. 5. PCA loading plot contribution of environmental variables to principal components.

Table 3. Eigenvectors.

Variable	PC1	PC2	PC3	PC4	PC5	PC6
Temperature	0.486	-0.076	0.163	0.137	0.742	0.402
Humidity	-0.488	0.065	-0.125	-0.345	-0.011	0.789
Sunlight intensity	0.483	0.033	0.220	0.290	-0.658	0.448
Wind speed	0.382	0.474	0.184	-0.763	-0.044	-0.107
Noise level	0.375	-0.161	-0.900	-0.132	-0.063	0.043
Elevation	-0.080	0.858	-0.255	0.423	0.104	0.026

Table 4. Eigenanalysis of the correlation matrix.

Principal component	Eigenvalue	Proportion of variance	Cumulative variance
PC1	3.8480	0.641 (64.1%)	0.641 (64.1%)
PC2	1.2123	0.202 (20.2%)	0.843 (84.3%)
PC3	0.5225	0.087 (8.7%)	0.930 (93.0%)
PC4	0.2519	0.042 (4.2%)	0.972 (97.2%)
PC5	0.0981	0.016 (1.6%)	0.989 (98.9%)
PC6	0.0672	0.011 (1.1%)	1.000 (100%)

data variation is lower than that of PC1 and PC2. Nonetheless, these components still reflect the specific contribution of each variable in local variations, such as temperature changes to noise levels in certain conditions or the impact of humidity in areas with particular elevations.

Overall, the results of this analysis categorise the variables into two main dimensions: 1) the meteorological dimension, which includes temperature, humidity, sunlight intensity, and noise, and 2) the geographical dimension, which includes altitude and wind speed. The negative correlation between humidity and other weather variables confirms that high-temperature environments tend to be drier and noisier. Meanwhile, altitude variations contribute significantly to wind speed,

broadly affecting atmospheric dynamics. Based on the PCA score plot visualisation in Figure 6 of six environmental parameters, each area has a different distribution pattern. Massepe Stadium Park (blue) tends to cluster in the negative quadrant of the first axis, indicating different environmental characteristics compared to the other sites. Lasinrang Monument Park (red) is more widely distributed on the first and second axes, suggesting a more dynamic variation in environmental parameters. Lasinrang Park (green) is in the negative quadrant of the first axis and positive quadrant of the second axis, indicating significant differences in ecological patterns compared to other locations. Meanwhile, Pinrang Urban Forest (purple) has a more sep-

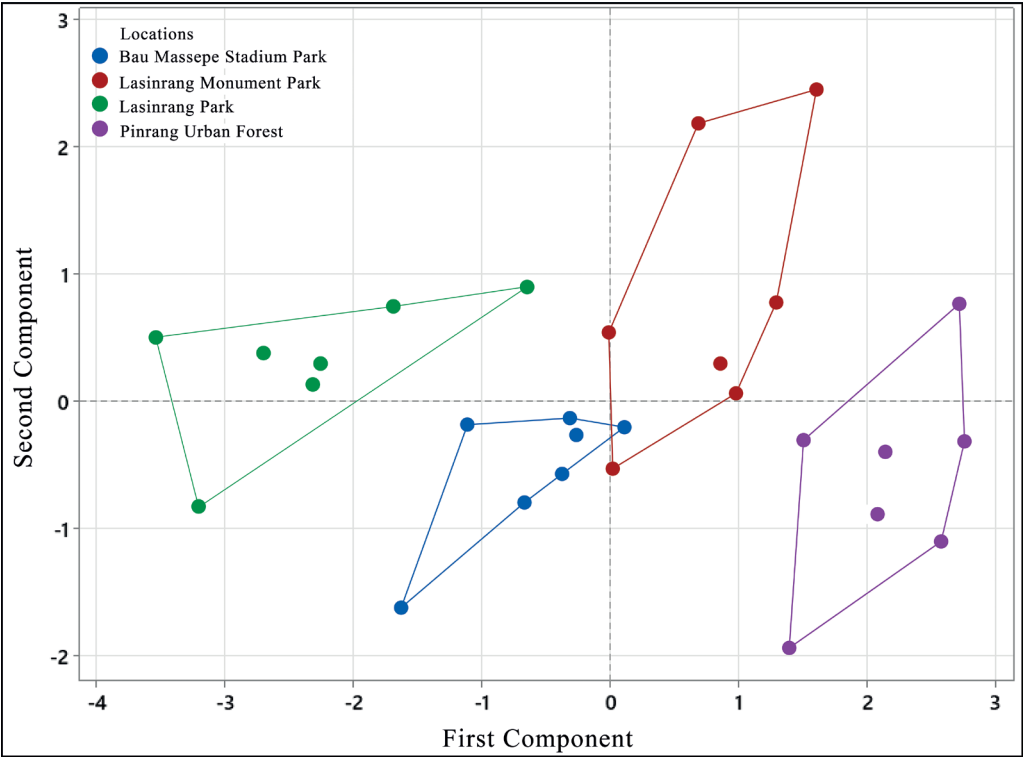


Fig. 6. PCA score plot of environmental parameters in four GOS locations.

arated distribution on the first axis with higher positive values, indicating unique characteristics that distinguish it from other sites. This distribution pattern reflects the microclimate conditions in each GOS that can be influenced by environmental factors, such as vegetation, topography, and human activities.

It should be noted that the PCA results presented here are exploratory in nature and do not imply definitive causal relationships between the variables. In addition, surrounding urban elements, such as building density, traffic, and human activity, may influence local microclimate measurements and therefore affect the patterns identified in the PCA. These factors are recognised as potential limitations of this analysis.

Conclusions

The results of this study show significant differences in environmental parameters between areas inside and outside GOS in Pinrang Regency. The analysis indicates that GOS is important in reducing air temperature, increasing relative humidity, reducing sunlight intensity, slowing wind speed, and muffling noise.

In particular, vegetation within GOS has been shown to reduce air temperature by 5–6 °C compared to areas outside GOS. The main mechanisms contributing to this cooling effect include evapotranspiration, the shading effect, and increased air humidity. In addition, the higher humidity inside the GOS, which reaches up to 15–20 % difference compared to the area outside the GOS, provides better thermal comfort for the community. The lower intensity of sunlight inside the GOS also strengthens its role as a natural shade, re-

ducing it by up to 70 % compared to open areas. In addition, wind speeds inside the GOS tend to be lower due to the barrier effect of the vegetation, which helps create a more stable microclimate environment. The study also confirmed that the vegetation within the GOS is an effective natural acoustic barrier, with a 10–15 dB reduction in noise levels compared to areas outside the GOS.

Based on the results of this study, it can be concluded that GOS not only functions as an aesthetic element of the city but also has a crucial role in maintaining the balance of urban ecosystems and improving the community's quality of life. Therefore, efforts to manage and develop GOS must continuously improve quantity and quality to mitigate the negative impacts of urbanisation and climate change. Considering these findings, it is recommended that local governments accelerate the realisation of the 30 % target area as GOS under applicable regulations. In addition, implementing more effective vegetation-based design strategies, such as increasing plant diversity, arranging tree canopies, and integrating water elements in GOS, can be a more optimal solution in supporting urban environmental sustainability.

However, it is important to note that the effectiveness of GOS in regulating the microclimate is influenced by various factors not examined in this study, such as tree age, vegetation density, seasonal variation, and historical land management. These factors may enhance or limit the environmental benefits observed. Therefore, future studies are encouraged to incorporate these elements to provide more comprehensive understanding of the role of vegetation structure and dynamics in urban climate regulation.

Acknowledgments

The authors thank the Department of Housing, Residential Areas, and Environmental Affairs of Pinrang Regency for granting permission and providing access to GOS data. Appreciation is also extended to Nurfadila BSc., Amanda BSc., Fitri-diana Sukardi BSc., Alwan Mahdi BSc., and Al Fitra Rosa Monica BSc. for their assistance in the field measurement process. Furthermore, the authors sincerely thank their family, Mr. La Bege BSc, and Mrs. Siti Hajrah, for their unwavering support throughout this research.

References

- ALUYAH C., RUSDIANTO 2019. The Influence of Types and Number of Trees on the Microclimate in the Bukit Siguntang Archaeological Park, Palembang City, South Sumatra Province. *SYLVA* 8(2): 53–59. <https://doi.org/https://doi.org/10.32502/sylva.v8i2.2696>
- AMANI-BENI M., ZHANG B., XIE G.D., ODGAARD A.J. 2021. Impacts of the microclimate of a large urban park on its surrounding built environment in the summertime. *Remote Sens (Basel)* 13, 4703. <https://doi.org/10.3390/rs13224703>
- BEUTE F., DE KORT Y.A.W. 2018. The natural context of wellbeing: Ecological momentary assessment of the influence of nature and daylight on affect and stress for individuals with depression levels varying from none to clinical. *Health & Place* 49: 7–18. <https://doi.org/10.1016/j.healthplace.2017.11.005>
- BOWLER D.E., BUYUNG-ALI L., KNIGHT T.M., PULLIN A.S. 2010. Urban greening to cool towns and cities: A systematic review of the empirical evidence. *Landsc Urban Plan* 97(3): 147–155. <https://doi.org/10.1016/j.landurbplan.2010.05.006>
- CLARK C., PAUNOVIC K. 2018. Who environmental noise guidelines for the European region: A systematic review on environmental noise and quality of life, wellbeing and mental health. *International Journal of Environmental Research and Public Health* 15(11), 2400. 27 p. <https://doi.org/10.3390/ijerph15112400>
- COLUNGA M.L., CAMBRÓN-SANDOVAL V.H., SUZÁN-AZPIRI H., GUEVARA-ESCOBAR A., LUÑA-SORIA H. 2015. The role of urban vegetation in temperature and heat island effects in Querétaro city, Mexico. *Atmosfera* 28(3): 205–218. <https://doi.org/10.20937/ATM.2015.28.03.05>
- DENG Q., ZHOU Z., SHAN X., LI C., LIU D. 2022. Effects of greening areas and water bodies on urban microclimate in Wuhan – a simulation study considering prospective planning. *Atmosphere (Basel)* 13, 725. <https://doi.org/10.3390/atmos13050725>
- DZHAMBOV A.M., DIMITROVA D.D. 2014. Urban green spaces' effectiveness as a psychological buffer for the negative health impact of noise pollution: A systematic review. *Noise & Health* 16(70): 157–165. <https://doi.org/10.4103/1463-1741.134916>
- DU H., ZHOU F., CAI W., CAI Y., XU Y. 2021. Thermal and Humidity Effect of Urban Green Spaces with Different Shapes: A Case Study of Shanghai, China. *International Journal of Environmental Research and Public Health* 18(11), 5941. 14 p. <https://doi.org/10.3390/ijerph18115941>
- EL MASRI J., FINGE H., AFYOUNI A., BAROUD T., AJAJ N., GHAZI M., EL MASRI D., YOUNES M., SALAMEH P., HOSSEINI H. 2024. The Effects of Green Spaces and Noise Exposure on the Risk of Ischemic Stroke: A Case–Control Study in Lebanon. *International Journal of Environmental Research and Public Health* 21(10), 1382. 13 p. <https://doi.org/10.3390/ijerph21101382>
- ENVIRONMENTAL PROTECTION AGENCY 2012. Reducing Urban Heat Islands: Compendium of Strategies. Trees and Vegetation. 29 p. <https://www.epa.gov/sites/default/files/2014-06/documents/treesandveg-compendium.pdf>
- ERLWEIN S., ZÖLCH T., PAULEIT S. 2021. Regulating the microclimate with urban green in densifying cities: Joint assessment on two scales. *Building and Environment* 205, 108233. <https://doi.org/https://doi.org/10.1016/j.buildenv.2021.108233>

- org/10.1016/j.buildenv.2021.108233
- FEBRITA Y., EKASIWI S.N.N., ANTARYAMA G.N.I. 2021. Urban river landscape factors impact on urban microclimate in tropical region. In: IOP Conference Series: Earth and Environmental Science 764, 012032. 8 p. <https://doi.org/10.1088/1755-1315/764/1/012032>
- GIDLÖF-GUNNARSSON A., ÖHRSTRÖM E. 2010. Attractive 'quiet' courtyards: A potential modifier of urban residents' responses to road traffic noise? *International Journal of Environmental Research and Public Health* 7(9): 3359–3375. <https://doi.org/10.3390/ijerph7093359>
- GUNAWARDENA K.R., WELLS M.J., KERSHAW T. 2017. Utilising green and bluespace to mitigate urban heat island intensity. *Science of the Total Environment* 584–585: 1040–1055. <https://doi.org/10.1016/j.scitotenv.2017.01.158>
- HUI Y., TANG Y., YANG Q., MOCHIDA A. 2024. Numerical study on influence of surface vegetation on aerodynamics of high-rise buildings. *Sustainable Cities and Society* 107, 105407. <https://doi.org/https://doi.org/10.1016/j.scs.2024.105407>
- HWANG B.M., SOU H.-D., OH J.-H., PARK C.-R. 2023. Cooling effect of urban forests on the urban heat island in Seoul, South Korea. *PLoS One* 18(7), e0288774. <https://doi.org/10.1371/journal.pone.0288774>
- INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE (IPCC) 2021. Weather and climate extreme events in a changing climate. In: *Climate Change 2021 – The Physical Science Basis*. Cambridge University Press: 1513–1766. <https://doi.org/10.1017/9781009157896.013>
- INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE (IPCC) 2023. Technical Summary. In: Masson-Delmotte V., Flato G.M., Yassa N. (Eds), *Climate Change 2021 – The Physical Science Basis*. Cambridge University Press: 35–144. <https://doi.org/10.1017/9781009157896.002>
- JOLLIFFE I.T. 2002. *Principal component analysis*, 2nd ed. Springer Verlag. 487 p. <https://doi.org/10.1007/b98835>
- KANJIR U., ĐURIĆ N., VELJANOVSKI T. 2018. Sentinel-2 based temporal detection of agricultural land use anomalies in support of common agricultural policy monitoring. *ISPRS Int J Geoinf* 7(10), 405. <https://doi.org/10.3390/ijgi7100405>
- KEMEN-ATR/BPN 2022. Regulation of the Minister of Agrarian Affairs and Spatial Planning/Head of the National Land Agency of the Republic of Indonesia Number 14 of 2022 concerning the Provision and Utilization of Green Open Spaces. <https://www.peraturan.go.id/>
- KRAEMER R., KABISCH N. 2022. Parks Under Stress: Air Temperature Regulation of Urban Green Spaces Under Conditions of Drought and Summer Heat. *Frontiers in Environmental Science* 10, 849965. 14 p. <https://doi.org/10.3389/fenvs.2022.849965>
- LI Y., SVENNING J.C., ZHOU W., ZHU K., ABRAMS J.F., LENTON T.M., RIPPLE W.J., YU Z., TENG S.N., DUNN R.R., XU C. 2024. Green spaces provide substantial but unequal urban cooling globally. *Nature Communications* 15, 7108. 13 p. <https://doi.org/10.1038/s41467-024-51355-0>
- LIVESLEY S.J., MCPHERSON E.G., CALFAPETRA C. 2016. The Urban Forest and Ecosystem Services: Impacts on Urban Water, Heat, and Pollution Cycles at the Tree, Street, and City Scale. *Journal of Environmental Quality* 45(1): 119–124. <https://doi.org/10.2134/jeq2015.11.0567>
- MARGARITIS E., KANG J. 2017. Relationship between green space-related morphology and noise pollution. *Ecological Indicators* 72: 921–933. <https://doi.org/https://doi.org/10.1016/j.ecolind.2016.09.032>
- MBAREP D.P.P., HASIBUAN H.S., MOERSIDIK S.S. 2021. The green open space functions as a water catchment area and a source of thermal comfort. In: IOP Conference Series: Earth and Environmental Science 716, 012127. 8 p. <https://doi.org/10.1088/1755-1315/716/1/012127>
- MUKRIMIN M., PRATIWI A.N., HASANUDDIN H., SULTAN S., HARTATI W. 2025. The urban forests affecting the environmental parameters in Makassar City, Indonesia. *J Nat Resour Environ Manag* 15(2): 335–346. <https://doi.org/10.29244/jpsl.15.2.335>
- MÜNZEL T., SCHMIDT F.P., STEVEN S., HERZOG

- J., DAIBER A., SØRENSEN M. 2018. Environmental Noise and the Cardiovascular System. *Journal of the American College of Cardiology* 71(6): 688–697. <https://doi.org/10.1016/j.jacc.2017.12.015>
- NOWAK D.J., GREENFIELD E.J., ELLIS A. 2022. Assessing Urban Forest Threats across the Conterminous United States. *Journal of Forestry* 120(6): 676–692. <https://doi.org/10.1093/jofore/fvac019>
- ORNELAS A., CORDEIRO A., LAMEIRAS J.M. 2023. Thermal Comfort Assessment in Urban Green Spaces: Contribution of Thermography to the Study of Thermal Variation between Tree Canopies and Air Temperature. *Land (Basel)* 12(8), 1568. 18 p. <https://doi.org/10.3390/land12081568>
- PARAMITA B., MATZARAKIS A. 2019. Urban morphology aspects on microclimate in a hot and humid climate. *Geographica Pannonica* 23(4): 398–410. <https://doi.org/10.5937/gp23-24260>
- RAHMAN M.M., HASAN J. 2024. Evaluating the impact of green spaces on urban heat reduction in Rajshahi, Bangladesh using the InVEST model. *Land (Basel)* 13, 1284. <https://doi.org/10.3390/land13081284>
- REY-GOZALO G., BARRIGÓN MORILLAS J.M., MONTES GONZÁLEZ D., VÍLCHEZ-GÓMEZ R. 2023. Influence of Green Areas on the Urban Sound Environment. *Current Pollution Reports* 9: 746–759. <https://doi.org/10.1007/s40726-023-00284-5>
- RIZWAN A.M., DENNIS L.Y.C., LIU C. 2008. A review on the generation, determination and mitigation of Urban Heat Island. *Journal of Environmental Sciences* 20(1): 120–128. [https://doi.org/https://doi.org/10.1016/S1001-0742\(08\)60019-4](https://doi.org/https://doi.org/10.1016/S1001-0742(08)60019-4)
- ROBERTS M., GIL SANDER F., TIWARI S. (EDS) 2019. *Time to ACT: Realizing Indonesia's Urban Potential*. World Bank. Washington, DC. 305 p. <https://doi.org/10.1596/978-1-4648-1389-4>
- RÖTZER T., MOSER-REISCHL A., RAHMAN M.A., PAULEIT S. 2023. Urban Forest and Urban Microclimate. *Forests* 14(12), 2391. 4 p. <https://doi.org/10.3390/f14122391>
- SARI D.P. 2021. A review of how building mitigates the urban heat island in Indonesia and tropical cities. *Earth (Switzerland)* 2(3), 38. <https://doi.org/10.3390/earth2030038>
- SETIOWATI R., HASIBUAN H.S., KOESTOER R.H. 2018. Green open space masterplan at Jakarta Capital City, Indonesia for climate change mitigation. In: *IOP Conference Series: Earth and Environmental Science* 200, 012042. 8 p. Institute of Physics Publishing. <https://doi.org/10.1088/1755-1315/200/1/012042>
- SHI L., WURM M., HUANG X., ZHONG T., LEICHTLE T., TAUBENBÖCK H. 2022. Estimating housing vacancy rates at block level: the example of Guiyang, China. *Landsc Urban Plan* 224, 104431. <https://doi.org/10.1016/j.landurbplan.2022.104431>
- STATISTICS INDONESIA (BPS) PINRANG REGENCY 2023. *Gross Regional Domestic Product Report of Pinrang Regency*. <https://pinrangkab.bps.go.id/petasitus.html>
- SYAFITRI R.A.W.D., PAMUNGKAS A., SANTOSO E.B. 2020. The Impact of Urban Configuration to the Urban Heat Island in East Surabaya. *IPTEK Journal of Proceedings Series No. 6*: 470–477. <https://doi.org/10.12962/j23546026.y2020i6.11145>
- TAKEBAYASHI H., KASAHARA M., TANABE S., KOUYAMA M. 2017. Analysis of solar radiation shading effects by trees in the open space around buildings. *Sustainability (Switzerland)* 9(8), 1398. 9 p. <https://doi.org/10.3390/su9081398>
- VARŞAK N.A., ALTAY E.E. 2024. Thermal Comfort and Green Spaces: The Role of Temperature-Regulating Elements in Neighborhood Parks. *Sustainability (Switzerland)* 16(22), 9801. 19 p. <https://doi.org/10.3390/su16229801>
- WU B., LIU C. 2023. Impacts of Building Environment and Urban Green Space Features on Urban Air Quality: Focusing on Interaction Effects and Nonlinearity. *Buildings* 13(12), 3111. 13 p. <https://doi.org/10.3390/buildings13123111>
- WU C., LI J., WANG C., SONG C., HAASE D., BREUSTE J., FINKA M. 2021. Estimating the cooling effect of pocket green space in high density urban areas in Shanghai, China. *Front Environ Sci* 9, 657969. <https://doi.org/10.3389/fenvs.2021.657969>

- WU T., ZHAO Y., WANG S., SU H., YANG Y., JIA D. 2021. Improving the accuracy of fractional evergreen forest cover estimation at subpixel scale in cloudy and rainy areas by harmonizing Landsat-8 and Sentinel-2 time-series data. *IEEE J Sel Top Appl Earth Obs Remote Sens* 14: 3373–3385. <https://doi.org/10.1109/JSTARS.2021.3064580>
- YAN L., JIA W., ZHAO S. 2021. The cooling effect of urban green spaces in metacities: a case study of Beijing, China's capital. *Remote Sens (Basel)* 13, 4601. <https://doi.org/10.3390/rs13224601>
- ZANNIN P.H.T., ENGEL M.S., FIEDLER P.E.K., BUNN F. 2013. Characterization of environmental noise based on noise measurements, noise mapping and interviews: A case study at a university campus in Brazil. *Cities* 31: 317–327. <https://doi.org/https://doi.org/10.1016/j.cities.2012.09.008>
- ZHANG T., ZHANG J., YANG N., LI J., GAO Y., ZHANG L., LI S. 2025. Cooling effects of urban park green spaces in downtown Qingdao. *Sustainability (Switzerland)* 17(10), 4521. <https://doi.org/10.3390/su17104521>
- ZHAO H., WANG S., ZHANG Y., ZHAO L., ZHAI Y., BROWN R.D., JIN L., WU R. 2023. The effect of solar radiation on pedestrian thermal comfort: A climate chamber experiment. *Build Environ* 245, 110869. <https://doi.org/https://doi.org/10.1016/j.buildenv.2023.110869>
- ZITER C.D., PEDERSEN E.J., KUCHARIK C.J., TURNER M.G. 2019. Scale-dependent interactions between tree canopy cover and impervious surfaces reduce daytime urban heat during summer. *Proceedings of the National Academy of Sciences of the USA* 116(15): 7575–7580. <https://doi.org/10.1073/pnas.1817561116>

Community and forest linkages in food, water, fuelwood of community residing nearby Wan Abdul Rachman Forest Park, Indonesia

Zainal Abidin^{1*}, Muhammad Irfan Affandi², Hari Kaskoyo³,
Dewi Lengkana⁴, and Eny Puspasari⁵

¹Department of Agribusiness, Faculty of Agriculture, University of Lampung, Jl. Soemantri Brojonegoro 1, Bandar Lampung 35145, Indonesia. *E-mail: zainal.abidin@fp.unila.ac.id

²University of Lampung, Jl. Soemantri Brojonegoro 1, Bandar Lampung 35145, Indonesia. E-mail: irfan.affandi@fp.unila.ac.id

³Department of Forestry, University of Lampung, Jl. Soemantri Brojonegoro 1, Bandar Lampung 35145, Indonesia. E-mail: hari.kaskoyo@fp.unila.ac.id

⁴Department of Science Education, University of Lampung, Jl. Soemantri Brojonegoro 1, Bandar Lampung 35145, Indonesia. E-mail: dewi.lengkana@fkip.unila.ac.id

⁵Regional Technical Implementing Unit (RTIU) of Wan Abdul Rachman Forest Park, Jl. Wan Abdul Rachman, Bandar Lampung 35158, Indonesia. E-mail: enypuspa2015@gmail.com

Received: 20 April 2025 / Accepted: 18 July 2025 / Available online: 24 July 2025



Open Access: This work is distributed under the Creative Commons Attribution 4.0 License.

Abstract

Wan Abdul Rachman Forest Park (WARFP) serves various benefits to Lampung Region such as: water, food, cash crops, energy, and ecosystem services. Since WARFP is located nearby a city, it is under constant pressure from human. This study intends to identify how community is dependent on WARFP in terms of food, economy, water, and energy, especially fuelwood. The study involves 61 forest farmer members of Regional Technical Implementing Unit (RTIU) of WARFP. The study employs a mixed-method approach, combining qualitative descriptive techniques and quantitative analysis. Five components were used to assess the level of dependence, namely: 1) use of forest resources such as water, fuelwood, medicinal plants, and food, 2) economy, 3) environment, 4) access and rights to the forest, 5) participation. The study suggests that forest farmers were highly dependent on WARFP in terms of water, food sources, fuelwood energy, economy, and protection of forest from natural hazards such as flooding and forest fire. The community also enjoy the rights to cultivate forest land under partnership. However, participation from forest farmers are still limited and therefore necessary to be improved.

Key words: family expenditures, non-timber products, partnership, mix method.

Introduction

According to Liddle et al. (2016) and Si-amabele et al. (2020), community based

natural resource management (CBNRM) has various meanings. They suggested CBNRM as a process where local people or organisation/s manage themselves

of their surrounding natural resources. In this view, local community is the proper institution to manage local resources.

In residential areas that border forest areas, people lives are very much determined by the forest (Poudyal et al. 2018). In general, communities living in areas around forests are poor due to limited resources and non-agricultural work as opportunities for non-agricultural activities are very limited. Study by Sunderlin et al. (2005) and Suyanto et al. (2007) state that there is a causal relationship between forest destruction and increasing poverty in developing countries.

According to Newton et al. (2016) the term forest dependency is a term to describe communities that benefit from forests. More specifically, the term describes poor communities including indigenous, traditional communities in developing countries. This occurs in many part part of the world like in Europe, Africa, Asia, and Latin America. A study by Talpă et al. (2022) in Moldova identified various types of forest products used by the community such as for food, firewood, medicine, fruits, seeds, etc. The study stated that the frequency of taking forest products was 314 times annually with a distribution for taking fuel of 44.59 %, nuts 11.78 %, straw mushrooms 17.58 %, medicinal materials 12.74 %, dog rose 11.15 %, fruits 2.74 %, and seeds 1.27 %. So, the use of forest products for fuel and food is very dominant in Moldova. In Tanzania, a study done by Ntiyakunze and Stage (2022) suggested the important of forest to alleviate poverty. In their study, using multiple linear analysis they proved that variables influencing dependence on forests are: 1) income with a negative coefficient, 2) distance to the forest with a negative coefficient, 3) off-farm activities with a negative coefficient, 4) land size

with a positive coefficient, and 5) area with a positive coefficient. These results indicate that the higher the income, distance to the forest, and off-farm activities, the less dependence on forests will be. Other study using multiple regression by Chu et al. (2019) suggested gender, ethnicity, farming experience, area of managed forest, access to non-timber products, environmental services and participation in training have a very significant impact on household income.

This study is intended to investigate degree of dependency of community on Wan Abdul Rachman Forest Park (WARFP) an area set for conservation zone according the Decree of the Minister of Forestry Number 408/Kpts-II/93. This area has high natural resource potential, including various fauna species such as the Sumatran tiger, Sumatran elephant, siamang, monkey, and hornbill, as well as various types of flora such as Medang (*Actinodaphne nitida* Teschn.), Pulai (*Alstonia scholaris* (L) R.Br., Durian (*Durio zibethinus* L.), Gintung (*Bischofia javanica* Blume), rattan, orchids, and ferns. In addition, this area also plays an important role in the conservation of germplasm and supports education, research, science, cultivation, culture, tourism, and recreation activities.

However, current conditions show that several species, such as the Sumatran tiger and Sumatran elephant, are no longer found in WARFP, which is most likely due to habitat destruction. However, based on the installation of camera traps by WWF in 2017, other protected species were found. The WARFP area faces significant management challenges, particularly because, as of 2019, open land accounted for 18,471 ha out of a total area of 22,249 ha – approximately 83 %. This is due to community activities that utilize the

land for plantation crops, especially coffee. The conservation partnership policy is expected to overcome this problem. According to Lampung Provincial Regulation Number 13 of 2019, this area is included in the Provincial Strategic Area which has an important influence on the economy, social, culture, environment, and technology in Lampung Province (Lampung Forest Agency 2020). Kristin et al. (2018) has concluded moderate interaction between community and forest in WARFP. The interaction was mostly in terms of getting benefits from land cultivation inside forest. But, high interactions with forest were shown by farmers who owned medium land cultivation in the forest. Further, farmer with low income tend to be more active in farm activities inside the forest.

Other study by Arianto et al. (2018) summarized the valuation of water service of WARFP forest to community both for domestic used and for paddy using Contingent Valuation Method or Willing to Pay. Their study concluded that in terms of value of water service, the WARFP provided more than IDR 10 billion (€ 527 thousand) annually for Batu Putuk Village.

Since the proximity of WARFP to population and economic centre in Lampung, this park is of strategic important to the region, especially for Bandar Lampung City, the capital of Lampung Province. On the other hand, community who resides nearby and run smallholder agroforest farming use WARFP as the most important source of livelihoods. This study intends to analyse the dependence of community residing in the border of WARFP in terms of the use of forest resource such as water, fuelwood energy, economy, environment, access on forest, and participating in guarding forest.

Object and Method

Research site and time of study

The study was held in Bogorejo Village, Gedong Tataan Subdistrict, Pesawaran Regency of Lampung Province (Fig. 1). The site is located around 25 km north-east of Bandar Lampung City, capital city of Lampung Province. According to Badan Pusat Statistik (2024), Bogorejo village has area of 1744 ha with a population of 5436 people of which 51 % were male. Further, population density was 3 people per ha.

The reasons to choose the site are explained in following. First, this village has direct border to WARFP and around 45 % of the population has been active farmers in WARFP. The second, forest farmers in the study site has been awarded partnership status by Forestry Agency which allows them to lawfully cultivate land inside forest with condition of farmers should enhance forest condition. The third is that farmers' groups have shown good performance in maintaining forest condition.

According to Lampung Forest Agency (2020), WARFP has an area of 22,249.31 ha in which land covers are grouped into three:

1. Primary forest – 3304.74 ha or 15 %;
2. Secondary forest – 12,968.07 ha or 58 %;
3. Farmland – 5976.5 ha or 27 %.

It is obvious that big part of WARFP has been used for agriculture activities, predominantly with agroforest farming.

The study was carried out from July to November 2024 which consists of the following steps:

1. Preparation;
2. Preliminary observation;

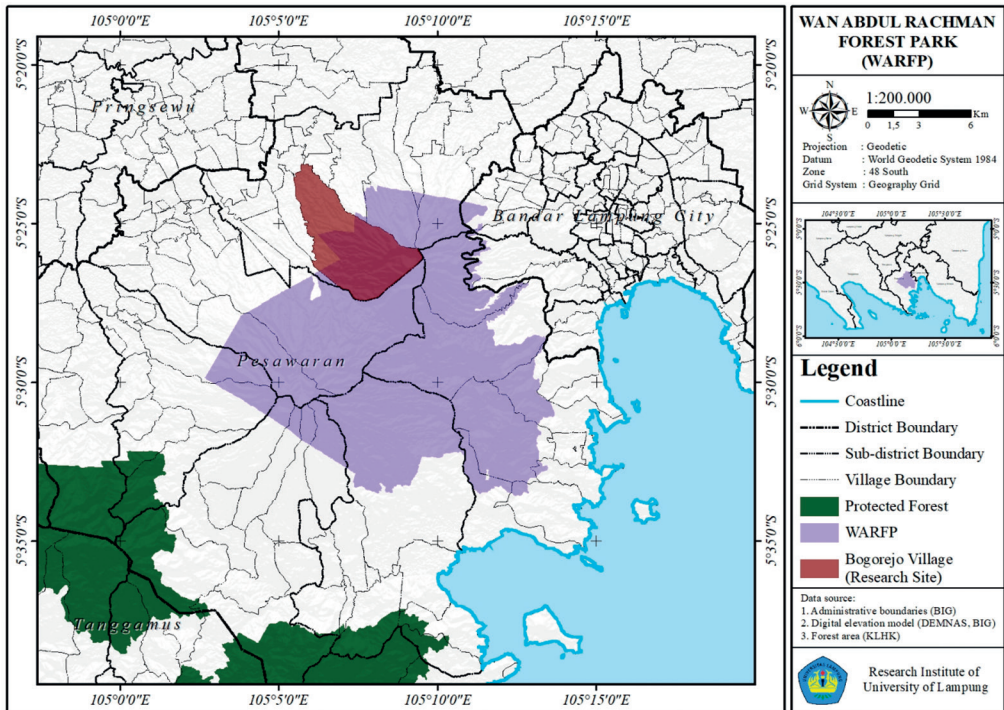


Fig. 1. Map of research site.

3. Developing research instrument (mainly questionnaire);
4. Field data collection;
5. Data analysis;
6. Reporting.

Respondents

Respondents are selected purposively, i.e.: farmers reside nearby of WARFP and are members of Forest Farmers Group (FFG) that has been given as partner by technical unit of WARFP. Partners status is a recognition for their activity and has rights to have access in using and getting benefits from forest. However, they are not allowed to cut trees inside the forest.

Sample size was determined using the approach Isaac and Michael (1995) by formula (1).

$$n = \frac{N \cdot Z^2 \cdot \sigma^2}{N \cdot u^2 + Z^2 \cdot \sigma^2}, \quad (1)$$

where: N = 229 – population of farmers or members of FFG; n – sample size; Z – z distribution with validity of 95%, i.e. $Z = 1.96$; σ – standard of deviation set at 0.25; u – error estimate at 5.5 %, i.e. $u = 0.055$.

With this formula, the total sample size is 61. Distribution of respondents are allocated in 8 FFGs as shown in Table 1.

Analysis

The study uses mix method (Creswell and Clark 2007) a combination of 1) descriptive qualitative analysis and 2) quantitative data analysis. Qualitative data analysis is the dependent of community towards for-

Table 1. Distribution of sample/respondents.

FFGs	Members (persons)	Proportion, %	Respondents
E	35	15	9
F	18	8	5
G	15	7	5
K	20	9	5
L	25	11	7
MJ	32	14	8
N	43	19	11
O	41	18	11
Total	229	100	61

est from 5 components as summarised by Angelsen et al. (2011) and FAO (2020):

1. The use of forest resource;
2. Economy;
3. Environment;
4. Access and rights on forest;
5. Participation in forest management.

Each component is scored: 1 – very low to 5 – very high.

The quantitative analysis designed to determine the influence of size of land cultivation inside WARFP to family income, the study employs simple regression. The model is provided by equation (2) (Gujarati 2004, Wooldridge 2012).

$$y = \beta_0 + \beta_1 \cdot x + \mu, \quad (2)$$

where: y – family income per year, IDR per year; – intercept; – error term. β_1 – slope coefficient, representing the change in family income per additional hectare of land cultivated within WARFP; x – size of land cultivated within WARFP, ha.

The reason to use size of landholding inside WARFP as independent variable is due to land status and has caused long term conflict between community nearby forest and government. By giving tenurial status or right to cultivate inside conservation forest, it supports policy of welfare

and stability in the region or called forest conserved while enhancing community's welfare.

Results and Discussion

Characteristics of respondents

As stated in previous chapter, the research respondents were the Bogorejo Village community who live around the WARFP area and are members of the Gapoktanhut or Aggregation of Forest Farmers Group (AFFG) of Wana Karya. According to the Guideline of Forest Farmer set in the Ministry of Environment and Forestry Regulation No. P. 89 year 2018 Farmers Group (FG) is a group of Indonesian citizen farmers who manage businesses in the forestry sector inside and outside forest areas. The aggregation of FFGs is hereinafter referred to as AFFG (Ministry of Environment and Forestry Republic of Indonesia 2018).

Tables 2a and 2b summarise some socio-economic characteristics of the respondents. It suggests that majority of respondents were male and the majority were born in the research site. In terms of age, the youngest respondent was 22 years while the oldest 73 year, and the median age was 54 year. This suggests that respondents are at stage of heading to aging farmers shown with median age.

Table 2a. Quantitative characteristics of respondents.

Variable	Minimum	Maximum	Median
Age, years	22	73	54
Land rights inside WARFP, ha	0.08	4.03	1.00
Number of family members (persons)	1	4	3

Table 2b. Categorical characteristics of respondents.

Variable	Category	Frequency
Education level	elementary school	39 (64%)
	junior high school	15 (24%)
	senior high school	5 (8%)
	not attending school	2 (4%)
Gender	Male	54 (89%)
	Female	7 (11%)
Place of birth	in village	53 (87%)
	outside village	8 (13%)

In terms of education, majority of respondents has completed elementary school (64 %) and very few (8 %) has completed senior high school. Furthermore, in terms of land tenure ship inside WARFP, the data suggests the land rights were ranging from very small (0.08 ha) to quite large (4.03 ha). However, the rights to cultivate is limited only to undertaking agroforest system. They are not allowed to cut trees or clear land for growing food crops, such as paddy, cassava, or maize.

Analysis of community dependent on WARFP

1. The use of forest resources

Sources of clean water

Clean water sources consist of four types, i.e.: well, pipe water, creeks, and springs. The most dominant source of clean water is pipe water. Source of water for pipe water service is from WARFP. The pipe water system is actually clean water services provided by community for community. The system is benefitting from abundance sources of water inside forest area. Abidin et al. (2023) study on analysis of water consumption in area nearby WARFP suggests that supply of water from protected forest has been far more than what communities daily needed. Their study suggests that the use of surplus water is

very minimum. Abidin et al. (2024) concluded that community in nearby WARFP obtained surplus in water supply as their consumption is less than what they daily obtained. Further, water from WARFP was essential as source of water needs. The data suggests of high dependency of community to WARFP in terms of water. Sources of water of community are presented in Table 3.

Table 3. Sources of clean water.

No	Main source of clean water	Location	Percentage
1	Well	hamlet	11
2	Pipe water	WARFP	69
3	Creeks	hamlet	3
4	Spring water	WARFP	17
Total			100

From Table 3, it is concluded that the majority of respondents use pipe and spring water coming from WARFP. This revealed water from WARF has been important source for community living nearby. The picture of the community's dependence on water and forests is described well by Wohlleben (2023) and sketches how local people nearby forest has used waters serves by forest ecosystem. Gilmour (2014) explained in detailed about the relationship of forest water and community. He explained about the relationship between forest and water yield and provision of water downstream. He concluded that the better the forest, the better water yield and hence more water service of forest to community. His explanation is consistent with this in which community is guarding forest that has served them with constant water supply.

Source of fuelwood

Although officially management of WARFP discouraged farmers to use woods from

WARFP, in reality most farmers (59 %) collect fuelwoods from WARFP for family fuelwood needs on weekly based. They took dried or fallen tree branches and transported them either on foot, bicycles, or on motorbike (Fig. 2). Type of branches mostly used was rubber trees. Each month, they collect woods at around 0.5 m³.



Fig. 2. A farmer collect fuelwood using bicycle.

In terms of energy spending such as for gas, gasoline, electricity, and fuelwood, monthly spending was about € 9.32. In addition, spending for fuelwood is very small, i.e. 5 %, thanks to availability of woods in WARFP. In this sense, forest helps farmers to provide cheap source of energy.

The dependence of community and fuelwoods as source of domestic energy is very common in many countries as

suggested by Brears (2023) and more comprehensively studied by Raihan and Tuspekova (2022). This study implied that policy of WARFP to discourage community to collect wood branches for fuelwood should not be rigorously implemented. Family expenditures for energy are quite high. Therefore, giving access for fuelwood from forest will help community reduce their family expenditures.

Source of food

Source of food were coming both from WARFP and the village. However, staple food such as rice, cassava, sweet potatoes, and corn were not grown in WARFP. Very few farmers did grow cassava or sweet potatoes within WARFP. Provision of staple food was mainly from village or sub-district markets. The study summarized community's dependent of staple food from WARFP that is presented in Table 4.

Therefore, community's dependent on staple food commodities from WARFP is considered very low.

However, a study by Maulita et al. (2022) reiterated the following plants related with food are grown well in WARFP. Among of them are fruit trees such as durian (*Durio zibethinus*), Duku (*Lansium domesticum* Corrêa), avocado (*Persea americana* Mill.), banana (*Musa* sp.), and rambutan (*Nephelium lappaceum* L.) (Lampung Forest Agency 2020). They are

Table 4. Summary of respondents' dependence on staple food from WARFP.

No	Level of dependence on staple food from WARFP	Range	Number of respondents
1	Very low	< 20 %	37 (61 %)
2	Low	20–40 %	0 (0 %)
3	Moderate	41–60 %	3 (5 %)
4	High	61–80 %	14 (23 %)
5	Very high	>80 %	7 (11 %)

considered important income sources but also for food as those fruits are highly marketable. Banana for example, is important commodity not only for local food, but also for local banana chips industries of nearby cities. Other commodity such as cocoa is important for income sources and also for food as Murniati et al. (2022) pointed out in their study recently. Therefore, vegetables and fruits plants grown in WARFP are important and farmers are highly depended on those plants.

Source of medicinal plants

In 2019, Mayangsari and Bintoro (2019) have identified 29 types of medicinal plants that are potentially beneficial to human as well as can be used for commercial purpose. They are widely grown in the area but not so many farmers are able to identify the benefits of those plants. Among important plants included: cogongrass (*Imperata cylindrica* (L.) P.Beauv.), temulawak (*Curcuma zanthorrhiza* Roxb.), billygoat-weed (*Ageratum conyzoides* L.), ebolo (*Crassocephalum crepidioides* (Benth.) S.Moore), and Koster's curse (*Climexia hirta* (L.) D.Don).

The study noted that 66 % of respondents recognized some medicinal plants grown widely in WARFP. Furthermore, 67 % have used medicinal plants for personal needs while 33 % of farmers did not use the plants. Therefore, the dependence of farmers from medicinal plants is

moderate. In Kenya, the number of farmers use medicinal plants for medicine is a lot higher. More than 75 % farmers in Western Kenya used medicinal plants taken from forest for medicine (Ojunga et al. 2023). Hence, further education for introducing medicinal plants to farmers is imperative.

2. Economy – family income and expenditures

Family income consists of the following sources: a) farming, b) non-farming, and c) off-farming. The study suggests that average income from farming was about 986 € per year in which farm income from WARFP contributed 92 % to it. This suggests high dependent of community from forest in terms of income as also shown by other study as stated in Suyanto et al. (2007) and Chu et al. (2019).

Influence of land permits on family income was analysed using simple regression model. Analysis concluded that income is significantly affected by landholding size, meaning larger landholding within forest results in higher family income. Statistics in Table 5 provide evidence that granting land rights in specific areas for farming – particularly agroforestry – supports community welfare while ensuring forest conservation.

Further, size of landholding inside forest has highly significantly influenced on family annual income, as shown in Table 6.

Table 5. Simple regression model between size of landholding inside forest and annual family income.

Anova	df	SS	MS	F	p-value
Regression	1	1.36785·10 ¹⁶	1.36785E+16	58.20541695	2.3222E-10
Residual	60	1.41002·10 ¹⁶	2.35003E+14		
Total	61	2.77786·10 ¹⁶			

Note: df – degrees of freedom, SS – sum of squares, MS – mean square, F – F-statistic, p-value – probability value.

Table 6. Influence of land cultivation inside WARFP on family annual income.

Variable	Coefficient	Standard Error	t-Statistic	p-value
Intercept	0	–	–	–
Land cultivation in WARFP (X_1)***	13,147,102.4	1,723,250.226	7.63	$2.11 \cdot 10^{-10}$

Note: *** significant at $p < 0.001$.

The contribution of independent variable in explaining family income is summarized in Table 7.

Table 7. Regression statistics.

Regression statistic	Value
Multiple R	0.702
R Square	0.492
Adjusted R Square	0.476
Standard Error	15,329,812
Observations	61

In addition, the R^2 value was 0.49, suggesting that 49 % of variation annual income was explained by land cultivation inside forest.

Family expenditure has been used to indicate the ability of family to purchase goods and services needed for family. There are two categories of family expenditure: food and non-food. The study suggests that average monthly food and non-food expenditures are presented in Table 8.

Table 8. Monthly family expenditures on food items.

No	Items	Expenditure, €	Share, %
1	Staple food (rice)	18.21	33
2	Side dishes	9.42	17
3	Vegetables	5.92	11
4	Fruits	0.99	2
5	Cooking oil	0.88	2
6	Drinks	0.21	0
7	Spices	0.10	0
8	Sugar	0.58	1
9	Cigarettes	6.96	12
10	Others	12.65	23

No	Items	Expenditure, €	Share, %
	Total	55.92	100

Note: 1 euro (€) = IDR 18,911.

The study reveals that staple food accounts for the highest proportion on food followed by other expenses (include eating outside the home) and side dishes. From Table 8, it is revealed that spending on cigarettes is relatively high – about 12 % of monthly spending. The majority of respondents (83 %) were active smokers. This number is consistent with national statistics, which reported that approximately 29 % of the Indonesian population are smokers (Indonesia Center of Statistics 2024).

In terms of non-food expenditures, the study summarised expenditures are shown in Table 9.

Table 9. Monthly family expenditure on non-food items.

No	Expenditure	Monthly, €	Share, %
1	Energy	9.31	17
2	Education and related spending	4.52	8
3	Health-related	0.52	1
4	Neighbourhood contribution	2.98	6
5	Transportation for all family	31.89	59
6	Soap, toothpaste, cosmetics	4.15	8
7	Helping families	0.70	1
	Total	54.07	100

Table 9 suggests that total monthly expenditure of family is approximately around € 55. The three items contributing most to family expenditures are transportation, energy, and education. Tables 8 and 9 show that total monthly expenditures amount to € 110 with food and non-food expenditures being almost equal, although food expenditure was slightly higher.

Furthermore, monthly expenditure *per capita* was about € 37, it is lower than monthly expenditure *per capita* of the Pesawaran Regency at around € 61 *per capita* (Badan Pusat Statistik 2024). Using monthly expenditure standard, people in the research site is above poverty line. The set of poverty line was € 27 per month *per capita* according to Badan Pusat Statistik Provinsi Lampung (2024).

Local market is crucial for ensuring that community products both from WARFP and in the village can be sold easily with no barriers. The study area has close access to local market as well as bigger market in Bandar Lampung, capital city of Lampung Province. With good road system, farmers can choose alternative local markets that offer the best for their products. In addition, most farmers used motorbike for transporting their agricultural products, such as coffee, rubber, and cocoa.

However, as typical of marketing of agricultural products, it usually positioned farmers in weak bargaining. Commodities such as rubber, cocoa, coffee are internationally traded and the information of price are available online and real-time.

For example, rubber farmers in this village could contact big buyers using cell phone asking information about price and usually they answer shortly. This is also happening for coffee or cocoa farmers which could be easily sold to the local merchants.

3. Dependent on forest environment

Protection from natural hazard

Respondents have expressed their thanks that living nearby forest has been protected from natural disasters. During rainy season, farmers reported no flooding in the village. During dry season, the environment is still green and water from forest was adequate to satisfy community's need.

To avoid forest fires, forest farmers group team up with Technical Unit of WARFP were doing intensive monitoring to anticipate such an incident of forest fire. In the last 3 years, accidents of forest fires have been reduced to very minimal number. According to officer of Regional Technical Implementing Unit (RTIU), in 2022, 2 forest fire incidents occurred during dry season in Bogorejo Village. That was because one farmer unintentionally set small fire for farming preparation but it turned to bigger fire. In 2023 and 2024, forest fire incidents were down to none.

Good quality of environment

The community overwhelmingly felt very lucky living nearby WARFP in terms of good quality environment they benefit. Community enjoys the forest that they access on daily basis. The study found out that 92 % agreed that environmental condition has been improving as WARFP forest was improving. They feel the improvement also increases their living conditions.

With good environment, community feel their life is better not only in terms economy, but also environmental aspect. There is strong connection of economy and environment according to locals. For example, production of rubber inside WARFP has always been good.

4. Access of ownership

The WARFP is a conservation forest and therefore a state-owned property. The community holds no ownership rights over this land. However, according to Lampung Forest Agency (2020), approximately 76 % of the WARFP area has been cultivated by farmers. At the same time, the removal of farmers from within the forest was neither socially nor politically acceptable.

Instead, the Government of Indonesia employed social forestry model and set regulation of Ministry of Forestry No 83/2016 on social forestry. In it, partnership in conservation forest is regulated in order to educate and empower community residing nearby forest. Settlement inside the forest is no longer permitted. However, community is still given access of their old parcels, as long as they grow trees/agroforestry and not to harvest forest.

Community could also be given rights to use water resources from the forest as long as it is not for commercial use. The partnership has created the so-called win-win solution for government and for farmers in WARFP. In the past, community and officers of forest park has been at odd due to strict regulation stating that in conservation forest, farmers were not allowed to access and take benefits of forest. With this partnership, community has been granted access and took benefits from forest. In partnership, forest farmer groups in WARFP have also obligation to control and monitor forest on regular basis. Farmers have to report should any illegal activities in the forest occur, such as illegal logging. This in turns have reduced the incidents of illegal logging in the area. Such positive outcome of partnership also reported in other region in Indonesia. Henceforth, partnership in conservation

forest increase community engagement and trust as well as welfare.

5. Participation in guarding forest

Facing budget and personnel constraints, the Technical Unit of WARFP has had to work closely with nearby forest farmers to ensure forest integrity and conserve local flora and fauna. At the same time, the RTIU of WARFP has created opportunities for farmers to pursue new economic prospects, such as supporting palm sugar production, providing ecotourism education, offering training in tree grafting, and assisting with participatory mapping.

The majority of farmers (67 %) knew well WARFP boundary. On average, farmers went to WARFP 5 times to do farming activities as many regular farmers, except this case the farm inside conservation forest. The respondents refused to answer their respond should any illegal activities occurred in their area. This is very concerning because the partnership was designed to secure farmers access to conservation forest and in return farmers are expected to help government in monitoring the forest situation. Summary of community dependence on WARFP is presented in Table 10.

Conclusion

The study found that the community residing near the forest was dependent on WARFP. They are highly dependent on water, fuelwood (energy), medicinal plants, food, income sources, and good quality of environment. Rights to cultivate lands inside WARFP not only enhance welfare but also maintain forest conditions. Forest farmers also enjoyed forest protection from natural hazards such as

Table. 10. Summary of community dependence on WARFP.

No	Components	Notes	Level on dependence (1–5)
1	Use of forest resources:		
	a. Water	Close to 70 % of community fulfil water needs from WARFP.	5
	b. Fuelwoods	Use of fuelwood is limited due to office of WARFP regulation which did not allow for using fuelwood from forest. However, many farmers regularly use fallen tree branches for fuelwood.	4
	c. Foods	Staple foods (rice, corn, and cassava) are not from WARFP. However, banana, some fruits such as: durian, jackfruit, papaya, avocado are mostly from WARFP.	3
	d. Medicines	29 types of medicinal plants identified by Mayangsari and Bintoro (2019).	3
2	Economy:		
	a. Income sources	Coffee, chocolate, rubber, and durian are among important sources of family revenues.	5
	b. Local market	Nearby, local markets are open on weekly based where farmers could buy and sell non-wood forest products and imported goods. Farmers could also sell their product directly to bigger market in Bandar Lampung city or to exporters.	5
3	Environment:		
	a. Protection from natural disasters such as landslide, flooding, wind, and forest fire	Good forest provides protection to community nearby from flooding, landslide, and forest fire.	5
	b. Good quality of water and air		5
4	Access and ownership:		
	a. Access rights	All members of the community have been granted access to WARFP to obtain benefits such as obtain fruits, food, and water.	5
	b. Access to non-wood resources		4

No	Components	Notes	Level on de- pendence (1–5)
5	Participation on forest management	Active in controlling forest team with government unit. This community engagement helps reduces incidents of poaching, illegal cutting, and incidents of forest fire in the dry season. However, only few farmers, leader who actively monitor the forest situation. Community engagement is still limited.	3
Total score			49
Average			4.4 (high)

flooding and forest fires. However, participation to control and monitor forest is still limited. The study could be used as the basis for policy makers to continue facilitate people engagement in forest management in WARFP.

Acknowledgment

The authors acknowledge LPPM contribution in providing research facilities to make this study possible.

References

ABIDIN Z., AFFANDI M.I., NUGRAHA A., LENGKANA D. 2024. Analysis of water consumption in community-based water service surrounding Wan Abdul Rachman Forest Park, Lampung province. *Forestry Ideas* 30(1): 38–49.

ABIDIN Z., ZAKARIA W.A., ENDARYANTO T. 2023. Benefit and Sustainability of Community Water Services Near Forest in Besai Watershed, Lampung, Indonesia. *Journal of Sustainability Science and Management* 18(11): 185–197. <https://doi.org/10.46754/jssm.2023.11.014>

ARIANTO S., WULANDARI C., BAKRI S., YUWONO S.B. 2018. Economic Value of Water for Domestic and Rice Farms in Surrounding Wan Abdul Rachman Forest Park. *Ju-*

rnal Sylva Lestari 6(3): 46–55. <https://doi.org/10.23960/jsl3646-55>

ANGELSEN A., LARSEN H.O., LUND J.F., SMITH-HALL C., WUNDER S. (Eds) 2011. *Measuring Livelihoods and Environmental Dependence: Methods for Research and Fieldwork*. Center for International Forest Research. Bogor, Indonesia: CIFOR. 263 p.

BADAN PUSAT STATISTIK 2024. Pringsewu Regency in Figures 2024 [Kabupaten Pringsewu Dalam Angka 2024]. Jakarta: BPS, vol. 13. 381 p. (in Indonesian). Available at: <https://pringsewukab.bps.go.id/publication/2024/02/28/62c7ee004bed88aa8bcdec6b.html>

BADAN PUSAT STATISTIK KABUPATEN PRINGSEWU 2024. Poverty Line by Regency/Municipality in Lampung Province 2024 [Garis Kemiskinan Menurut Kabupaten/Kota di Provinsi Lampung 2024]. Pringsewu: BPS Kabupaten Pringsewu (in Indonesian). Available at: <https://pringsewukab.bps.go.id/id/statistics-table/2/Nzc5lzl=/garis-kemiskinan-menurut-ka>

BADAN PUSAT STATISTIK PROVINSI LAMPUNG 2024. Poverty by Regency/City in Lampung Province 2024 [Kemiskinan Menurut Kabupaten/Kota di Provinsi Lampung 2024]. Bandar Lampung: BPS Provinsi Lampung. Available at: <https://lampung.bps.go.id/id/statistics-table/1/NTgzlZE=/kemiskinan-menurut-kabupaten-kota-di-provinsi-lampung-2024.html>

BREARS R.C. 2023. The Green Economy and the Water-Energy-Food Nexus in Canada. In: *The Green Economy and*

- the Water-Energy-Food Nexus. Palgrave Macmillan, Cham: 229–255. https://doi.org/10.1007/978-3-031-39679-3_9
- CRESWELL J.W., CLARK V.L.P. 2007. Designing and Conducting Mixed Methods Research. Sage Publications, Inc. London. 6-12.
- CHU T.V., THOAI T.Q., AN C.Q., TOAI P.M., CAMACHO L.D., SAM H.V. 2019. Contribution of forest to rural households' livelihood: Evidences from the river basin in the north-west mountainous region of Vietnam. *Forest and Society* 3(2): 235–247. <https://doi.org/10.24259/fs.v3i2.7050>
- FAO 2020. The State of the World's Forest: Forest, Biodiversity and People. Rome: FAO. 188 pages. <https://openknowledge.fao.org/items/d0f20c1c-7760-4d94-86c3-d1e770a17db0>
- GILMOUR D. 2014. Forests and water: A synthesis of the contemporary science and its relevance for community forestry in the Asia-Pacific region. RECOFTC Issue Paper No. 3. RECOFTC – The Center for People and Forests, Bangkok, Thailand. 30 p. <https://www.recoftc.org/sites/default/files/publications/resources/recoftc-0000191-0001-en.pdf>
- GUJARATI D.N. 2004. Basic Econometrics. 4th Edition. McGraw Hill. Boston: 25–28.
- INDONESIA CENTER OF STATISTICS 2024. Percentage of Population Aged 15 Years and Over Who Smoked Tobacco in the Last Month by Province (Percent). Badan Pusat Statistik Indonesia (in Indonesian). Retrieved from <https://www.bps.go.id/id/statistics-table/2/MTQzNSMy/persentase-penduduk-berumur-15-tahun-ke-atas-yang-merokok-tembakau-selama-sebulan-terakhir-menurut-provinsi.html>
- ISAAC S., MICHAEL W.B. 1995. Handbook in research and evaluation: a collection of principles, methods, and strategies useful in the planning, design, and evaluation of studies in education and the behavioral sciences. San Diego, Edits Pub, 3rd edition. 262 p.
- KRISTIN Y., QURNIATI R., KASKOYO H. 2018. The Interaction of Community around the Forest towards Land Use Tahura Wan Abdul Rachman. *Jurnal Sylva Lestari* 6(3): 1–8 (in Indonesian). <https://doi.org/10.23960/jsl361-8>
- LAMPUNG FOREST AGENCY 2020. Profile of Wan Abdul Rachman Forest Park, Lampung Province. Bandar Lampung: Lampung Forest Agency. 41 p.
- LIDDLE E.S., MAGER S.M., NEL E.L. 2016. The importance of community-based informal water supply systems in the developing world and the need for formal sector support. *Geographical Journal* 182(1): 85–96. <https://doi.org/10.1111/geoj.12117>
- MAULITA K., ASMARAHMAN C., INDRIYANTO 2022. Species of Food-Producing Plants on Forest Stands at the Arable Area of KTH Sejahtera 4 in Tahura Wan Abdul Rachman [Jenis Tanaman Penghasil Pangan pada Tegakan Hutan di Areal Garapan KTH Sejahtera 4 dalam Tahura Wan Abdul Rachman]. *Garontalo Journal of Forestry Research* 5(2): 70–80 (in Indonesian). <https://doi.org/10.32662/gjfr.v5i2.2034>
- MAYANGSARI A., BINTORO A. 2019. Identification of Medicinal Plants in the Area of KPPH Farmer at Talang Mulya on Wan Abdul Rachman Great Forest Park. *Jurnal Sylva Lestari* ISSN 7(1): 1–9 (in Indonesian). <https://doi.org/10.23960/jsl171-9>
- MINISTRY OF ENVIRONMENT AND FORESTRY REPUBLIC OF INDONESIA 2018. Regulation of the Minister of Environment and Forestry Number P.89/MENLHK/SETJEN/KUM.1/8/2018 concerning Guidelines for Forest Farmer Groups [Peraturan Menteri Lingkungan Hidup dan Kehutanan Nomor P.89/MENLHK/SETJEN/KUM.1/8/2018 tentang Pedoman Kelompok Tani Hutan]. Jakarta: Kementerian Lingkungan Hidup dan Kehutanan. 24 p. (in Indonesian). <https://jdih.maritim.go.id/cfind/source/files/permen-lhk/p.89-2018-kth.pdf>
- MURNIATI, SUHARTI S., YENY I., MINARNINGSIH 2022. Cacao-based Agroforestry in Conservation Forest Area: Farmer Participation, Main Commodities and Its Contribution to the Local Production and Economy. *Forest and Society* 6(1): 243–274. <https://doi.org/10.24259/fs.v6i1.13991>
- NEWTON P., MILLER D.C., BYENKYA M.A.A., AGRAWAL A. 2016. Who are forest-de-

- pendent people? A taxonomy to aid livelihood and land use decision-making in forested regions. *Land Use Policy* 57: 388–395. <https://doi.org/10.1016/j.landusepol.2016.05.032>
- NTIYAKUNZE M.S., STAGE J. 2022. Forest dependence in Tanzania: Analysis of the determinants of perceived forest dependence. *Trees, Forest and People* 8, 100277. 9 p. <https://doi.org/10.1016/j.tfp.2022.100277>
- OJUNGA S.O., LANGAT D.K., OWANGE K., OTUOMA J., AYAGA G., MUSKITON K.C., WANYIRI M., ISACK M. 2023. Medicinal plants and their economic value in Kakamega Forest Ecosystem: A case study of sustainable land/forest project in Western Kenya. *Journal of Medicinal Herbs and Ethnomedicine* 9: 18–25. <https://doi.org/10.25081/jmhe.2023.v9.8193>
- POUDYAL M., RAKOTONARIVO O.S., RAZAFIMANAHAKA J.H., HOCKLEY N., JONES J.P.G. 2018. Household economy, forest dependency & opportunity costs of conservation in eastern rainforests of Madagascar. *Scientific Data* 5, 180225. 12 p. <https://doi.org/10.1038/sdata.2018.225>
- RAIHAN A., TUSPEKOVA A. 2022. Nexus between energy use, industrialization, forest area, and carbon dioxide emissions: New insights from Russia. *Journal of Environmental Science and Economics* 1(4): 1–11. <https://doi.org/10.56556/jescae.v1i4.269>
- SIAMABELE B., MULONDA M., KALIBA M., KALONJE V., MELINDA M. 2020. Community Based Natural Resource Management: Exploring the Benefits and Challenges. *International Journal of Humanities, Art and Social Studies (IJHAS)* 5(3): 33–44. <https://www.researchgate.net/publication/371695649>
- SUNDERLIN W.D., BELCHER B., SANTOSO L., ANGELSEN A., BURGERS P., NASI R., WUNDER S. 2005. Livelihoods, forests, and conservation in developing countries: An overview. *World Development* 33(9): 1383–1402. <https://doi.org/10.1016/j.worlddev.2004.10.004>
- SUYANTO S., KHUSUSIYAH N., LEIMONA B. 2007. Poverty and environmental services: Case study in Way Besai Watershed, Lampung Province, Indonesia. *Ecology and Society* 12(2), 13. 13 p. <https://doi.org/10.5751/ES-02070-120213>
- TALPĂ N., LOZA A., HĂLĂLISAN A.F., POPA B. 2022. Forest Dependence of Rural Communities in the Republic of Moldova. *Forests* 13(6), 954. 24 p. <https://doi.org/10.3390/f13060954>
- WOHLLEBEN P. 2023. The hidden life of trees: Graphic adaptation. Adapted by F. Bernard. Vancouver, BC: Greystone Books. 160 p.
- WOOLDRIDGE J.M. 2012. *Introductory Econometrics: Modern Approach*. 5th Edition. Cengage Learning. Mason OH: 878–912.