

CONTENTS

Borys Honcharenko and Olena Demchenko. Seasonal growth and development of taxa of the genus <i>Forsythia</i> Vahl in the conditions of Kyiv	211
Adriana Marinova and Svetoslav Anev. Impact of silvicultural interventions on growth and survival of <i>Fagus sylvatica</i> L. saplings.....	221
Vasil Kolev, Gradimir Guychev, and Alexander Mikhailichenko. Age-size structure and growth rate of <i>Barbus strumicae</i> (Cyprinidae) in the Mesta River, Southwest Bulgaria.....	233
Fembriarti Erry Prasmatiwi, Rusdi Evizal, Tri Novi Astuti, and Asyifa Rahmita Zahra. Agroforestry coffee reduces household vulnerability to climate change.....	244
Puji Lestari, Ahdiar Fikri Maulana, Ridla Arifriana, and Masendra. Inducible resistance of <i>Falcataria falcata</i> (L.) Greuter & R.Rankin for gall rust disease using plant extracts as elicitors	261
Krassimir D. Naydenov, Michel K. Naydenov, Alexander Alexandrov, Todor Gurov, Georgi Hinkov, Sofiya Ivanovska, Veselka Gyuleva, Silvi-Maria Gurova, Makech Balakumar, and Biljana Nikolic. Molecular markers vs. phylogeographic memory dilemma: an example of length-dependent mutation processes	272
Antoaneta Frantzova, Nikolai Dobrev, Plamen Ivanov, Miroslav Krastanov, and Boyko Berov. Review of satellite-based platforms and algorithms for near real-time monitoring of wildfires.....	288
Nexhat Balaj, Hyzer Rizani, Zenel Hajrizi, Adnan Gajtani, Nol Dedaj, and Lavdim Lepaja. Growth characteristics and flowering stage of some <i>Digitalis purpurea</i> L. cultivars and <i>Gaillardia</i> sp. Foug. in the agro-ecological conditions in Kosovo	297
Oussama Bekakra, El-Yamine Guergueb, Soumia Haddad, Yassine Noudjem, Choayb Bounab, and Hichem Khammar. Effect of the structural composition of a Saharan agricultural landscape on bird communities in the Algerian Northern Sahara.....	308
Kevin Ortega Quispe, Betty Cordova Torres, Meliza Molina Damas, Judith Oscanoa Ramos, Lucia Enriquez Pinedo, Itala Flores Torres, and Dennis Ccopi Trucios. An approach to the impact of weather variables on the growth of <i>Polylepis</i> species in the central Andes of Peru (RETRACTED).....	321

Seasonal growth and development of taxa of the genus *Forsythia* Vahl in the conditions of Kyiv

Borys Honcharenko¹  and Olena Demchenko^{2*} 

¹Department of Dendrology, M.M. Gryshko National Botanical Garden of the National Academy of Sciences of Ukraine, 1 Timiryazevska Str., 01014, Kyiv, Ukraine. E-mail: boris_nbs@ukr.net

²Department of Botany, Dendrology and Forest Tree Breeding, National University of Life and Environmental Sciences of Ukraine, 15 Heroiv Oborony Str., 03041 Kyiv, Ukraine.

*E-mail: demchenkoo@nubip.edu.ua

Received: 07 February 2024 / Accepted: 14 July 2024 / Available online: 02 August 2024



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

Abstract

In the Right-Bank Forest-Steppe of Ukraine, 6 species, 2 hybrids, 2 varieties and about 10 cultivars of the genus *Forsythia* Vahl are cultivated. The phenology of the species of the genus is not sufficiently covered in the literature. The available information is mostly about flowering and fruiting periods of individual species, varieties and cultivars at various points of introduction. Due to the lack of information on the rhythms of growth and development of plants of most taxa of the genus *Forsythia* in the Right-Bank Forest-Steppe of Ukraine, there was a need to conduct such studies. The purpose of the work is to recognize the features in seasonal rhythms of growth and development of *Forsythia* taxa in the Right-Bank Forest-Steppe of Ukraine and to study their consistency with the natural and climatic conditions of this region. The studied objects are within the normal limits of 3–4 phoenodata. Only *Forsythia ovata* Nakai, whose phenophases are shorter than normal, does not fit into this range. 20 % of the research objects are within the normal range for all phoenodata, and 93.33 % are within the normal range for 3–4 phoenodata. *F. giraldiana* Lingelsh., *F. ovata* 'Tetragold', *F. suspensa* (Thunb.) Vahl, *F. suspensa* var. *fortunei*, and *F. suspensa* var. *sieboldii*, growing in the city of Kyiv, are within the norm for the dates of onset of all phenophases and have an unused part of the growing season in reserve. In the majority of forsythias (86.67 %), the phenological atypicality indicator is less than 1, which indicates the correspondence of the seasonal rhythms of growth and development of most of the studied forsythias to the climatic conditions of the Right-Bank Forest-Steppe of Ukraine.

Key words: phoenodate, phenological abnormality indicator, phenology, phenophase.

Introduction

In Ukraine, over the years, 6 species, 2 varieties, 2 hybrids and more than 10 cultivars of the genus *Forsythia* Vahl have been introduced (Kokhno and Kurdyuk

1994). Six species, 2 varieties, 2 hybrids and 10 cultivars of the genus *Forsythia* grow in the Right-Bank Forest-Steppe of Ukraine (Andriienko et al. 2007; Honcharenko 2009, 2014).

It is known that fluctuations in the tim-

ing of the onset of any phenophase over the years mainly depend on the meteorological conditions of the year. The difference in the timing of the onset of the same phenophases in different species during the year indicates different rhythms of development that have developed in the process of phylogenesis (Plotnikova 1971).

The phenology of *Forsythia* taxa is not sufficiently covered in the literature. The available information is mostly about the flowering and fruiting periods of individual species, varieties and cultivars at various points of introduction (Visyulina 1957, Misnik 1976, Kokhno et al. 1991). Some information on the peculiarities of the growth and development of forsythia in the conditions of the city of Vinnytsia (Ukraine) are presented in the works of Matusiak and Vargatiuk (2020) and (Matusiak 2020). Information on the phenology of *Forsythia velutina* in Korea is given in the work of Sung et al. (2021). As there is a lack of information on the rhythms of growth and development of most *Forsythia* taxa in Right-Bank Forest-Steppe of Ukraine, we believe it is relevant to study these issues and to generalize them.

The purpose of the work is to recognize the features in the seasonal rhythms of growth and development of *Forsythia* taxa in the Right-Bank Forest-Steppe of Ukraine and to study their consistency with the natural and climatic conditions of this region.

Material and Methods

The research was conducted with the following taxa of the genus *Forsythia*: *F. giraldiana* Lingelsh., *F. × intermedia* Zab., *F. × intermedia* 'Densiflora', *F. × intermedia* 'Golden Ranchen', *F. × intermedia* 'Lynwood', *F. × intermedia* 'Spectabilis', *F.*

ovata Nakai, *F. ovata* 'Tetragold', *F. suspensa* (Thunb.) Vahl, *F. suspensa* var. *fortunei* (Lindl.) Rehd., *F. suspensa* var. *sieboldii* Zab., *F. suspensa* 'Decipiens', *F. suspensa* 'Variegata', *F. viridissima* Lindl., *F. europaea* Deg. et Bald. The research objects grow in open ground in the collection plantations of the M. M. Gryshko National Botanical Garden of the National Academy of Sciences of Ukraine, A.V. Fomin Botanical Garden of Taras Shevchenko National University of Kyiv, National University of Life and Environmental Sciences of Ukraine. The city parks and plantings of Kyiv were also surveyed. Research was conducted in 2010–2015.

Phenological observations were carried out according to the 'Methodology of phenological observations in botanical gardens of the USSR' (Lapin 1975). For the integral evaluation of each studied plant based on the complex of all its phenodata, we applied the phenological atypicality (F) and the phenological abnormality (F_1) indicators according to Zaitsev (1981). The phenological atypicality indicator or the average standard deviation is calculated without taking into account the signs of deviations according to formula (1), and the phenological abnormality indicator is calculated taking into account the signs of deviations according to formula (2).

$$F = \sum |t| \cdot n^{-1}, \quad (1)$$

$$F_1 = \sum t \cdot n^{-1}, \quad (2)$$

where: $t = (x - M) \cdot \sigma^{-1}$ – normalized deviations of features, x – the value of the characteristics of an individual, M – the arithmetic mean of the characteristic, σ – the root mean square deviation of the characteristic; n – the number of features in this complex.

Statistical processing of the data was

carried out according to the method of Zaitsev (1984). Six main indicators were determined: the arithmetic mean, its error, the root mean square deviation, standard deviation, the coefficient of variation and the indicator of accuracy of the experiment.

Phoenospectra were compiled according to the method of Bulygin (1985). Field data expressed as ordinary calendar dates are difficult to process mathematically, so they were converted into a continuous series of numbers in the form of the number of days starting from 1 March according to the method (Zaitsev 1981).

The phoenodates were statistically processed and summarized according to the following phenophases: the beginning of flowering, the end of flowering, the appearance of a green cone of leaves (vegetative bud break), the beginning and end of shoot growth, fruiting and the beginning of abscission. These phoenodata also made it possible to determine the duration of periods of flowering, growth of shoots and vegetation of the studied plants.

In total, 720 phoenodates (15 objects $\times$ 8 phenophases $\times$ 6 years) were statistically processed.

For each phenophase, there is an optimum combination of environmental factors, taking into account the qualitative difference of the phases. The arithmetic mean date of a phenological phase is the typical date of onset of a separate phase, and species with their mean phoenodates the closest to the general mean are in optimal conditions for the realization of the corresponding phenological phase. To assess the compliance of phoenodates with the general norm of one or another phenophase, standard deviations were used.

The phenological atypicality indicator

(F) or the average standard deviation, is calculated without taking into account the signs of deviations and characterizes the degree of compliance of the phenophases of a specific plant of a certain species with the environmental conditions in which it grows. The closer the F value is to 0, the more optimally the phenology of plants of a certain species is following the environmental conditions. At the same time, the plants not only receive everything necessary for their growth and development, but also use the available resources of the environment in most rationally during the growing season (Zaitsev 1981, 1983).

The phenological abnormality indicator (F_1) is calculated taking into account the signs of deviations and characterizes the degree of deviation of the phoenodata of the research object from the norm (its limits from -1 to +1) based on the complex of all phoenodata. This indicator is used to assess the degree of plant phenophase shift of a particular taxon in one direction or another compared to others. The sign of the indicator shows in which direction (late or early onset) the phoenodates of plants of a certain taxon deviate. The negative value of the indicator (F_1) means that the phoenodates of the plants of this taxon come earlier than the average ones, and these plants fit into the vegetation period of the area of their growth and, even, some part of the vegetation period remains unused. A positive value of this indicator demonstrates that plants of a certain taxon are late with their phenology compared to the general average terms, and with a large value of F_1 , it may not even have time to complete the seasonal cycle of its growth and development during the growing season (Zaitsev 1981).

Deviations are within the normal range if its absolute value is less than 1. If the

deviation with the '+' sign is greater than 1, then the corresponding phoenodata is longer than normal; if the deviation with the '-' sign is more than 1, then this phoenodata is shorter than normal in duration.

In accordance with the value of the indicator F_1 , Zaitsev (1981) created scale to assess the mismatch of the phenology of introduced species to the climate of the secondary range.

The characteristic of the climate of Kyiv is presented according to Vyshnevskiy et al. (2023). Observations have shown that average air temperatures in Kyiv are higher than in the suburbs. In clear weather

during the day, air temperature in the central areas of the city is 2.0–3.0 °C higher than in its outskirts. In the evening hours of summer, this difference can reach 6.0–8.0 °C. Data on the average monthly air temperature in the city are shown in Table 1.

Relative air humidity is highest in winter (primarily in December), lowest – in April–August (Table 2).

During 1991–2020, the average annual rainfall in Kyiv was 618 mm. On average, over many years, the most precipitation occurred in summer, the least in January–March (Table 3).

Table 1. Average air temperature in Kyiv by month during 1991–2020, °C.

Monts												Annual average
I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	
3.2	2.3	2.5	10.0	15.8	19.5	21.3	20.4	14.9	8.6	2.6	1.8	9.0

Table 2. Average relative air humidity in Kyiv for 1991–2020, %.

Monts												Annual average
I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	
84	80	72	61	62	64	66	64	71	77	85	86	73

Table 3. Typical rainfall in Kyiv by month for the period 1991–2020, mm.

Indicator	Monts												Sum
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	
Average	37	39	40	42	65	74	68	56	58	46	46	47	618
Min	9	12	7	2	25	7	6	3	5	0	5	11	450
Max	59	79	113	123	172	190	153	132	211	110	98	133	805

Among the other factors influencing the climate of the city is its terrain, including significant differences in elevation between its left-bank and right-bank parts. The left-bank area has a typical height of 100–110 m above sea level, while the right-bank area ranges from 140 to 160 m. The highest points reach elevations of 195–197 m, whereas the lowest points correspond to the level of the Dnipro River, approximately 91.5 m.

Results and Discussion

After calculating the standard deviations from the arithmetic mean for specific phenophases in the array of species, we determined the species whose individual phenophases occur at optimal times (Table 4). The phase of 'flowering bud break' takes place at the optimal time in *Forsythia × intermedia* 'Lynwood', *F. ovata* 'Tetragold', *F. suspensa* 'Decipiens', *F. sus-*

Table 4. Average annual phenodates of species, varieties, hybrids and cultivars of the genus *Forsythia* in Kyiv, 2010–2015.

Species, hybrids, varieties, cultivars	Flowering			Duration of shoot growth, days	Fruiting	Beginning of abscission	Vegetation duration, days	Phenological	
	Flowering bud break	Beginning	End					atypicality indicator F_1	Phenological abnormality indicator F_2
<i>Forsythia europaea</i>	29.40 -1.853	45.20 -0.606	65.20 0.053	20.00 1.041	117.00 -0.801	—	244.6 -0.503	0.75 -0.73	—
<i>F. giraldiana</i>	38.6	46.40	62.4	16.00	122.40	—	236.20	0.81	—
	0.538	-0.216	-0.681	-0.974	-0.439	—	-1.814	-0.54	—
<i>F. x intermedia</i>	42.40	49.20	68.40	19.20	129.20	—	254.20	1.03	—
	1.525	0.694	0.892	0.638	0.017	—	0.994	1.03	—
<i>F. x intermedia</i>	40.20	50.00	66.40	16.40	123.20	—	255.20	0.86	—
'Densiflora'	0.954	0.954	0.368	-0.772	-0.385	—	1.150	0.86	—
<i>F. x intermedia</i>	38.80	49.00	63.20	14.20	143.00	—	259.20	0.87	—
'Golden Ranchen'	0.590	0.629	-0.471	-1.881	0.944	—	1.774	0.63	—
<i>F. x intermedia</i>	35.8	43.60	62.60	19.00	104.60	—	250.80	0.60	—
'Lynwood'	-0.190	-1.126	-0.628	0.537	-1.634	—	0.464	-0.37	—
<i>F. x intermedia</i>	39.80	50.20	70.00	19.80	115.6	—	250.00	0.88	—
'Spectabilis'	0.850	1.019	1.311	0.940	-0.895	—	0.339	0.88	—
<i>Forsythia ovata</i>	29.00	38.00	54.20	16.20	134.60	—	240.8	2.21	—
	-1.957	-2.946	-2.830	-0.873	0.380	—	-1.096	-2.21	—
<i>F. ovata</i> 'Tetragold'	37.40	46.60	64.80	18.20	122.4	—	254.80	0.38	—
	0.226	-0.151	-0.052	0.134	-0.439	—	1.088	0.28	—
<i>F. suspensa</i>	38.75	47.75	63.75	16.00	124.5	—	242.00	0.51	—
	0.577	0.223	-0.327	-0.974	-0.298	—	-0.909	-0.11	—
<i>F. suspensa</i>	38.40	48.00	69.00	21.00	161.4	—	249.00	0.51	—
'Decipiens'	0.486	0.304	1.049	1.545	2.179	—	0.183	0.51	—

<i>F. suspensa</i> 'Variegata'	35.20 -0.345	47.00 -0.021	67.20 0.577	20.20 1.142	126.60 -0.157	244.20 -0.566	209.00 -0.386	0.38 -0.09
<i>F. suspensa</i> var. <i>fortunei</i>	34.80 -0.449	47.60 0.174	64.60 -0.104	17.00 -0.470	125.4 -0.238	243.80 -0.628	209.00 -0.386	0.41 0.06
<i>F. suspensa</i> var. <i>sieboldii</i>	37.00 0.122	48.20 0.369	65.00 0.001	19.00 -0.571	127.80 -0.076	242.80 -0.784	205.80 -0.924	0.40 -0.2
<i>F. viridissima</i>	32.40 -1.073	49.20 0.694	68.20 0.839	19.00 0.537	156.40 1.843	249.80 0.308	217.40 1.026	0.73 0.19
<i>M</i>	36.53	47.06	65.00	17.93	128.94	247.83	211.30	
σ	3.848	3.077	3.815	1.985	14.900	6.411	5.948	
$\pm m$	0.993	0.794	0.985	0.513	3.847	1.655	1.536	
<i>V</i> , %	10.535	6.538	5.870	11.070	11.555	2.587	2.815	
<i>P</i> , %	0.027	1.69	1.516	2.858	2.980	0.668	0.727	

Note: in the numerator are the average phoenodata, in the denominator are the standard deviations; the data in columns 2–4 and 7–8 are the number of days after March 1 until the corresponding phoenological manifestation; *M* is the arithmetic mean, σ is the root mean square deviation, $\pm m$ is an error of the arithmetic mean, *V* is coefficient of variation, *P* is the indicator of the accuracy of the experiment.

pensa 'Variegata', *F. suspensa* var. *sieboldii*. The 'beginning of flowering' phase occurs at the optimum time in *F. giraldiana*, *F. ovata* 'Tetragold', *F. suspensa*, *F. suspensa* 'Variegata', *F. suspensa* var. *fortunei*. The 'end of flowering' phase takes place at the optimal time in *F. europaea*, *F. ovata* 'Tetragold', *F. suspensa*, *F. suspensa* var. *fortunei*, *F. suspensa* var. *sieboldii*. The 'beginning of abscission' phase occurs at the optimum time in *F. europaea*, *F. × intermedia* 'Lynwood', *F. × intermedia* 'Spectabilis', *F. suspensa* 'Decipiens' and in *F. viridissima* (Table 4). These forsythias have minimum standard deviations according to these phoenodata. The objects studied by us are within the normal limits of 3–4 phoenodata. Only *F. ovata*, whose phoenophases are shorter than normal, does not fit into this range. Within the normal range for all phoenodata lies 20 % of the research objects. Within the normal range for 3–4 phoenodata lies 93.33 % of them.

The minimum phoenological atypicality indicators are observed in *F. ovata* 'Tetragold' (0.38), *F. suspensa* (0.51), *F. suspensa* 'Decipiens' (0.51), *F. suspensa* 'Variegata' (0.38), *F. suspensa* var. *fortunei* (0.41), *F. suspensa* var. *sieboldii* (0.40). It should be noted that in most of the forsythia (86.67 %), the phoenological atypicality indicator is less than 1, which shows that the seasonal rhythms of growth and development of most of the studied forsythia correspond to the climatic conditions of Kyiv.

According to the value of the phoenological abnormality indicator (F_1), all studied forsythia are with-

in the normal range, except for *Forsythia ovata* ($F_1 = -2.35$) and *F. × intermedia* ($F_1 = 1.03$). Of this series, only *F. viridissima* does not match the forsythia range obtained using the indicator F . The phenophases of *Forsythia ovata* take place earlier compared to the corresponding phenophases of plants of other taxa of this genus, and the phenophases of *F. × intermedia* take place later (the phenological phase of 'flowering bud break'). *F. ovata* fits with excess into the growing season. In *F. × intermedia*, the 'flowering bud break' phase is observed somewhat later compared to plants of other forsythia taxa. In general, of the 15 studied taxa of forsythia plants, only *F. × intermedia* and

F. ovata are not within the normal range according to indicators F and F_1 .

Based on the sign of the indicator F_1 , it can be concluded that *F. giraldiana*, *F. ovata* 'Tetragold', *F. suspensa*, *F. suspensa* var. *fortunei* and *F. suspensa* var. *sieboldii*, growing in the city of Kyiv, are within the norm for the dates of onset of all phenophases and have an unused part of the growing season in reserve.

According to the scale of assessments of the discrepancy of the phenology of the climate introducers of the secondary range following the value of the indicator (F_1) according to Zaitsev (Zaitsev 1981), we divided the research objects into four groups (Table 5).

Table 5. Groups of representatives of the genus *Forsythia* depending on the indicator of phenological abnormality (F_1) and their assessment in points.

Group	Phenological abnormality indicator F_1	Point	Species, hybrids, varieties, cultivars
I	from -2 to -3	2	<i>F. ovata</i>
II	from 0 to -1	4	<i>F. europaea</i> , <i>F. giraldiana</i> , <i>F. × intermedia</i> 'Lynwood', <i>F. suspensa</i> , <i>F. suspensa</i> 'Variegata', <i>F. suspensa</i> var. <i>sieboldii</i>
III	from +1 to 0	5	<i>F. × intermedia</i> 'Densiflora', <i>F. × intermedia</i> 'Gold Ranchen', <i>F. × intermedia</i> 'Spectabilis', <i>F. ovata</i> 'Tetragold', <i>F. suspensa</i> 'Decipiens', <i>F. suspensa</i> var. <i>fortunei</i> , <i>F. viridissima</i>
IV	from +2 to +1	6	<i>F. × intermedia</i>

Forsythia ovata plants fit with excess into the growing season. Plants of species, varieties and cultivars from the second group are in the upper half of the normal (supernormal) region or optimum for the realization of their phenophases, their development cycle meets the requirements of the growing season of the place of introduction. Plants of the species, varieties and cultivars from the third group are in the lower half of the normal range (subnormal).

Species with 4–5 points can grow successfully in the appropriate introduction

area. These are all studied plants, except of *F. × intermedia* plants (6 points), the phenological rhythm of which does not completely fit into the growing season. Due to this, in the conditions of the research region, *F. × intermedia* plants can freeze in severe winters. However, the value of the indicator F_1 of *F. × intermedia* plants is close to 1.

For plants with 2–5 points, the ratio between their needs to satisfactorily overcome the seasonal processes of growth and development and the possibilities of the growing season is optimal. Their de-

velopment cycle corresponds to the growing season of the place of introduction, so they can be successfully cultivated in the research region. Our research findings align with those of the study on the seasonal rhythms of the development of forsythia in the conditions of Vinnytsia according to Matusiak (2020).

According to the results of phenological observations in 2010–2015, phenospectra of the seasonal development of introducers of the genus *Forsythia* in the conditions of Kyiv were compiled (figs 1 and 2).

Vegetation of forsythia in Kyiv begins at the end of March with the phase of 'flowering bud break'. *F. ovata* (28.03), *F. europaea* (29.03) are the first to start vegetation, after 3–6 days, this phase starts in *F. viridissima* (2.04), *F. suspensa* var. *fortunei* (4.04), *F. suspensa* 'Variegata' (5.04), *F. × intermedia* 'Lynwood' (5.04). The rest

of the forsythia plants start growing from 6 April (*F. suspensa* var. *sieboldii*) to 12 April (*F. × intermedia*). The beginning of flowering of representatives of the genus *Forsythia* was noted from 28.03. (the earliest date of the beginning of flowering in *F. ovata*) to 28.04. (the latest date of the beginning of flowering in *F. viridissima*).

Conclusion

Based on the analysis of the results of the studies, taxa of the genus *Forsythia* were identified, some of the phenological phases of which occur in optimal time frames.

Forsythia giraldiana, *F. ovata* 'Tetragold', *F. suspensa*, *F. suspensa* var. *fortunei* and *F. suspensa* var. *sieboldii*, growing in the city of Kyiv, are within the norm for the dates of onset of all phenophases

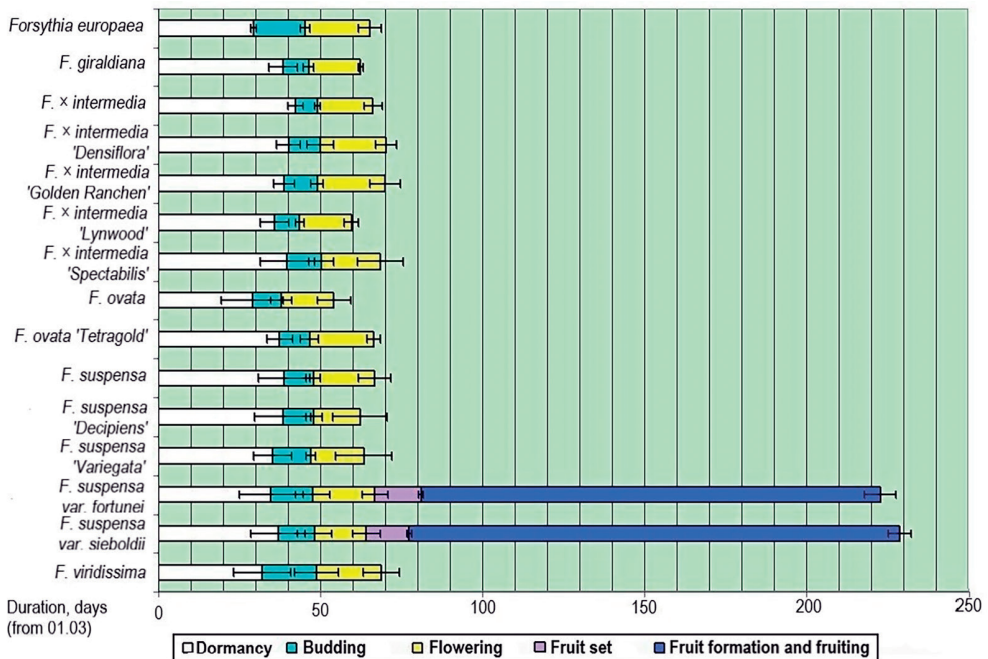


Fig. 1. Phenospectrum of seasonal generative development of introducers of the genus *Forsythia* in the conditions of Kyiv.

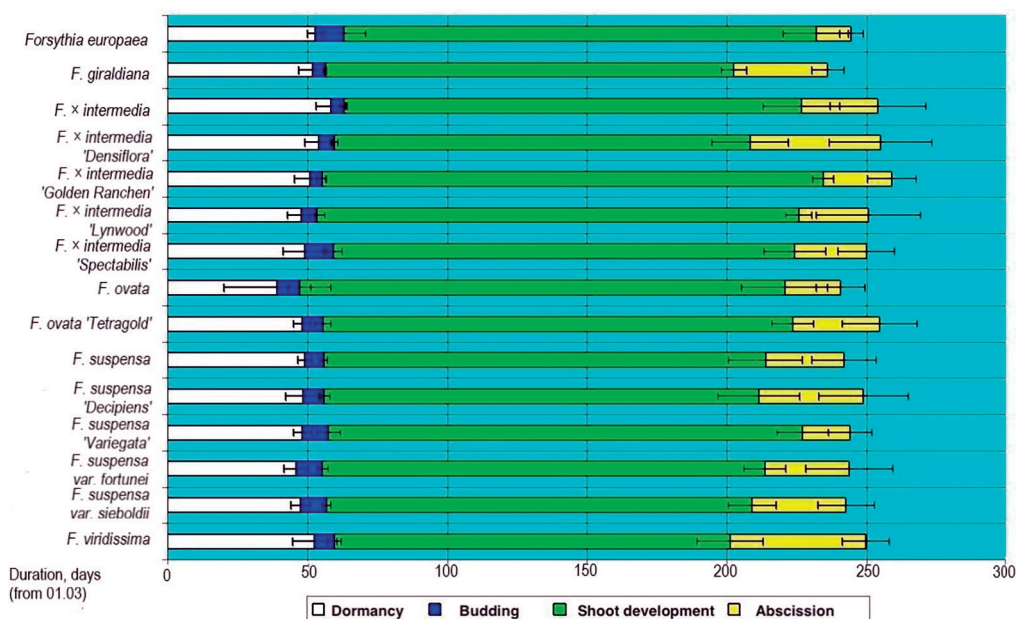


Fig. 2. Phenospectrum of seasonal vegetative development of introducers of the genus *Forsythia* in the conditions of Kyiv.

and have an unused part of the growing season in reserve.

Of the plants of 15 studied forsythia taxa, only two (*F. × intermedia* and *F. ovata*) are not within the normal range according to indicators of phenological atypicality and phenological abnormality.

F. ovata fits with excess into the growing season. Plants of species, varieties and cultivars from the second group are in the upper half of the normal (supernormal) region or optimum for the realization of their phenophases, their development cycle meets the requirements of the growing season of the place of introduction. Plants of the species, varieties and cultivars from the third group are in the lower half of the normal range (subnormal).

The plants with 4–5 points usually grow successfully in the relevant introduction area. In our case, these are all the studied plants, with the exception of *F. ×*

intermedia, whose phenological rhythm does not completely fit into the growing season. Due to this, in the conditions of the research region, *F. × intermedia* can freeze in severe winters.

References

- ANDRIIENKO T.L., HREVTSOVA H.T., DIDUKH Y.P., DUBYNA D.V., DUDKA I.O., KONDRATIUK S. Y., LUKASH O.V., MOISEIENKO I.I., PALAGECHA R.M., PEREHRIM M.M., SOLOMAKHA V.A., SOLOMAKHA T.D., TKACHENKO V.S., CHORNEI I.I., TSARENKO P.H., SHELIAK-SOSONKO Y.R., YAKUSHENKO D.M. 2007. A. V. Fomin Botanical garden. Catalog of plants. Nature reserves of Ukraine. The plant world. [Botanichnyi sad im. akad. O. V. Fomina. Katalog roslin. Prirodno-zapovidni teritoriyi Ukrayiny. Roslinnyi svit]. Vol. 7. Kyiv, Fitosociotsentr. 320 p. (in Ukrainian).

- BULYGIN N.E. 1985. Dendrology: a textbook [Dendrologiya: uchebnoe posobie]. Moscow, Agropromizdat. 279 p. (in Russian).
- HONCHARENKO B.V. 2009. Prospects for the use of species and cultivars of the genus *Forsythia* (*Forsythia* Vahl) in green construction in the Right Bank Forest Steppe of Ukraine [Perspektyvy vykorystannia vydiv ta kultivariv rodu forsitsiia (*Forsythia* Vahl) u zelenomu budivnutstvi v Pravoberezhnomu Lisostepu Ukhainy]. Introduction of plants 1: 68–72 (in Ukrainian).
- HONCHARENKO B.V. 2014. Decorative leafy species and cultivars of the genus *Forsythia* Vahl in the Arboretum of the M.M. Hryshko National Botanical Garden of the National Academy of Sciences of Ukraine [Dekoratyvno-lystiani vydy ta kultivary rodu *Forsythia* Vahl u dendrarii Natsionalnoho botanichnoho sadu im. M.M. Hryshka NAN Ukhainy]. Introduction of plants 1: 79–83 (in Ukrainian).
- KOKHNO N.A., KURDYUK A.M. 1994. Theoretical foundations and experience of the introduction of woody plants in Ukraine [Teoreticheskie osnovy i opyt introduktsii drevesnykh rasteniy v Ukraine]. Kyiv, Naukova dumka. 186 p. (in Russian).
- KOKHNO N.A., KURDYUK A.M., DUDIK N.M., MINCHENKO N.F., KAPLUNENKO N. F., PARKHOMENKO L.I., CHUPRINA P.Y., GORB V.K., DOROSHENKO A.K., BALABUSHKA V.K., LOGGINOV V.B., TROFIMENKO N.M., TSIKALYAK G.P., GRABOVA T.E., KUZNETSOV S.I., ZARUBENKO A.U., DIDENKO T.V., SKRIPKA E.V., KULIKOV G.V., SHKARLET O.D. 1991. Fruits and seeds of trees and shrubs cultivated in the Ukrainian SSR [Plody i semena derev i kustarnikov, kultiviruemiyh v Ukrainskoy SSR]. Kyiv, Naukova dumka. 320 p. (in Russian).
- LAPIN P.I. (Ed.) 1975. Methodology for phenological observations in botanical gardens of the USSR [Metodika fenologicheskikh nablyudenii v botanicheskikh sadakh SSSR]. Moscow. 27 p. (in Russian).
- MATUSIAK M.V. 2020. Features of grows and development of the genus *Forsythia* Vahl. in conditions of the Vinnytsia National agrarian university biostationary. Agriculture and Forestry 16: 162–175. doi: 10.37128/2707-5826-2020-1-12
- MATUSIAK M.V., VARGATIUK O.V. 2020. Determination of decorative and successful introduction of the *Forsythia* Vahl. in the conditions of the biostationary VNAU [Vyznachennia dekorativnosti ta uspishnosti introduktsii vydiv rodu *Forsythia* Vahl. v umovakh biostatsionaru VNAU]. Bulletin of Uman National University of Horticulture 1: 124–128 (in Ukrainian). doi: 10.31395/2310-0478-2020-1-124-128
- MISNIK G.E. 1976. Timing and nature of flowering of trees and shrubs [Sroki i harakter tsveteniya derev i kustarnikov]. Kyiv, Naukova dumka. 389 p. (in Russian).
- PLOTNIKOVA L.S. 1971. Introduction of tree plants of the Chinese-Japanese floristic sub-region in Moscow [Introduktsiya drevesnykh rasteniy Kitaysko-Yaponskoy floristicheskoy podoblasti v Moskve]. Moscow, Nauka. 135 p. (in Russian).
- SUNG J.-W., KIM G.-H., LEE K.-C., SHIM Y.-J., KANG S.-G. 2021. Monitoring the phenology of *Forsythia velutina*, an endemic plant of Korea. Journal of People Plants Environment 24(4): 355–363. <https://doi.org/10.11628/ksppe.2021.24.4.355>
- VISYULINA O.D. 1957. *Forsythia* (*Forsythia* Vahl). [Forzytsiia (*Forsythia* Vahl)]. In: Kotov M.I., Barbarych A.I. (Eds). Flora of the Ukrainian SSR. vol. 8. Publication of the Academy of Sciences of the Ukrainian SSR, Kyev: 200–202 (in Ukrainian).
- VYSHNEVSKIY V., DONICH O., KUTSYI A. 2023. Climate of Kyiv and its surroundings [Klimat Kyieva ta yoho okolyts]. Kyiv, Varto. 124 p. (in Ukrainian).
- ZAITSOV G.N. 1981. Phenology of woody plants [Fenologiya drevesnykh rasteniy]. Moscow, Nauka. 119 p. (in Russian).
- ZAITSOV G.N. 1983. Optimum and norm in the introduction of plants [Optimum i norma v introduktsii rasteniy]. Moscow, Nauka. 268 p. (in Russian).
- ZAITSOV G.N. 1984. Mathematical statistics in experimental botany [Matematicheskaya statistika v eksperimentalnoy botanike]. Moscow, Nauka. 421 p. (in Russian).

Impact of silvicultural interventions on growth and survival of *Fagus sylvatica* L. saplings

Adriana Marinova* and Svetoslav Anev

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

Received: 07 June 2024 / Accepted: 31 August 2024 / Available online: 05 August 2024



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

Abstract

This study aims to examine the impact of silvicultural interventions on the height and diameter growth, survival, and canopy structure of naturally regenerated European beech (*Fagus sylvatica* L.) saplings. In a field study, a system of six experimental sites was set up across three areas in the West Stara Planina region, selected according to the various types of cutting regimes within them. At each area, we chose two experimental sites – one of them with silvicultural intervention (Group selection system, Group shelterwood system and Short-term shelterwood system cuttings) and the other one – without silvicultural intervention during the last minimum twenty years (control). Biometric measurements of sapling number, height, and diameter were taken in 2018 and 2022, alongside assessments of the leaf area index (LAI). The results showed that cutting regimes influence beech regeneration growth patterns. Small canopy gaps (0.111 and 0.125 ha) in the Group selection and Short-term shelterwood systems led to similar survival and growth changes, selecting resilient individuals and increasing sapling sizes compared to controls, with no significant change in LAI. In contrast, the Group shelterwood system, with a larger canopy gap (0.555 ha), resulted in similar sapling numbers and sizes to the control but increased LAI over four years without sapling size growth. This indicates that larger gaps may have a less stimulating effect on beech regeneration compared to smaller gaps.

Key words: canopy, cutting regimes, European beech, gap, leaf area index, regeneration, silvicultural intervention, survival.

Introduction

European beech (*Fagus sylvatica* L.) is one of the main deciduous broad-leaved tree species in the Bulgarian mountains. It is widespread between 600 and 1800 m a.s.l. (Stefanov and Ganchev 1953), covering 14 % of the territory of the Bulgarian forests. The European beech is a typical

closed-stand forest tree species (Küppers 1985, Schütz et al. 2006, Matyssek et al. 2007), which becomes dominant only as late as in the final phase; when a climax microclimate has already been created (Kostov and Stipcov 2004).

Silvicultural practices significantly alter forest stand structure, leading to gaps in the forest canopy and modifications to

the light environment. Consequently, the creation of gaps triggers the regeneration processes in the understory, impacting stand dynamics (Yamamoto 2000). According to Nedyalkov (Kostov 2009), the heterogenous structure of beech stands is evident across all Bulgarian beech forests, with a more noticeable presence in areas where human intervention is minimal. Contemporary studies on the natural dynamics of beech forests confirm the notion that small-scale natural disturbances have a dominant influence on them. Within these created gaps of varying sizes, the beech regenerates successfully (Aleksandrov and Rafailova 2009). Group selection system, which mimics the prevailing natural disturbance regime, is considered a suitable method for managing beech stands (Atlegrim and Sjöberg 2004, Aleksandrov and Rafailova 2009, Hobi et al. 2015). Conversely, tree regeneration from seeds under a dense canopy may be poor (Lukyanets et al. 2022). Nevertheless, usually in potential beech habitats, beech trees typically regenerate and establish themselves effectively across a range of stand conditions resulting from various silvicultural systems. Natural regeneration process in the European beech forests is most often successful due to the ability of this species to form mono-dominated stands (Rafailov et al. 2009) where mature trees protect the saplings.

Several studies under controlled conditions suggest that beech seedlings can benefit rapidly from canopy opening (Tognetti et al. 1997, van Hees 1997, Welander and Ottosson 1997). Despite that, young European beech trees are very sensitive to late spring frost (Dittmar et al. 2003, Ammer et al. 2005) and direct sunlight (Stefanov and Ganchev 1953). Research carried out in several European beech stands found a possible 80–90 %

loss of germination capacity (Bílek et al. 2009), especially in a wet and not sufficiently cold winter. Such sensitivity risks damage for several saplings, especially few years after disturbance or forest cutting. The damage incidentally affects individuals and causes accidental nature of mortality, and therefore of natural selection at this stage of the beech forest development. Survived trees have post-stress physiological features (Dittmar et al. 2003), which remain permanent for a long time after cutting or disturbances (Wagner et al. 2010), especially in the context of climatic changes (Silva et al. 2012).

Silvicultural interventions have a significant impact on the light conditions within the understory, which are fundamental determinants of regeneration patterns in forest ecosystems (Gao et al. 2014). Competition for light and subsequent mortality are the primary processes that significantly influence the growth of young forest stands (King 1990). As the canopy closes, especially in stands generated through natural regeneration, the height of trees compared to neighbouring trees, as well as their position within the canopy, determine the amount of light accessible to their foliage (Richardson et al. 2001). Leaves possess the exclusive ability to capture energy, thereby propelling forest growth. Foliage exhibits high sensitivity to growth conditions prevailing within a stand.

Silvicultural practices that create canopy gaps influence light availability, which is crucial for beech regeneration, highlighting the need to understand how different cutting regimes affect sapling growth and survival, especially given the substantial role of microclimatic conditions in sapling survival before canopy assembly.

The aim of this research, within the context of forest management in the Bul-

garian mountains, is to investigate the effects of different silvicultural interventions altering beech regeneration. We hypothesized that differences in regeneration parameters like height and diameter growth, survival, and leaf area index of beech saplings will occur among stands managed with various cutting regimes.

Materials and Methods

Site description and field data collection

The study was carried out within the University of Forestry's Training and Experimental Forest Range 'Petrohan', located on the northeastern slopes of the Western Stara Planina Mt. The climate in this region is characterized as mountainous with a moderate continental influence. At an elevation of 1450 m, the average annual temperature is 4.8 °C, and the average annual precipitation, peaking in spring, is approximately 1080 mm. At an elevation of 700 m, the average annual temperature is 8.8 °C, and the average annual precipitation between 600 and 750 mm (Kutchuk-

ova 1983, Koleva and Peneva 1990). The soil type is identified as brown acid (eutric cambisol) developed on granite, with an average depth exceeding 80 cm (Malinova and Petrova 2019). Experimental sites were set up at different elevations ranging from 700 to 1450 m a.s.l. (Fig. 1), predominantly within European beech stands. Within the beech stands, singular occurrences of *Acer pseudoplatanus* L., *Sorbus aucuparia* L., *Acer heldreichii* Boiss, and *Carpinus betulus* L. were observed.

The experimental sites were chosen based on their varied silvicultural histories. Each study area consisted of two (ES) – with silvicultural intervention (cutting regimes – Group selection system (GSS), Group shelterwood system (GShS) and Short-term shelterwood system (StSS) (ES-O) and the other one – without silvicultural intervention during the last minimum twenty years (control) (ES-C, Table 1).

In 2011, the canopy of the ES1-O site underwent opening through the removal of all mature trees aged 120 years within a gap measuring 25 × 40 m (0.1 ha), which remained unchanged thereafter. In 2013, the canopy of the ES2-O site, consisting

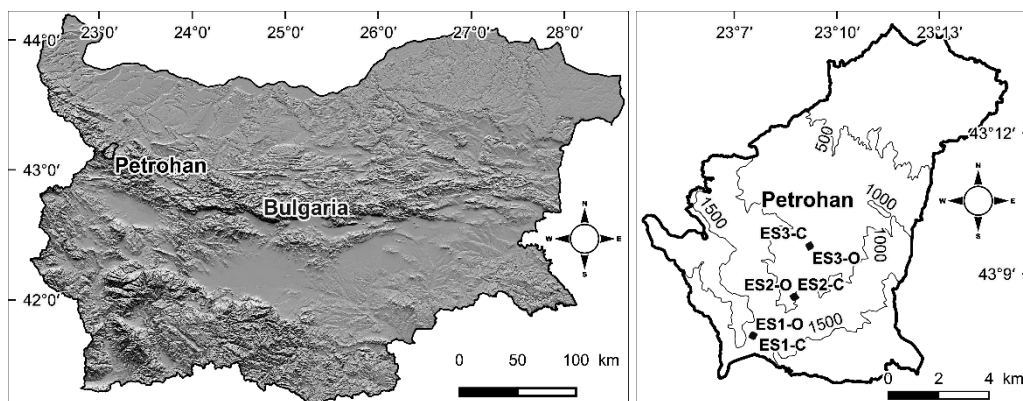


Fig. 1. Map of TEFR 'Petrohan' (left) and experimental plot location (right).

Note: Contour lines with 500 m intervals are shown on the right map.

Table 1. Properties of experimental sites.

Experimental site	ES1-C	ES1-O	ES2-C	ES2-O	ES3-C	ES3-O
Latitude, ° ' "	43° 7' 32"	43° 7' 30"	43° 8' 22"	43° 8' 23"	43° 9' 29"	43° 9' 27"
Longitude, ° ' "	23° 7' 25"	23° 7' 23"	23° 8' 33"	23° 8' 37"	23° 9' 00"	23° 8' 59"
Elevation, m	1439	1450	970	1015	713	718
Aspect, ° from North	74.9/E	105.3/E	276.3/W	251.7/SW	323.7/NW	322.9/NW
Slope, °	15.0	10.9	24.4	28.9	8.4	6.2
Type of cutting system	-	GSS	-	GShS	-	StSS
Gap size, ha	-	0.111	-	0.555	-	0.125
Year of intervention	-	2011	-	2013	-	2011

Note: GSS – group selection system, GShS – group shelterwood system, StSS – short-term shelterwood system.

of 120-year-old trees, was opened in a circular gap with a 50 m diameter, subsequently expanded to 80 m (~0.5 ha) by 2018. The canopy of ES3-O was opened by cutting eight mature trees aged 160 years, evenly distributed across a total area of 0.1 ha. Control ES-C sites were positioned adjacent to the (ES-O) sites within the stands, remaining untouched by cutting activities for a minimum of twenty years. All control sites are situated in forests dominated by common beech, originating from seed, with a uniform structure. In ES1-C, the mature trees are 140-year-old with a canopy density of 70 %. In ES2-C, the mature trees are 160-year-old with a canopy density of 60 %. In ES3-C, the mature trees are 160-year-old with a canopy density of 70 %.

In both intervention ES and control, we assessed the number (N) of beech regeneration plants within three randomly selected sample plots (2.5 × 4.0 m). Stem height (H, cm) was measured using a tape measure, while the diameter of the stem base (D, cm) of the beech regeneration plants was measured using a calliper. QGIS 3.16 open-source software was used to calculate the LAI index. The satellite images based on which the LAI indices were calculated are from the

Sentinel-2 satellites, which, in the channels used to calculate LAI, provide the highest resolution of 10 × 10 m for one px (D'Odorico et al. 2013). These images are publicly available at earthexplorer.usgs.gov, and we've only used those for August, when it's the clearest time in the region. These measurements were conducted at the onset of the growing season in both 2018 and 2022.

Data analysis

The field-collected data, including numbers, heights, diameters, and LAI of beech saplings across various experimental sites and examined years, underwent the following statistical analyses: 1) descriptive statistical analysis and 2) Shapiro-Wilk test for evaluation of the normal distribution. Two Way ANOVA test following all pairwise multiple comparison procedures (Tukey test) was used for tests of significant differences between the means among the numbers, biometric parameters, and LAI of seedlings at experimental sites with silvicultural interventions compared to control sites, as well as between the two studied years. All statistical calculations were performed with MS Excel (Microsoft Corp., Redmond, WA)

and with specially created visual basic user-defined script.

Results and Discussion

Regeneration and survival

In ES1-O, the number of saplings remained constant throughout the study period (Fig. 2). The lack of alterations in the sapling amounts seven years after GSS cutting, for a period of four years (2018–2022) suggests that the regeneration processes following the canopy opening have already decelerated. However, upon comparing with ES1-C, it becomes evident that, unlike ES1-O, the number of saplings in ES1-C has increased since the beginning of the study period. Even in 2022, the number of saplings ES1-C was greater than those in ES1-O. The significantly higher number of beech individuals in the ES1-C compared to those in ES1-O can likely be attributed to the shelter provided to saplings within the closed canopy stand, shielding them from adverse

environmental, such as frost, prevalent at the high elevation of 1450 m, as noted by Rafailov et al. (2009) in mono-dominated beech stands. Budeanu et al. (2016), Kolář et al. (2017) also state that higher elevations (exceeding 1200 m) are not favourable to beech growth due to lower temperatures and late frosts. As Stefanov and Ganchev (1953), Dittmar et al. (2003), and Ammer et al. (2005) indicate, beech saplings are very sensitive to late spring frost and direct sunlight, and this sensitivity is particularly pronounced few years after cutting. These factors contribute to an accidental form of mortality, which consequently influences the natural selection process during this beech forest development phase (Dittmar et al. 2003). Lukyanets et al. (2022) also observe a reduction in the volume of alder stands due to poor forest site conditions. This implies that the consistent absence of an increase in the number of beech saplings at ES1-O during the study period may be interpreted as a natural selection process favouring more adaptable and thus more promising individuals.

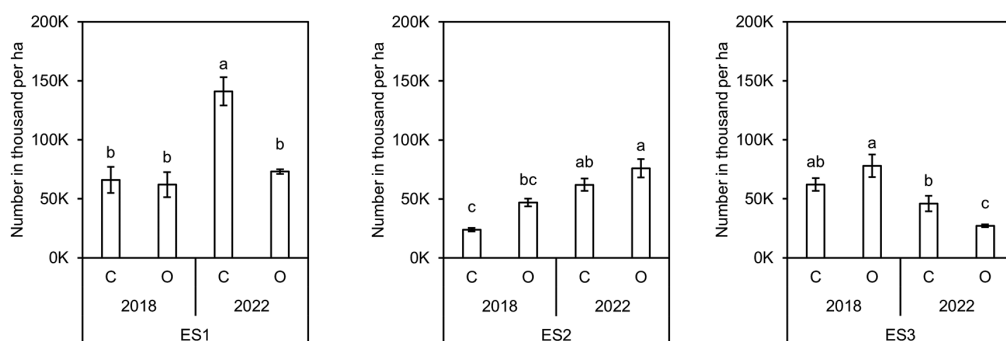


Fig. 2. Regeneration density of beech saplings within experimental sites during study period.

Note: The data represent the mean numbers of saplings $\pm$ SE. Different letters indicate statistically significant differences in averages among experimental sites with silvicultural interventions (O) and control (C), as well as between the two examined years (determined via one-way ANOVA using Tukey post hoc tests with an $\alpha = 0.05$).

In ES2-O, there was a significant increase in numbers of saplings observed over the studied four-year period, beginning five years after GShS cutting. However, there were no differences in the number of saplings in ES2-O and EC2-C in the two examination years. The absence of differences in sapling numbers between ES2-O and the control group suggests that the observed sapling growth in 2022 likely stemmed from favourable environmental conditions conducive to beech regeneration in the studied area. These conditions appear to stimulate beech regeneration irrespective of the presence or absence of silvicultural intervention.

Seven years after StSS cutting (in 2018), there were no significant differences in the number of saplings between ES3-O and ES3-C, similar to that observed in the ES1 and ES2 in the same year. The consistent sapling numbers observed in the initial year of the study likely result from the transition beyond the phase of intensive sapling mortality in the early years. However, in ES1-O and ES3-O, although there were no changes in sapling numbers in 2018 compared to their respective controls, a decrease in sapling numbers was observed in 2022. The reduced number of young beech individuals in ES3-O might also be influenced by damage from an ice disturbance (heavy ice on the tree crown) in January 2021 at ES3. The absence of an increase in sapling numbers by the study's conclusion after both types of cuttings, GSC and StSS, which are characterized by small gaps in the canopy (in our study, the gap size is respectively 0.111 and 0.125 ha), resembling the regime of natural disturbances in beech forests, could be attributed to the process of natural selection leading to the occupation of the habitat from more resilient beech individuals to

the changed environmental conditions post-cutting. Collet and Chenost (2006) note that partial cutting of single trees or small gaps may result in increased beech dominance. In GShS, there was no decrease in sapling numbers in 2022. However, the gap size (0.555 ha) is approximately five times larger compared to GSS and StSS, which is likely to influence the rate of regeneration processes occurring over time. Although the highest number of saplings was found in the count site nearest to the periphery of the gap, the variation (SE) was small, indicating relative homogeneity in this measure across the individual count sites.

Biometry

In ES1, there was no difference in height between ES1-O and ES1-C in 2018 (Fig. 3), but the diameter was higher in ES1-O (Fig. 4). In 2022, there was an increase in both height and diameter in ES1-O compared to ES1-C. However, in this experimental site, the exhibited height of saplings increased over the four-year study period, while their diameter decreased.

The absence of growth in sapling diameter during the study period, compared to the increase in height are probably influenced by the increased intraspecific competition in the stand. Collet et al. (2001), Prévosto and Balandier (2007) emphasize that interspecific competition affects the diameter growth of naturally regenerated beech individuals more significantly than their height growth. In Collet et al. (2001) study diameter growth increased immediately after the gaps had been opened and showed no clear increasing trend in the following years. Conversely, height growth did not increase immediately after canopy opening and increased regularly in the fol-

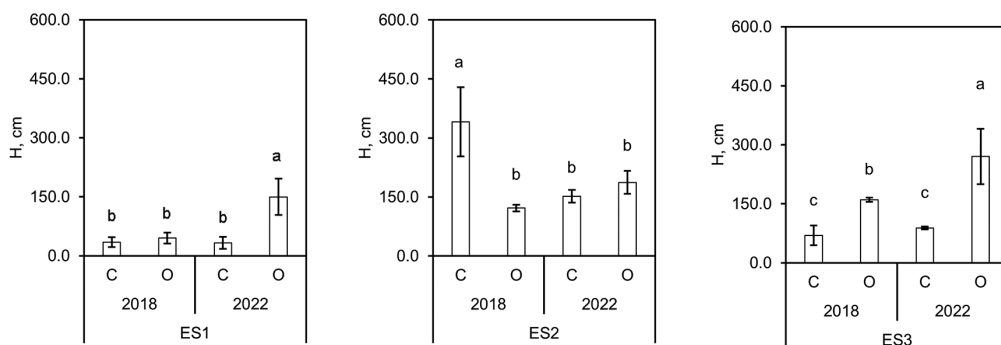


Fig. 3. Height of saplings within experimental sites during study period.

Note: The data represent the mean height of saplings $\pm$ SE. Different letters indicate statistically significant differences in averages among experimental sites with silvicultural interventions (O) and control (C), as well as between the two examined years (determined via one-way ANOVA using Tukey post hoc tests with an $\alpha = 0.05$).

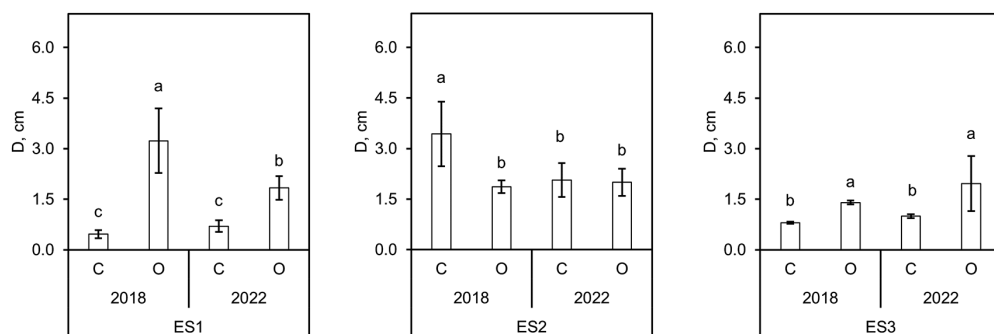


Fig. 4. Diameter of saplings within experimental sites during study period.

Note: The data represent the mean diameter of saplings $\pm$ SE. Different letters indicate statistically significant differences in averages among experimental sites with silvicultural interventions (O) and control (C), as well as between the two examined years (determined via one-way ANOVA using Tukey post hoc tests with an $\alpha = 0.05$).

lowing years. Nevertheless, the decrease in overall thickness over the study period suggests that competition has yielded to the more advanced individuals.

The steady number of individuals over the study period, along with increased heights and reduced diameters in ES1-O, suggests that, as plants grow larger, they require more space. The greater space demand likely prevents an increase in the number of plants per unit area. Such an

observation indicates that, at this stage, beech individuals that exhibit greater adaptability and resilience to environmental changes persist. As highlighted by Evans et al. (2003), intra-specific competition for space, nutrients, and light arises when plants surpass the optimal limit per unit area, resulting in diminished plant growth and development, ultimately leading to a reduction in plant biomass.

In 2022, ES1 and ES3 showed similar

growth patterns, with saplings in the experimental sites using the cutting system being larger compared to those in the control site. This increase in size corresponds with a smaller number of saplings in these experimental sites for the same year. This suggests that the similar opening of the canopy resulting from these cuttings has a similar positive impact on the survival and growth processes of the saplings. The survival and growth of saplings in ES2 are characterized by the lack of significant differences in both the number of saplings and growth parameters between ES2-O and ES2-C in 2022, distinguishing it from ES1 and ES3. From 2018 to 2022, in ES2-C there was a notable reduction in the heights and diameters of saplings, due to the emergence of smaller new individuals. Additionally, no increase was evident in the growth parameters of the saplings in ES2-O throughout the four-year study period. These results suggest a less stimulating effect of canopy openings through the GShS cutting system on beech regeneration growth.

During the studied period, after a transformation into a group-selective stand, the

number of saplings remained constant, their height increased, and their diameter decreased, indicating a balance between mortality and the emergence of new individuals. In the group shelterwood system, the number of saplings increased at a rate like that in the closed canopy control, while their height and diameter remained unchanged. This suggests that some individuals died, and new ones emerged, with a rapid height growth rate. In the short-term shelterwood system, there is significant differentiation of social classes, many individuals are lost, and this process is accompanied by an increase in average height and diameter. The intense mortality in this system is likely due to the negative carbon balance of suppressed saplings.

Leaf area index

Beech saplings had a higher leaf area index (LAI) in ES1-O compared to ES1-C (Fig. 5). Between 2018 and 2022 in ES1-C, there is a significant increase in the number of individuals, but the LAI remains unchanged. This lack of increase in

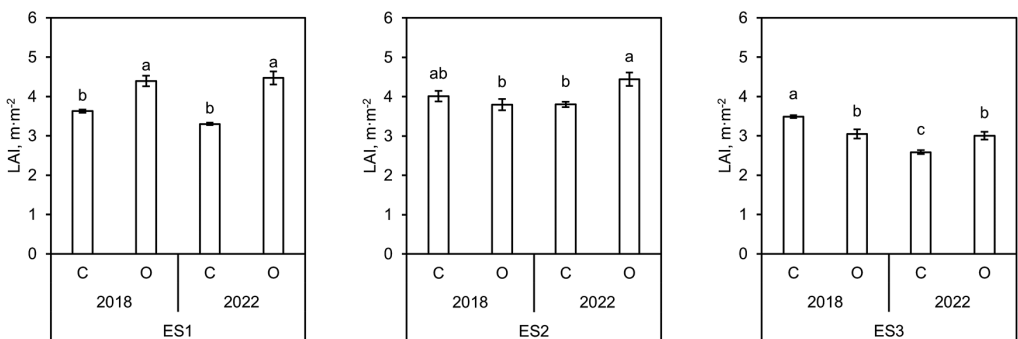


Fig. 5. Leaf area index of saplings within experimental sites during study period.

Note: The data represent the mean LAI of saplings $\pm$ SE. Different letters indicate statistically significant differences in averages among experimental sites with silvicultural interventions (O) and control (C), as well as between the two examined years (determined via one-way ANOVA using Tukey post hoc tests with an $\alpha = 0.05$).

LAI, despite the rising number of saplings in this experimental site, is likely because the C-experimental sites reflect the LAI of the mother stands. When LAI remains constant during the experimental period, it suggests that the canopy of mother stand has experienced disruptions over the years. These disruptions allow more light to penetrate, stimulating regeneration and thus increasing the number of individuals in this experimental site. However, there was no observed increase in the index in ES1-O over the four-year duration of the study, which was also observed in ES3-O. The elevated index in ES1-O and ES3-O in 2022 indicates the expanded foliage of the beech saplings, likely attributed to the opening of the canopy and increased light penetration, thereby stimulating leaf production. Nevertheless, the absence of a rise in the index post-GSS and ShSS cuttings indicates that small canopy opening (gap size – 0.111 and 0.125 ha) has a limited impact on leaf production over the years.

In ES2, LAI differs only in 2022 between ES2-O and ES2-C, with predictable higher values in EC2-O due to most light. On the contrary with ES1 and ES3, while the ES1-O and ES3-O LAI showed no growth, there was an increase in the ES2-O index over the study period. This suggests a potentially stronger impact of bigger canopy opening (gap size – 0.555) due to GShS cutting on the leaf development of beech saplings, compared to the effect of five times smaller canopy opening resulting from GSS and ShSS cuttings on leaf production.

After StSS cutting, in the initial year of the study, a reduced LAI was noted in ES3-O compared to ES3-C, indicating a limited stimulating effect of that cutting on leaf production. Conversely, by the study's conclusion, the index had increased in

ES3-O relative to ES3-C. However, this augmentation was likely due to additional canopy opening resulting from damage inflicted by the heavy snow in this experimental site. Furthermore, considering the absence of an increase in the ES3-O index throughout the study period, it can be assumed that StSS cutting has a minor impact on leaf production.

The results regarding LAI align with alterations in growth parameters, as highlighted by (Givnish 1982, Niklas 1992), as leaf height increases, plants must allocate biomass disproportionately to the stem to support their weight, thereby reducing the proportion of leaf mass in the plant.

Conclusion

According to the initial results of our research, there is a correlation between the type of gap opening and the growth of beech regeneration. The eco-physiological features of European beech, in combination with a wide variation of micro-environmental factors in its distribution area, are prerequisite for a significant variation regarding growth and presence of beech saplings after cuttings. European beech successfully regenerated in all experimental sites where silvicultural interventions occurred, confirming the species' broad ecological adaptability. Nevertheless, there are different efficiencies resulting from the way the canopy is opened. The short-term shelterwood system sets the stage for intensive self-healing from an early age, which will result in more homogeneous future stand. In contrast, the other two systems maintain conditions that preserve heterogeneity in stand structure, at least during the early stages of forest development. With further research on a larger scale, these observations could be

used as indicators of young trees' regeneration dynamics and physiological stress after forest interventions.

Acknowledgements

The present study was supported by grant No NIS-B-1292 'Evaluating the damage and recovery rate of forests impacted by ice storm in the TEFRR 'Petrohan' through remote methods', University of Forestry, Sofia.

References

- ALEKSANDROV N., RAFAILOVA E. 2009. Future close to nature management of beech forests as a precondition for improvement of their sustainability. *Forestry Ideas* 37(1): 160–165 (in Bulgarian, with English summary).
- AMMER C., ALBRECHT L., BORCHERT H., BROSINGER F., DITTMAR C., ELLING W., EWALD J., FELBERMEIER B., GILSA H., HUSS J. 2005. Future suitability of beech (*Fagus sylvatica* L.) in Central Europe: critical remarks concerning a paper of Rennenberg et al. 2004. *Allgemeine Forst- und Jagdzeitung* 176(4): 60–67.
- ATLEGIRIM O., SJÖBERG K. 2004. Selective felling as a potential tool for maintaining biodiversity in managed forests. *Biodiversity and conservation* 13(6): 1123–1133. <https://doi.org/10.1023/B:BIOC.0000018148.84640.f0>
- BÍLEK L., REMEŠ J., ZAHRADNÍK D. 2009. Natural regeneration of senescent even-aged beech (*Fagus sylvatica* L.) stands under the conditions of Central Bohemia. 55(4): 145–155. <http://dx.doi.org/10.17221/823-JFS>
- BUDEANU M., PERTRITAN A.M., FLAVIU P., VASILE D., NICU CONSTANTIN T. 2016. The resistance of European beech (*Fagus sylvatica*) from the eastern natural limit of species to climate change. *Notulae botanicae horti agrobotanici cluj-napoca* 44(2): 625–633. <http://dx.doi.org/10.15835/nbha44210262>
- COLLET C., CHENOST C. 2006. Using competition and light estimates to predict diameter and height growth of naturally regenerated beech seedlings growing under changing canopy conditions. *Forestry* 79: 489–502. <https://doi.org/10.1093/forestry/cpl033>
- COLLET C., LANTER O., PADOS M. 2001. Effects of canopy opening on height and diameter growth in naturally regenerated beech seedlings. *Annals of Forest Science* 58(2): 127–134. <https://doi.org/10.1051/forest:2001112>
- DITTMAR C., ZECH W., ELLING W. 2003. Growth variations of Common beech (*Fagus sylvatica* L.) under different climatic and environmental conditions in Europe – a dendroecological study. *Forest Ecology and Management* 173(1–3): 63–78. [https://doi.org/10.1016/S0378-1127\(01\)00816-7](https://doi.org/10.1016/S0378-1127(01)00816-7)
- EVANS S.P., KNEZEVIC S.Z., LINDQUIST J.L., SHAPIRO C.A., BLANKENSHIP E.E. 2003. Nitrogen application influences the critical period of weed control in corn. *Weed Science* 51(3): 408–417. doi: 10.1614/0043-1745(2003)051 [0408:NAITCP]2.0.CO;2
- GIVNISH T.J. 1982. On the adaptive significance of leaf height in forest herbs. *The American Naturalist* 120(3): 353–381. <http://dx.doi.org/10.1086/283995>
- GAO T., HEDBLUM M., EMILSSON T., NIELSEN A.B. 2014. The role of forest stand structure as biodiversity indicator. *Forest Ecology and Management* 330: 82–93 <https://doi.org/10.1016/j.foreco.2014.07.007>
- HOBİ M.L., COMMARMOT B., BUGMANN H. 2015. Pattern and process in the largest primeval beech forest of Europe (Ukrainian Carpathians). *Journal of Vegetation Science* 26(2): 323–336. <https://doi.org/10.1111/jvs.12234>
- KING D.A. 1990. The Adaptive Significance of Tree Height. *The American Naturalist* 135(6): 809–828. <https://www.jstor.org/stable/2462315>
- KOLÁŘ T., ČERMÁK P., TRNKA M., ŽID T., RYBNÍČEK M. 2017. Temporal changes in the climate sensitivity of Norway spruce and European beech along an elevation gradient in Central Europe. *Agricultural and For-*

- est Meteorology 239: 24–33. <http://dx.doi.org/10.1016/j.agrformet.2017.02.028>
- KOLEVA E., PENEVA R. 1990. Precipitation in Bulgaria. Climatic handbook. Bulgarian Academy of Science. 169 p. (in Bulgarian).
- KOSTOV G. 2009. Natural dynamics of the beechstands.. Collection of reports from a national scientific and practical conference on management of beech forests. TEFR 'Petrohan', 16–17.06.2009: 11–20 (in Bulgarian).
- KOSTOV G., STIPCOV V. 2004. Teaching aid in general forestry. Forest dynamics. Sofia: 67–76 (in Bulgarian).
- KUTCHUKOVA M. 1983. Temperatures of air and soil. Climatic handbook. Bulgarian academy of science. 440 p. (in Bulgarian).
- KÜPPERS M. 1985. Carbon relations and competition between woody species in a Central European hedgerow: IV. Growth form and partitioning. Oecologia 66(3): 343–352. <https://doi.org/10.1007/BF00378296>
- LUKYANETS V., RUMIANTSEV M., TARNOPILSKA O., KOBETS O., MUSIENKO S., OBOLONYK I., BONDARENKO V., POZNIAKOVA S. 2022. Distribution, productivity and natural regeneration of black alder (*Alnus glutinosa* (L.) Gaertn.) in Ukrainian Polissya. Folia Oecologica 49(2): 137–147. doi: 10.2478/foecol-2022-0016
- MALINOVA L., PETROVA K. 2019. Petrohan training and experimental forest range cambisols classification. Forestry Ideas 25(1): 147–160.
- MATYSSEK R., BAHNWEG G., CEULEMANS R., FABIAN P., GRILL D., HANKE D.E., KRAIGHER H., OSSWALD W., RENNENBERG H., SANDERMANN H., TAUSZ M., WIESER G. 2007. Synopsis of the CASIROZ case study: carbon sink strength of *Fagus sylvatica* L. in a changing environment – experimental risk assessment of mitigation by chronic ozone impact. Plant Biology (Stuttg) 9(2): 163–180. <https://doi.org/10.1055/s-2007-964883>
- NIKLAS K.J. 1992. Plant Biomechanics: an Engineering Approach to Plant Form and Function. The University of Chicago Press Ltd, London, UK: 410–415.
- PRÉVOSTO B., BALANDIER P. 2007. Influence of nurse birch and Scots pine seedlings on early aerial development of European beech seedlings in an open-field plantation of Central France. Forestry 80(3): 253–264. <http://dx.doi.org/10.1093/forestry/cpm017>
- RAFAILOV G., L. KOSTOV G., HUBCHEVA V., HRISTOV H., IVANOV V., BONEV T., GOGUSHEV G., VULKOV D. 2009. Guidelines for the management of beech forests in Bulgaria. In: Rafailov G. (Ed.), Collection of reports from the national scientific-practical conference on the management of beech forests. Petrohan: 3–6 (in Bulgarian).
- RICHARDS J.D., HART J. 2011. Canopy gap dynamics and development patterns in secondary Quercus stands on the Cumberland Plateau, Alabama. Forest Ecology and Management 262(12): 2229–2239. <https://doi.org/10.1016/j.foreco.2011.08.015>
- RICHARDSON A.D., ASHTON P.M.S., BERLYN G.P., MCGRODDY M.E., CAMERON I.R. 2001. Within-crown Foliar Plasticity of Western Hemlock, Tsuga heterophylla, in Relation to Stand Age. Annals of Botany 88(6): 1007–1015. <https://doi.org/10.1006/anbo.2001.1538>
- SCHÜTZ J.-P., GÖTZ M., SCHMID W., MANDALAZ D. 2006. Vulnerability of spruce (*Picea abies*) and beech (*Fagus sylvatica*) forest stands to storms and consequences for silviculture. European Journal of Forest Research 125(3): 291–302. <https://doi.org/10.1007/s10342-006-0111-0>
- SILVA D.E., REZENDE MAZZELLA P., LEGAY M., CORCKET E., DUPOUEY J.L. 2012. Does natural regeneration determine the limit of European beech distribution under climatic stress? Forest Ecology and Management 266: 263–272. <https://doi.org/10.1016/j.foreco.2011.11.031>
- STEFANOV B., GANCHEV A. 1953. Dendrology. 2 ed. Zemizdat, Sofia. 651 p. (in Bulgarian).
- TOGNETTI R., JOHNSON J.D., MICHELOZZI M. 1997. Ecophysiological responses of *Fagus sylvatica* seedlings to changing light conditions. I. Interactions between photosynthetic acclimation and photoinhibition during simulated canopy gap formation. Physiologia Plantarum 101(1): 115–123. <https://doi.org/10.1111/j.1399-3054.1997.>

- tb01827.x
- VAN HEES A. 1997. Growth and morphology of pedunculate oak (*Quercus robur* L.) and beech (*Fagus sylvatica* L.) seedlings in relation to shading and drought. *Annals of Forest Science* 54(1): 9–18. <https://doi.org/10.1051/forest:19970102>
- WAGNER S., COLLET C., MADSEN P., NAÜASHI-ZUKA 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>
- WELANDER N.T., OTTOSSON B. 1997. Influence of photosynthetic photon flux density on growth and transpiration in seedlings of beech (*Fagus sylvatica* L.). *Tree Physiology* 17(2): 133–140. <https://doi.org/10.1093/treephys/17.2.133>
- YAMAMOTO S. 2000. Forest gap dynamics and tree regeneration. *Journal of Forest Research* 5(4): 223–229. <https://doi.org/10.1007/BF02767114>

Age-size structure and growth rate of *Barbus strumicae* (Cyprinidae) in the Mesta River, Southwest Bulgaria

Vasil Kolev^{1*} , Gradimir Guychev¹ , and Alexander Mikhailichenko²

¹Department of Wildlife Management, University of Forestry, 10 St. K. Ohridski Blvd., 1797 Sofia, Bulgaria. E-mail: vassilie@abv.bg*, gradi.val@gmail.com

²IP 'Ecoexpertservice', North-Western micro district, 4, 48A, Kostanay, Kazakhstan. E-mail: alex_expert@inbox.ru

Received: 24 June 2024 / Accepted: 07 October 2024 / Available online: 17 October 2024



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

Abstract

The primary objective of this study was to determine the growth parameters of Thracian barbel in the middle zone of the Mesta River within the Aegean basin in Bulgaria. For this purpose, a total of 106 fish were caught and examined. The sample was collected by electrofishing along the Mesta River. Fish age was determined using scalimetry, while length and mass were calculated using scale length-radius and mass-length relationships, respectively. The study identified six age groups, with the majority of the sample comprising two and three-year-old fish. The lengths ranged from 46 mm to 242 mm. Growth analysis was performed by back-calculating the length using the equation $L = 3.0858 \cdot S + 20.759$ ($r^2 = 0.955$). Furthermore, a relationship between gutted weight (W) and standard length (L) was established using the equation $W = 0.00001 \cdot L^{2.9799}$ ($r^2 = 0.967$).

Key words: linear growth, size and age composition, Thracian barbel, W - L relation.

Introduction

Thracian barbel (*Barbus strumicae* Karman, 1955) is an endemic species of the Balkan Peninsula and of the Aegean watershed (Kottelat and Freyhof 2007). It was separated relatively recently as a different species from *B. cyclolepis* Heckel. The species has been recorded in the basins of the rivers Struma and Mesta, in Bulgaria, Greece and North Macedonia, and also in some rivers of the Chalkidiki Peninsula.

Its presence has also been reported in the basins of Lakes Volvi and Koronia, and the Kerkini Lake in Greece (Kottelat and Freyhof 2007, Barbieri et al. 2015, Sapounidis et al. 2015). The Thracian barbel prefers rivers with gravel and sandy bottoms, but it is also found in the littoral zone of lakes and reservoirs (Barbieri et al. 2015). According to Sapounidis (2015), its breeding period in the Mesta River is mainly in May-June. Males reach sexual maturity in their second year, while females in their

third and fourth year. In the Mesta River, the Thracian barbel reaches a maximum fecundity of 14,280 eggs (Kottelat and Freihof 2007, Sapounidis et al. 2015). The authors established that the main food objects are the larvae of Chironomidae and Ephemeroptera and the adults of Trichoptera and Amphipoda. They have also published data on the growth rate of the species in the Mesta River. Information on the growth parameters of the Thracian barbel in the Dzherman River and the Dospat Dam is given by Dikov and Zivkov (1985). Data on linear growth of this species in the rivers Mesta and Struma were also published by Marinov (1989).

Mesta River is formed by merging of two rivers: Bela Mesta River and Cherna Mesta River. However, Bela Mesta River is considered the main source of the Mesta River. Bela Mesta River originates from an elevation of 2690 m a.s.l., from the Granchar Lake in the west part of the Rhodopes Mountains. Near the village of Statmos (Greece), opposite the island of Thassos, the Mesta River flows into the Aegean Sea. There are 39 fish species in the Mesta River, 13 of which inhabit brackish and salt waters (Economidis et al. 2009). Two large reservoirs were built in the bed of the Mesta River on the territory of Greece – Thisavros and Platanovrysi (Economidis et al. 2009) and one small dam near the village of Toxotes (Sapounidis et al. 2015). These dams divide the Mesta River bed into four distinct parts (Sapounidis et al. 2015). The Dospat Dam was built along the Mesta River, in the bed of the Dospatska River on Bulgarian territory. Dospatska River flows into the Mesta River in Greece outside the Bulgarian part of the Mesta River. Therefore, this dam has an impact on the outflow of the Mesta River in Bulgaria, but not on the river connectivity there.

The purpose of this article is to clarify the current status of the Thracian barbel population in the Mesta River. For this purpose, some of its population parameters were studied and the differences with other populations of the species were analysed.

Materials and Methods

The material consists of 106 specimens of the Thracian barbel. Fieldwork took place in the autumn of 2021 and 2022. Sampling was via electrofishing by the use of a SAMUS 725G device with a 12V accumulator and 5–65 Amps with an output of 640 W. Studied area extends from the confluence of the rivers Cherna Mesta and Bela Mesta and reaches the vicinity of the village of Mesta. Study sites were located along the length of the area immediately following the trout area (Fig. 1, Table 1).

This section of the Mesta River has a slope ranging from 6 % to 8 %, and its width does not exceed 50 m. Species such as Grayling (*Thymallus thymallus* Linnaeus, 1758), Barbel (*Barbus barbus* Linnaeus, 1758), and Bream (*Abramis brama* Linnaeus, 1758) are not naturally distributed in rivers of the Aegean watershed (Kottelat and Freihof 2007). These

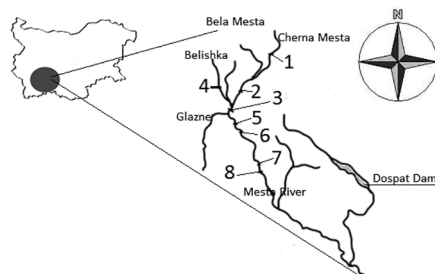


Fig. 1. Map of Mesta River, where Thracian barbel was collected.

Table 1. Mesta River sampling stations in November 2021 and October 2022.

No	Location	Geographic coordinates		Altitude, m a.s.l.	Month/ Year
		Latitude	Longitude		
1	In the Cherna Mesta River	42°04'18" N	23°43'33" E	1073	XI/2021
2	In the vicinity of the town Yakoruda	41°59'51" N	23°37'34" E	847	XI/2021
3	In the Belitsa River, the Mesta River' tributary	41°55'53" N	23°34'20" E	794	XI/2021
4	In the vicinity of village Kraishte	41°54'34" N	23°34'22" E	756	XI/2021
5	Near the confluence of the Glazne River with the Mesta River (a)	41°53'04" N	23°34'16" E	748	XI/2021
6	Near the confluence of the Glazne River with the Mesta River (b)	41°55'56" N	23°34'23" E	763	XI/2021
7	In the vicinity of village Mesta (a)	41°46'02" N	23°40'25" E	650	X/2022
8	In the vicinity of village Mesta (b)	41°45'45" N	23°40'39" E	649	X/2022

rivers are relatively short (Hristova 2012) and have a distinct fish fauna (Stefanov 2007), which does not align with Huet's ichthyological zonation (Huet 1949, Aarts and Nienhuis 2003).

Catch was performed according to the EN 14011:2003 instruction (Water quality, Sampling of fish with electricity – CEN). Upstream electrofishing was used. Species' identification was carried out according to the methodological guidance of Berg (1948, 1949), Drensky (1951), Kotelat and Freyhof (2007).

The linear growth was determined by performing a back-calculation of length data (L) based on the diagonal oral radius of a scale (S), following the methods described by Lea (1910), Zivkov (1980, 1981), Schneider et al. (2000). For this purpose, total length (L , mm) and full weight (W , g) were measured. The age was determined by counting the number of annuli or year marks of scales under an Olympus CX 31 light microscope. The diagonal oral radius of the scales (S) was measured using the divisions of an eyepiece micrometer. Weight was recorded with a digital electronic balance, accurate to 0.1 g. The relation can be expressed by the following linear equation (1):

$$L = a + b \cdot S, \quad (1)$$

where: L – the length of fish, cm; S – diagonal oral radius of scale (eyepiece micrometre scales divisions); a and b – coefficients.

The absolute annual linear increment was accepted as a characteristic of the growth (Zivkov 1972), calculated by formula (2):

$$t = L_n - L_{n-1}, \quad (2)$$

where: t – absolute annual linear increment, mm; L_n – n th year body length; L_{n-1} – the average length for two consecutive years, mm.

Growth in length was compared using the method proposed by Zhivkov (1999), which ranks populations by mean length (L) within each age group. Between two populations, the one with a larger L value at the age of the younger population is considered to have faster growth.

The determination of weight (W) was performed with the weight-length (W - L) relationship as described in formula (3) by Le Cren (1951). This method has been discussed by Schneider et al. (2000), Froese (2006), Froese et al. (2011). It has been widely used in various studies (Zivkov 1981, 1999; Prodanov 1982; Raiko-

va-Petrova and Zivkov 1993; Kukushkin 1997; Belomacheva et al. 2005).

$$W = a \cdot L^b, \quad (3)$$

where: W – body weight, g; L – standard length, mm; a and b – coefficients.

To compare the growth in length between populations, a method employed by Zivkov (1972) was followed in which population are ranged based on length at the same age.

The condition of a population was studied in three ways:

1) by calculating a classical Fulton coefficient (K_f) using the equation (4) (Froese 2006).

$$K_f = 100 \cdot W \cdot L^{-3}, \quad (4)$$

where: L – length, mm; W – body weight, g.

2) By calculating the factor K_b using Fulton's equation. In the case, the coefficient b from equation (3) is used as an exponent.

All data were calculated by using MS-Excel 2010. The Past program is also used for statistical processing.

Results

Species composition

In the sampling sites, we found five fish species – Macedonian trout (*Salmo macedonicus* Karaman 1924), Minnow (*Phoxinus phoxinus* Linnaeus 1758), Aegean dace (*Squalius orpheus* Kottelat & Economidis 2006), Thracian barbel (*B. strumicae* Karaman 1955), and Bleak (*Alburnus alburnus* Linnaeus 1758). However, only three specimens of Thracian barbel were caught in the vicinity of the town Yakoruda and the village Kraishte. In the rivers Cherna Mesta and Belishka, we did not detect the presence of fish at all. There was visible sewage and litters water pol-

lution in both tributaries. Ultimately, most of the research material was obtained in the section of the Mesta River, located between the confluence of Glazne River with the Mesta River and the section of the Mesta River near the village of Mesta.

Age and size composition

The age of specimens ranged from one to six years. In the sample, two and three-year-old fish were the most abundant, comprising 68 % of the overall capture (Fig. 2). One-year-old fish were less numerous than those in the following three age groups. From the second to the sixth year, the number of fish decreased. Five and six-year-old fish were relatively few.

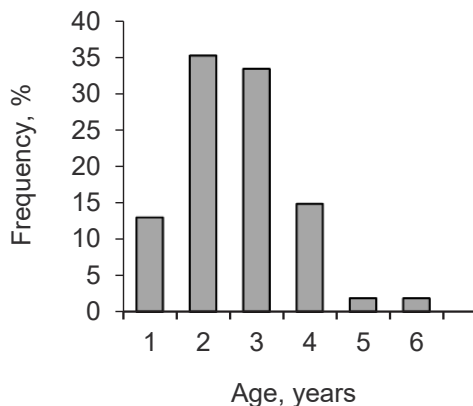


Fig. 2. Age structure of the population.

The largest specimen was a female of 242 mm length and 168.7 g weight. Mean weight was 24.2 g, and the mean length was 122.8 mm. The distribution of fish by size classes closely mirrored that of age groups. One-year-old fish, ranging from 40.1 mm to 80.0 mm in size, were scarce. More fish were found in the 80 mm to 170 mm range, which includes two-, three-, and four-year-olds. The size classes of 170.1–180.0 mm and 180.1–250.0 mm,

which include five- and six-year-old fish, were also less common (Fig. 3).

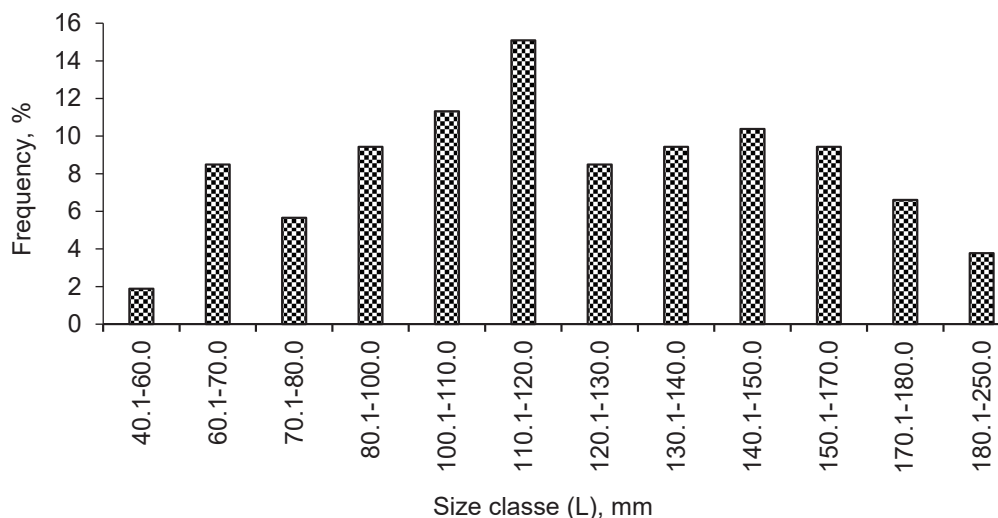


Fig. 3. Size classes of the Thracian barbel.

Growth in length

The relationship between length (L) and scale radius (S) was well expressed based on linear function (Fig. 4). This al-

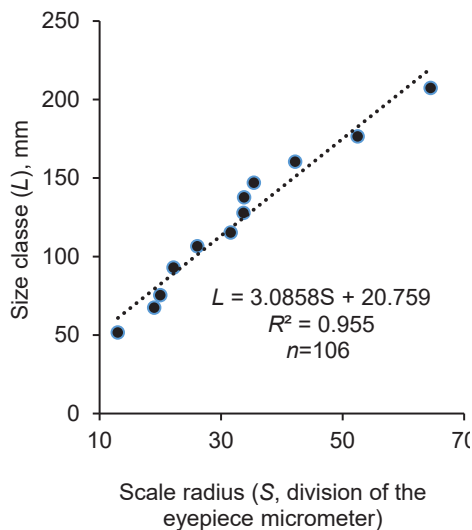


Fig. 4. Growth in length.

lowed a reliable back-calculation of the length along the scale radii.

The average lengths calculated this way at age are presented in Table 2. The study of the individual growth in length shows that in the first year the growth was the most intense. Fish from the other age groups grew by about 22 mm per year (with one exception, four-year-old fish). The measured real sizes of the fish were close to, but smaller than, the theoretically calculated ones (Table 2).

The W - L relation was very well expressed by power function (Fig. 5). As with other species of the genera *Barbus* (Rozdina 2009, Kolev and Raikova 2015, Kolev 2022), the Thracian barbel shows a regular increase in mass with increasing length.

We compared our data on the growth of the Thracian barbel with those of Marinov (1989) for the rivers Strumeshnitsa, Struma and Mesta (Table 3).

Table 2. Back-calculated L of the Thracian barbel in the Mesta River.

Age group	n	Mean calculated L , mm at age 1 to 6					
		L_1	L_2	L_3	L_4	L_5	L_6
I	2	60.9					
II	37	67.7	88.0				
III	46	70.1	99.1	124.4			
IV	10	66.7	94.5	125.7	151.0		
V	7	63.0	91.1	120.4	162.7	182.8	
VI	4	63.3	91.1	120.4	162.7	192.0	219.8
Mean calculated L , mm	106	65.3	92.8	122.7	158.8	187.4	219.8
Mean observed L , mm		51.5	85.5	131.9	160.3	176.4	207.3
Annual increment, mm		65.3	26.6	28.8	36.6	24.7	27.8

Table 3. Observed mean total length (TL) of the same age from some Bulgarian rivers.

River	n	Total body length (TL), mm						Source
		TL_1	TL_2	TL_3	TL_4	TL_5	TL_6	
Strumeshnica	15	63	96	156	-	-	-	Marinov (1989)
Struma	15	65	119	154	175	-	-	Marinov (1989)
Mesta	106	52	86	132	161	176	207	Our data (2024)
Mesta	32	71	120	127	-	-	-	Marinov (1989)

We also used more recent data. Since these are the calculated standard lengths (SL) for comparison we have transformed our data. For the Thracian barbel popula-

tion in the Mesta River SL was calculated as average 82 % of TL . Thus, TL data were recalculated as SL (Table 4).

Table 4. Mean calculated SL of the same age from some rivers.

River/Dam	n	Length (L), mm at age 1 to 7							Source
		L_1	L_2	L_3	L_4	L_5	L_6	L_7	
Dospat Dam	110	92	125	187	241	257	261	-	Dikov and Zivkov (1985)
Dzherman	167	54	90	126	152	167	180	185	Dikov and Zivkov (1985)
Mesta	106	53.5	76.1	100.7	130.2	153.7	180.2	-	Our data (2024)
Mesta	185	55.5	79.7	100.9	115.8	-	-	-	Sapounidis et al. (2015)

Growth in weight

The weight-length relationship W - L shown in Figure 5 is clearly defined. The exponent b was slightly less than 3, but very close to this value, making the difference

negligible.

The back-calculated masses of the Thracian barbel from the W - L relation are listed in Table 5. The values of the calculated and observed masses were closer in exception of one-year-old fish. In general,

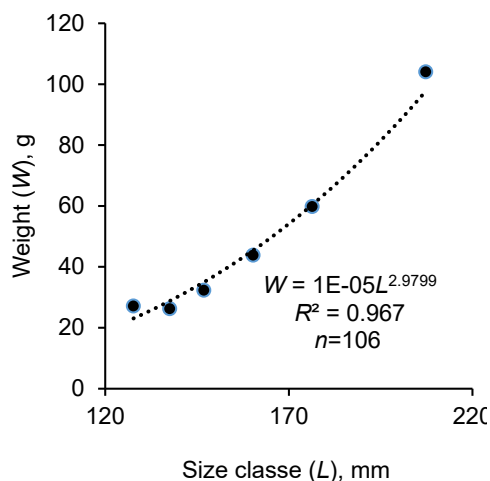


Fig. 5. Length-weight relationship of Thracian barbel in the Mesta River.

mass gain was slow. Annual growth progressively increased with age. Two- and three-year-old fish doubled their mass during the year. From the fourth year onwards, however, the annual increment began to slow down.

Condition coefficients

The condition was evaluated using the Fulton (K_f) and the K_b , coefficients derived by substituting the exponent n with b from equation 7 (as shown in Table 5). Data for Fulton coefficient (K_f) was available for fish populations of the Mesta River in the territory of Bulgaria and Greece. The data in Table 6 shows the coefficients K_f calcu-

Table 5. Back-calculated gutted body W .

Age group	n	Mean calculated W , g at age 1 to 6					
		W_1	W_2	W_3	W_4	W_5	W_6
I	2	2.1					
II	37	2.9	6.2				
III	46	3.2	8.9	17.5			
IV	10	2.7	7.7	18.0	31.1		
V	7	2.3	6.9	15.9	38.9	55.0	
VI	4	2.3	6.9	15.9	38.9	63.7	95.3
Mean calculated W , g	106	2.6	7.3	16.8	36.3	59.3	95.3
Mean observed W , g		1.8	6.3	28.5	43.8	59.8	104.0
Annual increment, g		2.6	4.7	9.2	19.7	20.5	31.6

lated from material obtained in November therefore they were comparable. In our research, K_b was much lower than K_f .

Table 6. Condition coefficients of the Thracian barbel.

Condition coefficients		Source
K_f	K_b	
1.011	0.730	Our data (2024)
0.903	-	Sapounidis et al. (2015)

Note: Coefficient of Fulton K_f ($n = 3$) and K_b ($n = b$), measured in November.

Discussion

The analytical discussion will now examine the growth patterns and mass accumulation of the Thracian barbel, focusing on the variations observed in the Mesta River in Bulgarian and comparing with data available from Greek territory. This discussion aims to offer a thorough understanding of the growth and mass accumulation patterns of the Thracian barbel across diverse river systems.

First of all, in order to explore the fish

population dynamics, it is important to investigate the potential factors affecting the survival rates and age structure. The low number of one-year-old fish suggests poor survival rates at a young age. Similarly, there is also low number of five- and six-year-old fish (Fig. 2). The scarcity of older fish could be due to both natural mortality and increased fishing activity (Pravdin 1965). However, given that the Thracian barbel is a popular target for sport fishing in this area of the Mesta River, the latter explanation seems more plausible.

The size distribution of the fish reflects these patterns (Fig. 4). The youngest and oldest fish classes have fewer individuals compared to other size classes, likely for the same reasons mentioned earlier. The growth in length is relatively consistent across the years (Table 2), with the highest growth expected in the first year. The rapid growth of one-year-old fish in length may be a strategy to evade predators by reaching a larger size (Nikolsky 1965).

The study utilised directly reported total fish lengths (TL) as presented by Marinov (1989). Discrepancies were noted in the lengths measured by the author compared to our findings. It was observed that fish in the Struma River basin exhibit a faster growth in length, likely influenced by the larger size and higher flow rate of the river (more than twice as high). The wider valley of the Struma River, exposed to Mediterranean climatic influences, may also contribute to this growth pattern. However, the limited number of specimens examined by Marinov (1989) may have impacted the accuracy of the data. Variations in fish length measurements were also observed in the Mesta River. For instance, one-year-old barbels with an average length of 50 mm typically weigh around 2–2.5 g, while three-year-old barbel at 100–120 mm length reach about

52 g in weight. It is only when the fish reach a length of 200 mm and are over six years old that they approach a weight of 100 g (tables 3 and 5).

Since only the mean values of L , by age, are reported in the literature, a statistical comparison between them is not possible. The assessment of the growth of the species in the individual populations was made according to the method proposed by Zivkov (1999). Our research findings show that the growth rate of the Thracian barbel closely aligns with those observed in the Mesta River in Greece (Sapounidis et al. 2015). Noticeably faster linear growth was reported for the species in the Dospat Reservoir (Dikov and Zhivkov 1985). Growth in the dam is especially rapid in the first year, with yearlings reaching the length of two-yearlings in the rivers probably due to the more abundant food there. However, due to the decrease in the speed of the water current, the Thracian barbel decreased in the Dospat reservoir and today it is no longer found there (Stefanov 2007).

Fulton coefficient values obtained from fish in both Bulgarian and Greek territories show similarities. Nonetheless, the coefficient K_b , which some authors, such as Zivkov (1981, 1999) and Raikova-Petrova and Zivkov (1993), consider more reliable, appears to be relatively low. This observation suggests that the Thracian barbel does not experience significant fattening before the onset of winter.

Conclusion

The comparative analysis of Thracian barbel populations in the Mesta River basin indicates a relatively slow growth rate for the species. In Dospat Reservoir, the species reaches the highest length-by-year

values reported in the literature.

This slow growth is reflected in the gradual mass accumulation observed within the population. Furthermore, the findings suggest that the condition factor for the Thracian barbel in this region is suboptimal. Notably, the population appears to have limited numbers of large and older specimens. Given that fecundity increases with age and size (Raikova-Petrova 1992, Rozdina 2009, Kolev 2021), it should be expected that the lack of larger fish has a negative impact on the reproductive potential of the species. All of these facts indicate that additional conservation efforts may be needed in the future, such as regulations in fishing for the species in order to maintain the long-term sustainability of its population in the Mesta River.

Conflict of interest

The authors of this article declare no conflict of interest.

Data availability statement

The data that support the findings of this study are available on request from the main author.

References

- AARTS B., NIENHUIS P.H. 2003. Fish zonations and guilds as the basis for assessment of ecological integrity of large rivers. In: Martens K. (Ed.), Aquatic Biodiversity. Hydrobiologia 5000: 157–178. doi: 10.1007/978-94-007-1084-9_11
- BARBIERI R., ZOGARIS S., KALOGIANNI E., STOUMBOUDI M., TH, CHATZINIKOLAOU Y., GIAKOUMI S., KAPAKOS Y., KOMMATAS D., KOUTSIKOS N., TACHOS V., VARDAKAS L., ECONOMOU A. 2015. Freshwater fishes and lampreys of Greece. An annotated checklist. Monographs on Marine Sciences No 8. Hellenic centre for marine research. 129 p.
- BASAMI R., GROVE D. 1985. Studies of feeding, growth and production of a recruited inshore populations of *Pleuronectes platessa* (L.) at East Anglesey, North Wales. Journal of Fish Biology 27(6): 765–783. <https://doi.org/10.1111/j.1095-8649.1985.tb03219.x>
- BELOMACHEVA G., ZHIVKOV M., KARAPETKOVA M. 2005. Growth rate and Condition of Bream, *Abramis brama* (Linnaeus, 1758), in the Danube River. Acta Zoologica Bulgarica 57(1): 71–82.
- BERG L. 1948. Freshwater fishes of the USSR and neighboring countries. Academy of the Sciences of the USSR. In three parts. 1381 p. (in Russian).
- BERG L. 1949. Freshwater fishes of the U.S.S.R. and adjacent countries. Moscow, Academy of the Sciences of the USSR, vol. II. 463 p. (in Russian).
- BIANCO P.G. 1998. Diversity of Barbinae fishes in southern Europe with description of a new genus and a new species (Cyprinidae). Italian Journal of Zoology 65 (sup1): 125–136. <https://doi.org/10.1080/11250009809386804>
- DRENSKY P. 1951. The fishes in Bulgaria. Sofia, Acad. Publ. House. 286 p. (in Bulgarian).
- DE SILVA S.S. 1985. Body condition and nutritional ecology of *Oreochromis mossambicus* (Pisces, Cichlidae) populations of man-made lake in Sri Lanka. Journal of Fish Biology 27(5): 621–633. <https://doi.org/10.1111/j.1095-8649.1985.tb03207.x>
- DIKOV Tz., ZIVKOV M. 1985. Analysis of the growth of the Barbel (*Barbus tauricus cyclolepis* Heckel) in the Dzherman River and Dospat Dam. Hydrobiology 26: 81–90 (in Bulgarian).
- ECONOMIDIS P., KUTRAKIS M., APOSTOLU A., VASILEV M., PECHLIVANOV L. 2009. Atlas of the fish fauna of the Mesta River. Telia & Pavla. 300 p. (in Greek and Bulgarian).

- FROESE R. 2006. Cub low, condition factor and length-weight relationships: History, meta-analysis and recommendations. *Journal of Applied Ichthyology* 22(4): 241–253. <https://doi.org/10.1111/j.1439-0426.2006.00805.x>
- FROESE R., TSIKIRAS A., STERGIU K.I. 2011. Editorial note on weight-length relationships in fish. *Acta Ichthyologica et Piscatoria* 41(4): 261–263. <https://doi.org/10.3750/AIP2011.41.4.01>
- GOLDSPINK C.R. 1979. The population density, growth rate and production of roach, *Rutilus rutilus*, in Tjeukemeer, the Netherlands. *Journal of Fish Biology* 15(4): 437–498. <https://doi.org/10.1111/j.1095-8649.1979.tb03632.x>
- HRISTOVA N. 2012. River waters of Bulgaria. Top Press Publishing House. 538 p. (in Bulgarian).
- HUET M. 1949. Evaluation of the Piscicultural Value of Fresh Water. Groenendaal, Imprimerie J. de Clercq. 55 p. (in French with abstract in English).
- KOLEV V. 2021. Maturation and fecundity of *Barbus petenysis* Stryama River of the Maritsa River drainage in Bulgaria. *Journal of limnology and freshwater fisheries research* 7(3): 233–240.
- KOLEV V. 2022. Age structure, growth rate and condition *Barbus petenysis* (Cyprinidae) in the middle and upper stream of the Ogosta River. *Forestry ideas* 28(2): 314–322.
- KOLEV V., RAIKOVA G. 2015. Age, growth rate and condition factor of the Maritsa barbel (*Barbus cyclolepis* Heckel, 1837) in the Stryama River. *Forestry ideas* 21(2): 277–283.
- KOTTELAT M., FREIHOF J. 2007. Handbook of European freshwater fishes. Edition Kottelat. 646 p.
- KUKUSHKIN N. 1997. Rate of growth of the Bream (*Abramis brama* L.) from the Tios-to lake. *Vestnik of the State University of Vitebsk?* 2(4): 77–81 (in Russian).
- LEA E. 1910. Contribution on the methods of the herring investigations. *ICES Journal of Marine Science* s1(53): 7–33. <https://doi.org/10.1093/icesjms/s1.53.7>
- LE CREN E.D. 1951. The Length-Weight Relationship and Seasonal Cycle in Gonad Weight and Condition in Perch (*Perca fluviatilis*). *Journal of Animal Ecology* 20(2): 201–219. <http://dx.doi.org/10.2307/1540>
- MARINOV B. 1989. Taxonomy, binomial and faunistic of some species of the family Cyprinidae and Cottidae (Pisces) from Bulgaria. PhD thesis, Sofia University 'St. Kliment Ohridski': 134–167 (in Bulgarian).
- NIKOLSKY G. 1965. Theory of fish population dynamics. Nauka, Moscow: 80–115 (in Russian).
- PRAVDIN I. 1966. Guide to the Study of Fishes. Food industry. Moscow. 267 p. (in Russian).
- PRODANOV K. 1982. Biology and state of stocks of whiting inhabiting the Bulgarian Black Sea coast, in view of its rational use through industrial fishing. PhD thesis. Institute of Fish Resources, Varna: 68–69 (in Bulgarian).
- RAIKOVA-PETROVA G. 1992. Comparative population biology of pike perch (*Stizostedion lucioperca* L.) in the dams Batak and Ovcharitsa. PhD thesis, Institute of Zoology, Bulgarian Academy of sciences. 181 p. (in Bulgarian).
- RAIKOVA-PETROVA G., ZIVKOV M. 1993. Age and growth rate of pike perch (*Stizostedion lucioperca* L.) in Ovcharitsa cooling reservoir. *Bulgarian Academy of Sciences. Hydrobiology* 38: 67–80 (in Bulgarian).
- ROZDINA D. 2009. Population biology of the Maritsa barbel (*Barbus cyclolepis* Heckel) from the middle courses of the Maritsa River. PHD thesis. Sofia University 'St. Kliment Ohridski', Faculty of Biology. Department of general and applied hydrobiology. 126 p. (in Bulgarian).
- SAPOUNIDIS S., KOUTRAKIS E., LEONARDOS D. 2015. Life history traits, growth and feeding ecology of native species (*Barbus strumicae* Karaman, 1955) in Nestos River, a flow regulated river in Northern Greece. *North-Western Journal of zoology* 11(23): 331–341.
- STEFANOV T. 2007. Fauna and distribution of fishes in Bulgaria, National museum of natural history, Bulgarian academy of sciences. In: Fet V. and Popov A. (Ed.), Bioge-

- ography and ecology of Bulgaria. Sofia, Bulgaria, Springer: 109–139.
- SCHNEIDER J.C., LAARMAN P.W., GOWING H. 2000. Age and Growth Methods and States Averages. Chapter 9 in Schneider J.C. (Ed.), Manual of fisheries survey methods II: with periodic updates. Michigan Department of Natural Resources, Fisheries Special Report 25, Ann Arbor. 13 p. <https://name.umd.umich.edu/4967594.0001.001>
- VASILIOU S., ECONOMIDIS P. 2005. On the life-history of *Barbus peloponensis* and *Barbus cyclolepis* in Macedonia, Greece. *Folia zoologica* 54(3): 316–336.
- ZIVKOV M. 1972. Critical analysis of some relative indexes of the intensity of growth in fishes. Bulgarian Academy of Sciences. Proceedings of the institute of zoology and museum 36: 81–101 (in Russian).
- ZIVKOV M. 1980. On the method for Studying Lee's Phenomenon and Growth Compensation of Fish. Bulgarian Academy of Sciences. *Hydrobiology* 11: 30–56 (in Russian with abstract in English).
- ZIVKOV M. 1981. Regularities and particularities in the growth rate, the maturity and the fecundity of the fish populations in the Batk Dam. PhD thesis, Institute of Zoology, Sofia. 316 p. (in Bulgarian).
- ZIVKOV M. 1999. Factors, regularities and methodological significances of population biological variability of some freshwater fishes. DSc thesis, Institute of Zoology, Sofia. 406 p. (in Bulgarian).

Agroforestry coffee reduces household vulnerability to climate change

Fembriarti Erry Prasmatiwi^{1*}, Rusdi Evizal², Tri Novi Astuti¹,
and Asyifa Rahmita Zahra³

¹Department of Agribusiness, Faculty of Agriculture, Lampung University, Jalan Soemantri Brodjonegoro 1, Bandar Lampung 35145, Indonesia. *E-mail: fembriarti.erry@fp.unila.ac.id

²Department of Agrotechnology, Faculty of Agriculture, Lampung University, Jalan Soemantri Brodjonegoro 1, Bandar Lampung 35145, Indonesia.

³Department of Agricultural Socioeconomics, Faculty of Agriculture, Gadjah Mada University, Bulaksumur, Catur Tunggal, Yogyakarta 55281, Indonesia.

Received: 18 July 2024 / Accepted: 09 October 2024 / Available online: 17 October 2024



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

Abstract

Global climate change impacts all aspects of human life, including agriculture. Coffee is a major export commodity for Lampung Province. El Niño and La Niña can reduce coffee production by 80 %. Agroforestry coffee planting pattern is one of the steps to minimize the impact of climate change. This research, conducted from November 2022 to March 2023 in West Lampung Regency, focused on the Way Tenong, Air Hitam, and Batu Brak sub-districts. A survey method was employed, and a sample of 233 coffee farmers was selected through random sampling. The samples in this research were divided into three groups, namely monocropping coffee systems (MCS), simple agroforestry systems (SAFS), and complex agroforestry systems (CAFS). The level of livelihood vulnerability of farm households was analysed using the Livelihood Vulnerability Index. Overall, farm households on monoculture coffee farms had higher livelihood vulnerability compared to farm households on SAFS and CAFS. Factors significantly affecting the vulnerability of coffee farming households to climate change include farmers' knowledge of climate change, drought, rainfall patterns, pest and disease outbreaks, as well as the adoption of SAFS and CAFS. Implementing agroforestry systems in coffee farming can help reduce this vulnerability.

Key words: agroforestry coffee farmer, coffee production, Indonesia, West Lampung.

Introduction

In Indonesia, climate change is characterised by changes in average daily temperature, rainfall patterns, rising sea levels, seasonal shifts, and climate variability events, such as El Niño and La Niña which cause extreme drought and high-intensity

rain. In plantation crops, these changes in rainfall patterns and intensity can lead to decreased productivity, shifts in flowering and harvest seasons, and changes in land suitability (Sarvina et al. 2023).

Indonesia ranks as the fourth-largest coffee producer globally, with an average annual production of 725,680 tons from

2016 to 2020, representing 7.21% of global coffee output. Lampung Province is a key robusta coffee-producing region, contributing 113,739 tons (14.68% of national production) in 2022. Within Lampung, West Lampung Regency is the largest producer, accounting for 55,080 tons or 48.43% of the province's robusta coffee production (Direktorat Jendral Perkebunan 2023).

Coffee is a climate-sensitive plantation crop (Bacon et al. 2017). Climate variability causes dynamics in coffee production (Chengappa and Devika 2016, Pham et al. 2019). Changes in climate variability as a result of climate change have a very significant effect on the growth and development of coffee plants, production, and economic life of coffee farmers. An increase in the intensity of climate anomalies due to climate change events such as El Niño has caused a decrease in coffee production by 34.79 %, as well as during La Niña, the output of coffee production decreased by 98.5 % (Supriadi and

Pranowo 2015).

Climate change in West Lampung results in high rainfall variability which causes variations in coffee productivity (Fig. 1). When the weather is good, coffee productivity can reach above 1000 kg·ha⁻¹, but when the climate is unfavourable, productivity drops to 800 kg·ha⁻¹. Resulted in reducing farmers' income. To reduce the impact of climate change, active efforts are needed to anticipate it through mitigation and adaptation strategies. Coffee farming patterns with agroforestry systems, which add trees to the farming system or combine crops and trees, can be a solution to address climate change by adopting mitigation and adaptation measures (Nandakishor et al. 2022) and help farmers earn a sustainable income (Supriadi and Pranowo 2015, Meragiaw 2017).

It is common for agroforestry systems to alter the risk of drought and flood impacts (van Noordwijk et al. 2016). Trees can reduce the consequences of climate change, storing carbon in biomass, and

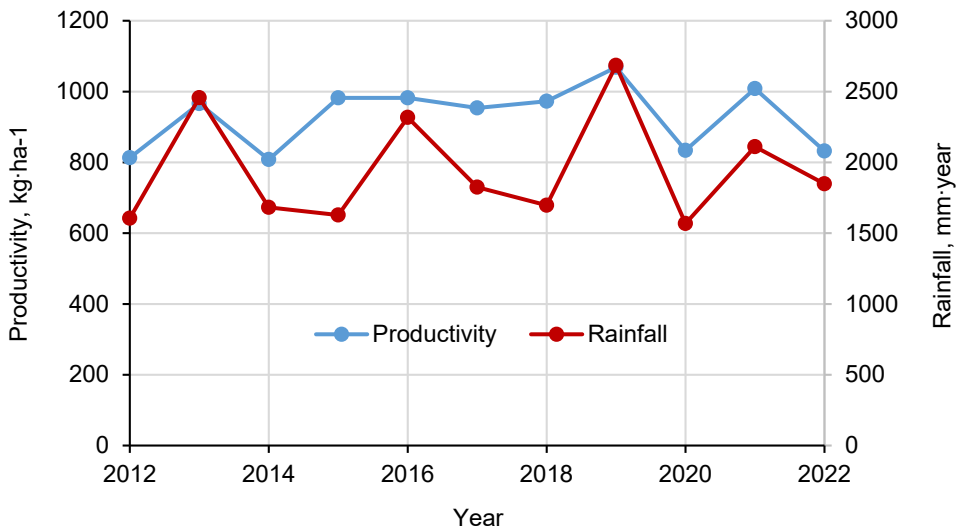


Fig. 1. West Lampung coffee productivity 2012–2022.

Sources: Badan Pusat Statistik (2022), BPS Provinsi Lampung (2023a, 2023b.)

soil and reducing atmospheric carbon dioxide (Hairiah et al. 2020). In addition, agroforestry can reduce land degradation (Mohebalian and Aguilar 2018). Agroforestry systems provide options to mitigate climate change with the possibility of increased crop yield and provide environmental benefits such as climate change adaptation (Coulibaly et al. 2017). Coffee agroforestry systems can mitigate projected climate change impacts by modifying the microclimate without reducing coffee productivity.

Coffee productivity with agroforestry systems tends to be more stable over the years than with coffee systems without shade (Nandakishor et al. 2022). According to Gidey et al. (2020), coffee production with agroforestry systems has a higher level of resilience in the face of climate change. Agroforestry systems can reduce the vulnerability of smallholders and act as a buffer for their livelihoods (Van Noordwijk et al. 2011, Minang et al. 2015).

In West Lampung Regency, not all farmers apply agroforestry systems on their coffee plantations. Prasmatiwi et al. (2010) reported that based on shade plants on coffee plantations, coffee cultivation was categorised into three: 1) monoculture or non-agroforestry coffee farming, 2) coffee farming with one type of intercropping plant or one type of dominant shade plant, and 3) coffee farming with complex or multi-strata agroforestry systems, namely coffee with various intercropping plants.

Coffee or cocoa plantations may be classified into monoculture without shade trees, monoculture with specialised shade trees (especially legume trees), and polyculture with complex shade trees (Somarriba and Lachenaud 2013). Pribadi et al. (2023) classified coffee plantations into monoculture (non-agroforestry), simple

agroforestry, and complex agroforestry. More specifically, Mattalia et al. (2022) classified cocoa plantation as monocropping if cocoa is grown under the sun (without shade tree), SAFS if cocoa is grown under 1-3 shade tree species, and CAFS if cocoa is grown under more than 3 shade tree species.

Research analysing farmers' vulnerability due to climate change has appeared before, reported by Dias et al. (2023), Quiroga et al. (2020), and Rahn et al. (2014). However, research examining whether non-agroforestry (monocropping) coffee farmers are more vulnerable to climate change compared to agroforestry coffee farmers has not been conducted. This research aims to assess whether agroforestry systems in coffee plantations can mitigate the vulnerability of farming households to climate change in West Lampung Regency and to identify the factors influencing the level of vulnerability among coffee farmers.

Method

Field research was conducted from November 2022 to March 2023. Researchers employed a survey-based approach, gathering primary data through direct interviews with coffee cultivators. The research respondents were coffee farmers in 3 coffee production center sub-districts in West Lampung, Indonesia, namely Batu Brak, Way Tenong and Air Hitam sub-districts. We selected 8 villages for the research and a visual representation of these sub-districts geographical locations is provided in Figure 2.

This research included 233 coffee farmers, categorised into three groups based on the classification adapted from Mattalia et al. (2022): (1) monocropping

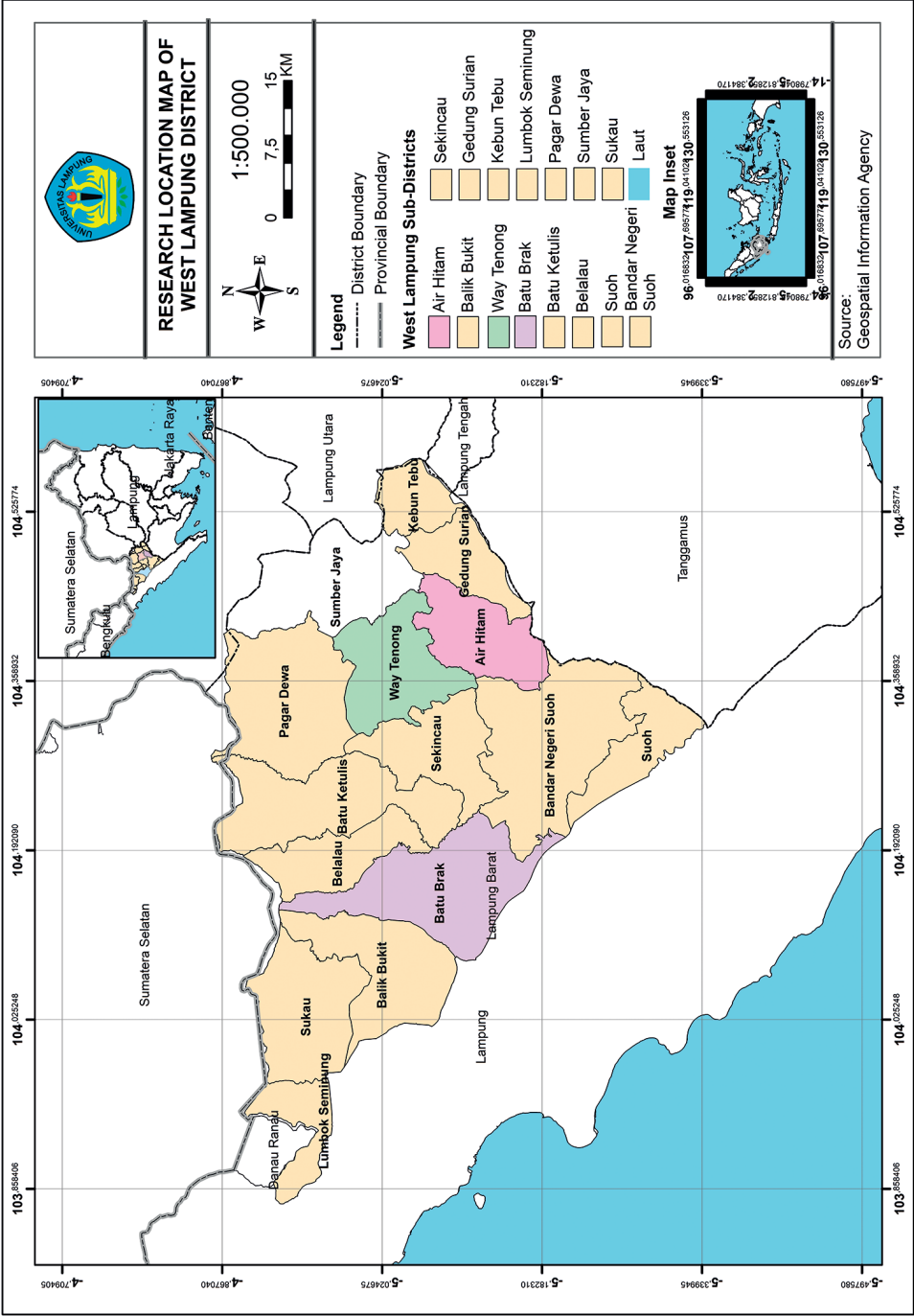


Fig. 2. Map of West Lampung District with the three sub-districts studied.

coffee systems (MCS), (2) simple agroforestry systems (SAFS), and (3) complex agroforestry systems (CAFS). In MCS (non-agroforestry system), coffee trees are grown alone without any shade. In SAFS, they are cultivated with up to three shade tree species. In CAFS, coffee trees are grown with four or more shade tree species. The number of respondents in each category is detailed in Table 1.

Table 1. Respondent categories.

Categories	Number of respondents
Monocropping coffee systems	69
Simple agroforestry systems	91
Complex agroforestry systems	73
Total	233

Researchers examined the susceptibility of coffee growers using the Livelihood Vulnerability Index (LVI), a framework established by Hahn et al. (2009). Vulnerability, as defined by Adger (2006), describes how prone individuals or communities are to disruptions in their way of life caused by social and environmental shifts. LVI methodology evaluates several crucial factors, including demographic characteristics, financial resources, educational attainment, consumption patterns, food availability, access to water, exposure to natural calamities, and fluctuations in climate conditions.

LVI analysis, as outlined by the Intergovernmental Panel on Climate Change (IPCC) (LVI-IPCC), indicates that vulnerability is determined by adaptive capacity, sensitivity, and exposure. This framework allows respondents to openly assess various questions related to these factors. The indicators used for LVI measurement are detailed in Table 2.

The data used in the index calculation

has different units and weights so it needs to be standardised to equalise the weights using equations (1) to (5) (Hahn et al. 2009).

$$Index_{sd} = \frac{S - S_{min}}{S_{max} - S_{min}}, \quad (1)$$

where: $Index_{sd}$ is a standardised value of each subcomponent, S is the observed value of each subcomponent, S_{min} and S_{max} are the maximum and minimum values for each subcomponent.

After determining the subcomponent's value, the next step is to calculate the value of the main component using equation (2).

$$M_i = \sum_1^n \frac{Index_{sd}}{n}, \quad (2)$$

where: M_i is one of the eight main components, $Index_{sd}$ is the sum of the subcomponents, and n represents the number of subcomponents within each main component.

After calculating the values for each main component, they must be averaged to determine the overall LVI level using equation (3) (Manaye 2024).

$$LVI = \frac{\sum_{i=1}^8 W_{mi} \cdot M_i}{\sum_{i=1}^8 W_{mi}}, \quad (3)$$

where: LVI is vulnerability of each agroforestry system, determined from the weighted average of the eight main components, W_{mi} is the weight of each main component, and M_i is the main component.

LVI employs a scale ranging from 0 to 1, where the lower bound signifies minimal vulnerability and the upper bound represents maximum vulnerability. In calculating the LVI-IPCC index, researchers evaluate three main vulnerability factors as outlined by the IPCC: sensitivity, adaptability, and exposure. Although it uses the same indicators as LVI, LVI-IPCC index integrates them based on their contributing factors before combining the main

Table 2. Indicators for measuring vulnerability of farming households.

Parameter	Main component	Definition	Reference
Exposure	Natural disasters and climate variability	Natural disasters experienced by farmers in the last decade due to climate variability.	Hahn et al. (2009), Ho et al. (2022)
Adaptation	Socio-demographics	Farmer traits refer to the attributes of farmers, such as age and gender, that affect their understanding and reaction to climate change impacts.	Hahn et al. (2009), Shen et al. (2022)
	Education	The attributes of farmers that shape their understanding of and reactions to the consequences of climate change.	Hahn et al. (2009), Shen et al. (2022)
	Income	The various sources of revenue for farmers influence their vulnerability to climate change.	Hahn et al. (2009), Murniati et al. (2017)
	Consumption	Consumption encompasses the sources and factors related to farmer's dietary habits, such as rice consumption and staple food choices, which affect their vulnerability to climate fluctuations.	Hahn et al. (2009), Murniati et al. (2017)
Sensitivity	Agriculture	The characteristics of a farm and elements that affect the resilience of livelihoods to climate change, including farm size, shade-producing crops, and crops other than coffee.	Hahn et al. (2009), Murniati et al. (2017)
	Water	Availability of water for farmers to irrigate their fields amid climate change impacts.	Adu et al. (2018), Ho et al. (2022)
	Food	Food security and the elements influencing farmers' susceptibility to climatic shifts encompass crop diversification and the capacity to preserve crops.	Hahn et al. (2009), Adu et al. (2018)

components. The value for each contributing factor is determined using equation (4).

$$CF_d = \frac{\sum_{i=1}^n W_{mi} \cdot M_{di}}{\sum_{i=1}^n W_{mi}}, \quad (4)$$

where: CF_d represents an *IPCC* defined contributing parameter (adaptive capacity, sensitivity, and exposure) for region 'd', M_{di} denotes the main component for region 'd' indexed by i ; W_{mi} is the weight of each main component, n is the number of main components within each contributing parameter.

After quantifying adaptive capacity, sensitivity, and exposure, the three contributing parameters are combined using equation (5).

$$LVI - IPCC = (e_d - a_d) \cdot S_d \quad (5)$$

where: $LVI - IPCC$ is for region 'd' based on the *IPCC* vulnerability framework. In this context, e_d denotes the exposure score calculated for region 'd' (including climate variability and natural disaster components), S_d denotes the sensitivity score (weighted average of the biophysical environment, agriculture, and water systems), and a_d denotes the adaptive ca-

capacity score (weighted average of assets and wealth, social networks, socio-demographics, and physical assets) (Asfaw et al. 2017). *LVI – IPCC* framework employs a scale ranging from -1 to +1, with -1 indicating minimal vulnerability (adaptive capacity exceeds sensitivity and exposure), 0 indicating moderate vulnerability (adaptive capacity and exposure are balanced), and +1 indicating high vulnerability (sensitivity and exposure exceed adaptability) (Hahn et al. 2009).

Factors influencing the vulnerability level of coffee farmers to climate change were analysed using binary logistic regression. This analytical approach examines the correlation between a binary or dichotomous dependent variable (y) and independent variable (x) which can be quantitative, qualitative, or a combination of both (Hosmer and Lemeshow 2000). In this research, the dependent variable (y) has two categories: 'not vulnerable' ($y = 1$) and 'vulnerable' ($y = 0$). The criteria for vulnerable and not vulnerable are determined by *LVI-IPCC* scale of -1 – -0.4 is not vulnerable, -0.41 – 0.3 is vulnerable, and 0.31 – 1 is highly vulnerable (Hahn et al. 2009). The independent variables include land area, education, climate change knowledge, age, drought level, rainfall, pest and disease attacks, number of adaptation strategies, simple agroforestry system, and complex agroforestry system. The logistic regression equation is based on the probability function $\pi(x) = E(Y|x)$, where $E(Y|x)$ represents the expected value of Y given x . The interpretation of this probability function is detailed in equation (6).

$$\pi(x) = \frac{e^{\beta_0 + \beta_1 \cdot x_1 + \beta_2 \cdot x_2 + \dots + \beta_p \cdot x_p}}{1 + e^{\beta_0 + \beta_1 \cdot x_1 + \beta_2 \cdot x_2 + \dots + \beta_p \cdot x_p}} \quad (6)$$

Then a logit transformation is performed to simplify equation (6) in logit

form as in equation (7).

$$g(x) = h \left[\frac{\pi(x)}{1 - \pi(x)} \right] = \beta_0 + \beta_1 \cdot x_1 + \dots + \beta_p \cdot x_p, \quad (7)$$

where: β_0 is the intercept, β_p is the regression coefficient of p -th variable estimator, and x is the estimator variable.

The logistic regression model with predictor variables is a logit model, where the function is a linear function of the parameters. In assessing the impact of the independent variables on the dependent variable, the Likelihood Ratio (LR) test and Wald test are utilised.

Result and Discussion

Characteristics of respondents

The characteristics of coffee farms of sampled farmers are shown in Table 3. The average land size of MCS is 1.1 ha which is similar to land size of SAFS, while land size of CAFS is 1.51 ha. In this research, farmers of those three categories are the owner of the land. Age of the average coffee plants in the three categories is almost the same, range between 22–23 years. The number of coffee trees per ha of MCS is greater than those of SAFS and CAFS. In SAFS and CAFS, beside coffee trees, there are intercrops including pepper (*Piper nigrum* L.) and banana (*Musa paradisiaca* L.), and shade trees including *Gliricidia sepium* (Jacq.) Walph., *Erythrina subumbrans* (Hassk.) Merr.), *Dalbergia latifolia* Roxb.), and *Maesopsis eminii* (Engl.).

Coffee productivity in CAFS was 948 kg·ha⁻¹, surpassing that in SAFS was 859 kg·ha⁻¹ and in MCS 817 kg·ha⁻¹. Farmers typically sell their coffee to village intermediaries. The price at which coffee is sold varies based on its quality and the

Table 3. Coffee farming profile.

Description	Monocropping coffee systems			Simple agroforestry systems			Complex agroforestry systems		
	mean	max	min	mean	max	min	mean	max	min
Land area, ha	1.11	4.00	0.25	1.16	4.00	0.50	1.51	7.00	0.40
Number of coffee trees	2552	4000	1250	2472	3000	1000	2390	3100	1000
Age of coffee plant, years	23.90	60.00	5.00	22.42	50.00	3.00	23.73	20.00	4.00
Number of intercropped trees per ha	-	-	-	236	198	584	349	295	669
Coffee price, IDR·kg ⁻¹	24,159	27,000	21,000	24,016	27,000	21,000	24,236	27,000	21,000
Coffee productivity, kg·ha ⁻¹	817	1350	300	859	1510	467	948	1690	400

Note: 1 IDR = 60,085,037·10¹² € and 1 € = 16,645.3 IDR.

selling location. The average selling price of coffee was IDR 24,159–24,236 per kg.

Income from agroforestry coffee farming is derived from two sources: revenue from coffee plants and earnings from intercropped plants. In MCS, farmers earned intercropping income of IDR 435,628 per ha in total. In SAFS, farmers get income from pepper plants climbed on gliricide plants and banana and chili plants. The total revenue of intercropping simple agroforestry systems is IDR 2,528,968. In the CAFS, farmers get additional income from avocado (IDR 267,428), pepper (IDR 1,201,228), banana (IDR 760,928), cloves (IDR 96,285), jengkol (IDR 248,571), petai (IDR 85,714), durian (IDR 232,857), and chili (IDR 113,571). The income of intercropping complex agroforestry systems is IDR 3,296,728 per ha.

The average income of coffee farming in CAFS was the highest compared to other systems at IDR 21,247,112. The findings of this research align with Huhasna et al. (2021), which indicate that the average net income from coffee agroforestry

systems is higher compared to that from coffee agroforestry systems with a single plant type (monoculture).

Farmer's knowledge of climate change

Overall, farmers' insights on climate change is mainly linked to the impact of the rainy and dry seasons. The most striking climate change felt by farmer households in the three agroforestry systems is the increase in rainfall. The increase in rainfall that was felt by farmers occurred in April and May, which amounted to 27.27 % and 136.09 % (Badan Pusat Statistik 2022). The increase in rainfall was felt by farmers, considering that this month was the coffee harvest season. Increased rainfall can cause flowers, pistils, and fruit to rot and hamper the harvest process (Evizal et al. 2019). In addition, due to increased rainfall, farmers need more time to spend drying coffee. Farmers need about more than two weeks. As much as 81.16 % farmers of MCS felt the increased rainfall more than the other two agroforestry sys-

tems.

The impacts of climate change most commonly experienced by farmers in monocropping coffee systems as well as in simple and complex agroforestry systems include pests and plant diseases. According to Syakir and Surmaini (2017), climate change can exacerbate the prevalence of coffee pests and diseases, such as coffee fruit borer and leaf rust. Additionally, changes in rainfall intensity are among the most noticeable impacts of climate change for farmers. In monocropping systems, 81.16% of farmers reported experiencing more significant effects from changes in rainfall intensity compared to those in agroforestry systems. This is because monocropping systems do not use shade, so increased rainfall directly impacts the coffee plants, potentially reducing flower and fruit production due to decreased photosynthesis from increased cloud cover. In addition, farmers also experienced crop failure as a consequence of climate change. Most MCS coffee farmers (53.62 %) experienced a production decline. In contrast SAFS coffee farmers (36.56 %) and CAFS (26.03 %) experienced a production declining. This crop failure is due to coffee fruit fall and coffee fruit drive disease due to increased rainfall. Harvest failure can also refer to the percentage of farmers who experienced a decreased production.

Exposure index

The purpose of calculating the exposure index is to have a closer sense of the impacts of climate change experienced by farming households. Based on Table 4, MCS coffee farmers have a greater exposure index (0.44) than SAFS and CAFS (0.36 and 0.30). A higher exposure index indicates that coffee SAFS farmers

in MCS are more vulnerable to climate change compared to those in SAFS and CAFS. Indicators that influence this are the increased risk of landslides and climate extremes. Climate extremes reported by farmers in the research location refer to increased rainfall and a prolonged rainy season. SAFS and CAFS have a lower exposure index because the shade trees help mitigate the impacts of climate change. Additionally, climate change can increase the risk of landslides. MCS coffee farming is more vulnerable to landslide risk (0.72) than SAFS (0.49) and CAFS (0.30). Agroforestry systems play a very important role in retaining run-off, which significantly reduces the occurrence of floods and landslides.

Another impact of increased climate extremes due to increased rainfall and prolonged rainy seasons is increased pest and plant disease attacks. Increased rainfall can reduce the ambient temperature, making coffee berry borer pests and rust disease spread faster. MCS coffee farmers are more susceptible to pests (0.52) than SAFS and CAFS (0.48 and 0.38). Pests spread more rapidly in coffee farms without shade plants. However, the use of shade plants in coffee farms can help reduce the rate at which pests and diseases spread (Rice 2018).

Sensitivity index

The calculation of the sensitivity index is intended to evaluate how susceptible farm households are to climate change. Results of Table 5 show that in the main component of agriculture, farm households on MCS have a higher sensitivity (0.23) than farm households on CAFS (0.39). This sensitivity is because the average farm household in MCS does not have farms other than coffee. MCS coffee

Table 4. Subcomponent, main component, and exposure index values due to climate change.

Main component	Subcomponent	Subcomponent value			Main component value		
		MCS	SAFS	CAFS	MCS	SAFS	CAFS
Natural disasters and climate variability	Households not aware of climate change information	0.32	0.18	0.14	0.44	0.36	0.30
	Number of drought-affected households	0.28	0.27	0.27			
	Frequency of climate extremes increases	0.46	0.51	0.43			
	Heat and soil drying out early	0.34	0.24	0.25			
	Crop failure	0.41	0.36	0.33			
	Landslide risk	0.72	0.49	0.30			
	Pests and diseases	0.52	0.48	0.38			
Exposure index					0.44	0.36	0.30

Table 5. Subcomponent, main component values, and sensitivity of farm households to climate change.

Main component	Subcomponent	Subcomponent value			Main component value		
		MCS	SAFS	CAFS	MCS	SAFS	CAFS
Agriculture	Land area cultivated	0.10	0.11	0.15	0.23	0.23	0.39
	Percentage of households with income other than agriculture	0.65	0.62	0.66			
	Number of shade plants that produce yields	0.10	0.12	0.12			
	Percentage of households with farms other than coffee	0.12	0.16	0.11			
	Percentage of households that grow food crops	0.50	0.52	0.56	0.43	0.42	0.39
Food	Percentage of households that have savings	0.04	0.05	0.03			
	Share of households that never store their harvest	0.75	0.70	0.59			
	Water availability is limited	0.20	0.28	0.06	0.41	0.40	0.26
Water	Using water wisely	0.49	0.47	0.38			
	Apply irrigation	0.38	0.30	0.23			
	Number of households with artificial water sources	0.38	0.35	0.22			
	Share of households that use water not from natural sources for household needs	62.32	59.34	41.10			
Sensitivity index					0.36	0.35	0.34

farmers depend solely on coffee farming as their main source of income. If both quantity and quality of farm production diminished due to climate change impacts, farm households on MCS are more affected by other agroforestry systems (Minai et al. 2014).

Based on the main component values for the food indicator, MCS coffee farmers exhibit higher sensitivity (0.43) compared to farm households in other agroforestry systems (0.42 and 0.39). This higher sensitivity is due to most MCS coffee farmers not storing their crops or planting food crops, resulting in a lack of food reserves. Consequently, if climate change impacts reduce the quantity and quality of farm production, MCS coffee farmers are more significantly affected in meeting their food needs compared to those in SAFS and CAFS systems. In the water indicator, the sensitivity level of the main component for farm households in MCS is higher (0.41) compared to those in other agroforestry systems, which have sensitivity levels of 0.40 and 0.26, respectively. This sensitivity is because most of MCS coffee farmers do not have a fixed water source such as a well compared to farm households in other agroforestry systems. MCS coffee farmers mostly rely on rain-fed systems, thus vulnerable to droughts and water shortages (Gidey et al. 2020).

Adaptability index

Calculating the adaptive capacity index is essential for understanding how farming households make efforts to cope with climate change. Based on Table 6, CAFS coffee farmers have better adaptability (0.42) compared to MCS (0.37) and SAFS coffee farmers (0.39). The most influential main component for farm households on CAFS in adaptability is income. House-

holds in CAFS farms earn more income than farm households in other agroforestry systems because most of them have income from non-farm sources. Thus, in the event of climate change that affects their farming activities, complex agroforestry systems farming households still have income reserves. According to (Purboningtyas et al. 2018) livelihood diversification is one of the economic adaptations carried out by farmers.

Livelihood vulnerability of farming households using the LVI method

The vulnerability status of farm households from climate change can be determined through LVI values formulated by Hahn et al. (2009). Table 7 shows that MCS coffee farmers (0.46) experience natural disasters and climate variability more than SAFS (0.38) and CAFS coffee farmers (0.30). Both areas have relatively moderate values because they are not disaster-prone areas. The losses experienced are economic losses caused by climate variability in coffee farming activities. Generally, MCS coffee farmers have higher livelihood vulnerability than in SAFS and CAFS coffee farmers. This result is indicated by LVI values of 0.39 for MCS coffee farmers, 0.35 for SAFS, and 0.33 for CAFS. Both regions have relatively moderate livelihood vulnerability relative to the LVI scale of 0 to 0.5.

Livelihood vulnerability of farming households using the LVI-IPCC method

The calculation of livelihood vulnerability to climate change using the LVI-IPCC involves combining the values of the seven main components. A higher LVI-IPCC value indicates greater livelihood vulnerabil-

Table 6. Subcomponent, main component values and farmer household adaptation to climate change.

Main component	Subcomponent	Subcomponent value			Main component value		
		MCS	SAFS	CAFS	MCS	SAFS	CAFS
Socio-demographics	Number of female household heads	0.01	0.00	0.01	0.24	0.22	0.25
	The average age of household head	0.47	0.47	0.50			
	Number of unproductive family members	0.25	0.47	0.22			
Income	Total household income	0.14	0.17	0.31	0.40	0.39	0.55
	Number of households with off-farm income	0.65	0.62	0.79			
Education	Household head education < 9 years	0.52	0.59	0.42	0.33	0.39	0.31
	Number of household members with > 9 years of education	0.14	0.18	0.19			
	Amount of household rice consumption per day	0.18	0.21	0.20	0.50	0.56	0.56
Consumption	Whether or not there is a combination of staple food consumption	0.96	1.00	1.00			
	Number of staple food combinations	0.37	0.48	0.49			
Index adaptive					0.37	0.39	0.42

Table 7. LVI value, farm household livelihood vulnerability index to climate change.

Main component	Main component value		
	MCS	SAFS	CAFS
Natural disasters and climate variability	0.46	0.38	0.30
Socio-demographics	0.24	0.22	0.25
Income	0.40	0.39	0.55
Education	0.33	0.39	0.31
Consumption	0.50	0.56	0.56
Agriculture	0.24	0.26	0.39
Food	0.43	0.42	0.39
Water	0.41	0.40	0.26
LVI	0.39	0.35	0.33

ity due to climate variability. According to the results in Table 8, farmer households in MCS exhibit higher livelihood vulnerability (0.03) compared to those in SAFS

(-0.01) and CAFS (-0.04). The elevated exposure and sensitivity indices (0.44 and 0.36, respectively), coupled with a lower adaptability index (0.37), demonstrate

Table 8. Farm household LVI-IPCC value.

LVI-IPCC parameter	MCS	SAFS	CAFS
Exposure	0.44	0.36	0.30
Adaptability	0.37	0.39	0.42
Sensitivity	0.36	0.35	0.34
LVI-IPCC	0.03	-0.01	-0.04

that monoculture coffee systems are more severely impacted by climate change and less capable of adapting to its effects. This limited adaptability in monoculture systems makes farmers more vulnerable in terms of their livelihoods.

Factors affecting the level of vulnerability of coffee farmer households

The analysis results in Table 9, show that farmers' knowledge of climate change has a negative coefficient and is significant at the 1% level. This indicates that the vulnerability index for farmer households with knowledge of climate change is 0.2186 lower than for those without such knowledge. The lack of awareness about climate change means that uninformed farmers are less likely to implement ad-

aptation strategies during disasters. Consequently, farmers who are unaware of climate change are more vulnerable than those who are informed. The level of drought related to climate change has a positive coefficient and is significant at the 5% level. This means that each unit increase in drought severity raises the vulnerability index by 1.2922. The direct impact of drought on farmers is a reduction in crop production, which lowers their income and increases their vulnerability to climate change. Additionally, the lack of awareness among farmers about the importance of building water reservoirs during the dry season hampers their ability to adapt to climate change.

Rainfall related to climate change has a positive coefficient and is significant at the 1% level. This indicates that each unit increase in rainfall raises the vulnerability index by 3.4513. Erratic rainfall significantly impacts household exposure levels, as inconsistent rainfall can reduce crop production. In fact, 53.62 % of farmers in monoculture coffee systems reported a decline in yields due to increased rainfall associated with climate change.

Table 9. Factors affecting the level of vulnerability of coffee farming households.

Variable	Coefficient	Std. Error	z-statistic	Prob.	Odds ratio
Constant	-0.5791	2.0608	-0.2810	0.7787	0.5604
Land area	-0.3217	0.2529	-1.2723	0.2033	0.7249
Education	0.0547	0.0576	0.9508	0.3417	1.0562
Climate change knowledge	-1.5205***	0.4202	-3.6185	0.0003	0.2186
Age	-0.0136	0.0143	-0.9549	0.3396	0.9865
Drought level	0.2564**	0.1289	1.9886	0.0467	1.2922
Rainfall	1.2387***	0.2785	4.4477	0.0000	3.4513
Pest and disease attacks	1.3492***	0.2874	4.6938	0.0000	3.8544
Total adaptation strategy	-0.4486	0.2420	-1.8532	0.0639	0.6386
Simple agroforestry systems	-0.8467**	0.4141	-2.0449	0.0409	0.4288
Complex agroforestry systems	-0.9850**	0.4665	-2.1117	0.0347	0.3734

Note: *** – significant at the α 1%, ** – significant at the α 5%, * – significant at the α 10%; z-statistic is coefficient/std error, Prob. is the probability of error for β_0 or β_1 predicted separately.

Pest and plant disease attacks have a positive coefficient and are significant at the 1% level against climate change. It means that every one time increase in pest and plant disease attacks will increase the vulnerability index by 3.8544. More than 60 % of farmers in the three agroforestry systems experienced increased pest and plant disease attacks due to increased temperature and rainfall. Increased pest infestation and plant diseases make farmers more vulnerable to crop failure.

Simple and complex agroforestry systems have negative coefficients and are significant at the 5% level against climate change. It means that the vulnerability index of households of simple and complex agroforestry systems is 0.4288 and 0.3734 lower than that of monoculture farmer households. Paudel et al. (2022) said that agroforestry practices contribute to climate change mitigation and adaptation while reducing their vulnerability to climate impacts. This statement is consistent with the *LVI-IPCC* values (Table 8), which indicate that complex and simple agroforestry systems are less vulnerable to climate change compared to monocropping coffee systems.

Conclusions

Overall, farm households engaged in monocropping coffee systems exhibit higher livelihood vulnerability (0.03) compared to those in simple (-0.01) and complex agroforestry systems (-0.04). In other words, incorporating agroforestry systems in coffee farming can reduce the vulnerability of farm households to climate change. The use of shade crops plays a significant role in both mitigating and adapting to climate change. Factors that significantly impact the vulnerability

of coffee farming households to climate change include farmers' knowledge of climate change, drought levels, rainfall patterns, pest and plant disease infestations, and the use of simple and complex agroforestry systems. Climate change leads to adverse social, economic, and environmental effects.

To reduce the vulnerability of coffee farming households to climate change, it is recommended that farmers implement a coffee agroforestry system by planting shade trees and economically valuable plants, such as spices and fruit trees.

Acknowledgement

The authors gratefully acknowledge the Faculty of Agriculture, University of Lam-pung for the funds and facilities provided to carry out this research.

References

- ADGER W.N. 2006. Vulnerability. *Global Environmental Change* 16(3): 268–281. <https://doi.org/10.1016/j.gloenvcha.2006.02.006>
- ADU D.T., KUWORNU J.K.M., ANIM-SOMUAH H., SASAKI N. 2018. Application of livelihood vulnerability index in assessing smallholder maize farming households' vulnerability to climate change in Brong-Ahafo region of Ghana. *Kasetsart Journal of Social Sciences* 39(1): 22–32. <https://doi.org/10.1016/j.kjss.2017.06.009>
- ASFAW A., SIMANE B., HASSEN A., BANTIDER A. 2017. Determinants of non-farm livelihood diversification: Evidence from rainfed-dependent smallholder farmers in northcentral Ethiopia (Woleka sub-basin). *Development Studies Research* 4(1): 22–36. <https://doi.org/10.1080/21665095.2017.1413411>
- BACON C.M., SUNDSTROM W.A., STEWART I.T., BEEZER D. 2017. Vulnerability to cumula-

- tive hazards: Coping with the coffee leaf rust outbreak, drought, and food insecurity in Nicaragua. *World Development* 93: 136–152. <https://doi.org/10.1016/j.worlddev.2016.12.025>
- BADAN PUSAT STATISTIK 2022. Jumlah curah hujan. Central Bureau of Statistics [Badan Pusat Statistik] (in Indonesia). Web site. <https://lampung.bps.go.id/indikator/151/217/1/jumlah-curah-hujan.html>
- BPS PROVINSI LAMPUNG 2023a. Luas areal tanaman. Central Bureau of Statistics [Badan Pusat Statistik] (in Lampung Province). Web site. <https://lampung.bps.go.id/statistics-table/2/MjU3Izl%3D/luas-areal-tanaman.html>
- BPS PROVINSI LAMPUNG 2023b. Produksi tanaman. Central Bureau of Statistics [Badan Pusat Statistik] (in Lampung Province). Web site. <https://lampung.bps.go.id/statistics-table/2/MjU4Izl%3D/produksi-tanaman.html>
- DIAS C.G., MARTINS F.B., MARTINS M.A. 2023. Climate risks and vulnerabilities of the arabica coffee in Brazil under current and future climates considering new CMIP6 models. *Science of The Total Environment* 907, 167753. <https://doi.org/10.1016/j.scitotenv.2023.167753>
- CHENGAPPA P.G., DEVIKA C.M. 2016. Climate variability concerns for the future of coffee in India: An exploratory study. *International Journal of Environment, Agriculture and Biotechnology* 1(4): 819–826. <https://doi.org/10.22161/ijeab/1.4.27>
- COULIBALY J.Y., CHIPUTWA B., NAKELSE T., KUNDHLANDE G. 2017. Adoption of agroforestry and the impact on household food security among farmers in Malawi. *Agricultural Systems* 155: 52–69. <https://doi.org/10.1016/j.agsy.2017.03.017>
- DIREKTORAT JENDRAL PERKEBUNAN 2023. Statistik Perkebunan Unggulan Nasional 2021–2023. Direktorat Jendral Perkebunan. Kementerian Pertanian, Jakarta. 1106 p.
- EVIZAL R., PRASMATIWI E.P., WIDAGDO S., NOVPRIANSYAH H. 2019. Adaptation of coffee growing in lampung on climate change [Adaptasi budidaya kopi di Lampung pada perubahan iklim]. In: Seminar dan Lokakarya Nasional Forum Komunikasi Perguruan Tinggi Pertanian Indonesia. 2–3 Oktober 2018, Banda Aceh: 14–21 (in Indonesian). <http://repository.lppm.unila.ac.id/11517/1/Prosiding%20Rusdi%20Evizal%20Aceh.pdf>
- GIDEY T., OLIVEIRA T.S., CROUS-DURAN J., PALMA J.H.N. 2020. Using the yield-SAFE model to assess the impacts of climate change on yield of coffee (*Coffea arabica* L.) under agroforestry and monoculture systems. *Agroforestry Systems* 94: 57–70. <https://doi.org/10.1007/s10457-019-00369-5>
- HAHN M.B., RIEDERER A.M., FOSTER S.O. 2009. The livelihood vulnerability index: A pragmatic approach to assessing risks from climate variability and change - a case study in Mozambique. *Global Environmental Change* 19(1): 74–88. <https://doi.org/10.1016/j.gloenvcha.2008.11.002>
- HAIRIAH K., VAN NOORDWIJK M., SARI R.R., SAPUTRA D.D., WIDIANTO, SUPRAYOGO D., KURNIAWAN S., PRAYOGO C., GUSLI S. 2020. Soil carbon stocks in Indonesian (agro) forest transitions: Compaction conceals lower carbon concentrations in standard accounting. *Agriculture, Ecosystems & Environment* 294, 106879. <https://doi.org/10.1016/j.agee.2020.106879>
- HO T.D.N., KUWORNU J.K.M., TSUSAKA T.W. 2022. Factors influencing smallholder rice farmers' vulnerability to climate change and variability in the mekong delta region of Vietnam. *European Journal of Development Research* 34: 272–302. <https://doi.org/10.1057/s41287-021-00371-7>
- HOSMER D.W., LEMESHOW S. 2000. Applied logistic regression. 2nd ed. John Wiley & Sons, Inc. United State of America. 375 p. https://ftp.idu.ac.id/wp-content/uploads/ebook/ip/REGRESI%20LOGISTIK/epdf.pub_applied-logistic-regression-wiley-series-in-probab.pdf
- HUHASNA R., USMAN M., FAUZI T. 2021. The effect of implementing coffee agroforestry with fruit trees, chili peppers, and livestock on increasing farmers' income in Atu Lintang, Central Aceh District [Pengaruh pen-

- erapan agroforestry kopi dengan tanaman buah-buahan, cabai, dan ternak terhadap peningkatan pendapatan petani di Atu Lintang Kabupaten Aceh Tengah]. *Jurnal Ilmiah Mahasiswa Pertanian* 6(4): 255–265 (in Indonesian).
- ISLAM M.S., WONG A.T. 2017. Climate change and food in/security: A critical nexus. *Environments* 4(2), 38. 15 p. <https://doi.org/10.3390/environments4020038>
- MANAYE A. 2024. Smallholder farmers vulnerability to climate change in Tigray, Ethiopia. *Sustainable Environment* 10(1). <https://doi.org/10.1080/27658511.2024.2345452>
- MATTALIA G., WEZEL A., COSTET P., JAGORET P., DEHEUVELS O., MIGLIORINI P., DAVID C. 2022. Contribution of cacao agroforestry versus mono-cropping systems for enhanced sustainability. A review with a focus on yield. *Agroforestry Systems* 96: 1077–1089. <https://doi.org/10.1007/s10457-022-00765-4>
- MINAI J.M., NYAIRO N., MBATARU P. 2014. Analysis of socio-economic factors affecting the coffee yields of smallholder farmers in Kirinyaga County, Kenya. *Journal of Agricultural and Crop Research* 2(12): 228–235.
- MERAGIAW M. 2017. Role of agroforestry and plantation on climate change mitigation and carbon sequestration in Ethiopia. *Journal of Tree Sciences* 36(1): 1–15. <https://doi.org/10.5958/2455-7129.2017.00001.2>
- MINANG P.A., VAN NOORDWIJK M., FREEMAN O.E., MBOW C., DE LEEUW J., CATACUTAN D. (Eds) 2015. *Climate-smart landscapes: Multifunctionality in practice*. World Agroforestry Centre (ICRAF). Nairobi, Kenya. 444 p.
- MOHEBALIAN P.M., AGUILAR F.X. 2018. Beneath the canopy: Tropical forests enrolled in conservation payments reveal evidence of less degradation. *Ecological Economics* 143: 64–73. <https://doi.org/10.1016/j.ecolecon.2017.06.038>
- MURNIATI K., MULYO J.H., IRHAM, HARTONO S. 2017. The livelihood vulnerability to climate change of two different farmer communities in Tanggamus Region, Lampung Province, Indonesia. *Asian Journal of Agriculture and Development* 14(2): 1–16. <https://doi.org/10.37801/ajad2017.14.2.1>
- NANDAKISHOR T.M., GOPI G., CHAMPATAN V., SUKESH A., ARAVIND P.V. 2022. Agroforestry in shade coffee plantations as an emission reduction strategy for tropical regions: Public acceptance and the role of tree banking. *Frontiers in Energy Research* 10, 758372. 11 p. <https://doi.org/10.3389/fenrg.2022.758372>
- PAUDEL D., TIWARI K.R., RAUT N., BAJRACHARYA R.M., BHATTARAI S., SITAULA B.K., THAPA S. 2022. What affects farmers in choosing better agroforestry practice as a strategy of climate change adaptation? An experience from the mid-hills of Nepal. *Heliyon* 8(6), e09695. 10 p. <https://doi.org/10.1016/j.heliyon.2022.e09695>
- PHAM Y., REARDON-SMITH K., MUSHTAQ S., COCKFIELD G. 2019. The impact of climate change and variability on coffee production: a systematic review. *Climatic Change* 156: 609–630. <https://doi.org/10.1007/s10584-019-02538-y>
- PRASMATIWI F.E., IRHAM, SURYANTINI A., JAMHARI 2010. Analisis keberlanjutan usahatani kopi di kawasan hutan kabupaten lampung barat dengan pendekatan nilai ekonomi lingkungan. *Pelita Perkebunan* 26(1): 57–69.
- PRIBADI T.A., AFIYANTI M., HAKIM L. 2023. Vegetation structure and composition of coffee agroforestry in Kalibaru District. *Jurnal Biodjati* 8(1): 139–150. <https://doi.org/10.15575/biodjati.v8i1.23826>
- PURBONINGTYAS T.P., DHARMAWAN A.H., PUTRI E.I.K. 2018. Dampak variabilitas iklim terhadap struktur nafkah rumah tangga petani dan pola adaptasi. *Sodality: Jurnal Sosiologi Pedesaan* 6(3): 189–197. <https://doi.org/10.22500/sodality.v6i3.21514>
- QUIROGA S., SUÁREZ C., SOLÍS J.D., JUAREZ P.M. 2020. Framing vulnerability and coffee farmers' behaviour in the context of climate change adaptation in Nicaragua. *World Development* 126, 104733. <https://doi.org/10.1016/J.WORLDDEV.2019.104733>
- RAHN E., LADERACH P., BACA M., CRESSY C., SCHROTH G., MALIN D., RIKXOOT H.V., JEFFERSON S. 2014. Climate change adaptation, mitigation and livelihood benefits

- in coffee production: Where are the synergies? *Mitigation and Adaptation Strategies for Global Change* 19: 1119–1137. <https://doi.org/10.1007/s11027-013-9467-x>
- RICE R.A. 2018. Coffee in the crosshairs of climate change: Agroforestry as abatis. *Agroecology and Sustainable Food Systems* 42: 1058–1076. <https://doi.org/10.1080/21683565.2018.1476428>
- SARVINA Y., SURMAINI E., SUPRIATIN L.S. 2023. Impact of climate change on priority sectors [Dampak perubahan iklim pada sektor prioritas]. *Technology and Local Wisdom for Climate Change Adaptation [Teknologi dan Kearifan Lokal untuk Adaptasi Perubahan Iklim]*: 1–21 (in Indonesian). <https://doi.org/10.55981/brin.901.c716>
- SOMARRIBA E., LACHENAUD P. 2013. Successional cocoa agroforests of the Amazon-Orinoco-Guiana shield. *Forests Trees and Livelihoods* 22(1): 51–59. <https://doi.org/10.1080/14728028.2013.770316>
- SHEN J., DUAN W., WANG Y., ZHANG Y. 2022. Household livelihood vulnerability to climate change in West China. *International Journal of Environmental Research and Public Health* 19, 551. 14 p. <https://doi.org/10.3390/ijerph19010551>
- SUPRIADI H., PRANOWO D. 2015. Prospects of Agroforestry Development Based on Coffee in Indonesia [Prospek pengembangan agroforestri berbasis kopi di Indonesia]. *Perspektif* 14(2): 135–150 (in Indonesian). doi: 10.21082/p.v14n2.2015.135-150
- SYAKIR M., SURMAINI E. 2017. Climate Change in the Context of Production System and Coffee Development in Indonesia [Perubahan iklim dalam konteks sistem produksi dan pengembangan kopi di Indonesia]. *Jurnal Penelitian dan Pengembangan Pertanian* 36(2): 77–90 (in Indonesian). <https://doi.org/10.21082/jp3.v36n2.2017.p77-90>
- VAN NOORDWIJK M., HOANG M.H., NEUFELDT H., ÖBORN I., YATICH T. (Eds) 2011. *How trees and people can co-adapt to climate change: Reducing vulnerability in multifunctional landscapes*. Nairobi: World Agroforestry Centre (ICRAF). 134 p.
- VAN NOORDWIJK M., KIM Y.-S., LEIMONAB., HAIRIAH K., FISHER L.A. 2016. Metrics of water security, adaptive capacity, and agroforestry in Indonesia. *Current Opinion in Environmental Sustainability* 21: 1–8. <https://doi.org/10.1016/j.cosust.2016.10.004>
- ZWANE E.M. 2019. Impact of climate change on primary agriculture, water sources and food security in Western Cape, South Africa. *Jamba: Journal of Disaster Risk Studies* 11(1), a562. 7 p. <https://doi.org/10.4102/JAMBA.V11i1.562>

Inducible resistance of *Falcataria falcata* (L.) Greuter & R.Rankin for gall rust disease using plant extracts as elicitors

Puji Lestari^{ID}, Ahdiar Fikri Maulana^{ID}, Ridla Arifriana^{ID}, and Masendra^{ID}

Forest Management Study Program, Department of Bioresources Technology and Veterinary, Vocational College, Universitas Gadjah Mada, Yogyakarta 55281, Indonesia.

*E-mail: pujilestari@ugm.ac.id

Received: 07 June 2024 / Accepted: 14 October 2024 / Available online: 22 October 2024



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

Abstract

Falcataria falcata is valuable species for timber production in Indonesia. Yields from this species, however, are reduced by gall rust caused by *Uromycladium falcatarium*. The aim of this research was to identify whether extracts of *Salix babylonica* and *Clerodendrum paniculatum* could induce systemic resistance of *F. falcata* to gall rust. Experiments were conducted at the nursery of Vocational College, Universitas Gadjah Mada. Three factors were tested, i.e. plant extract (*S. babylonica* or *C. paniculatum*), extract concentration (diluted or undiluted), and time of application (inoculated one day or seven days after elicitor application). Parameters measure were total phenolic compounds and the symptom of gall rust. The total phenolic compounds produced by seedlings treated with *C. paniculatum* extract were significantly lower than other treatments. After 5 months of observation, gall rust symptoms were only found on seedlings treated with *C. paniculatum* extract, i.e. stiff and bent shoot, stiff and slightly bent with a white stripe on branch, stiff and slightly bent leaf stalk, and gall formation.

Key word: *Clerodendrum paniculatum*, *Salix babylonica*, total phenolic, *Uromycladium falcatarium*.

Introduction

Falcataria falcata (L.) Greuter & R.Rankin has been planted widely in Indonesia both at industrial plantation forest and community forest with an aim to provide wood for industry (Dendang and Sudomo 2020, Nandini et al. 2023, Yunita et al. 2023). Growth of this important tree, however, can be severely affected by gall rust

(Suharti et al. 2019). This disease was identified causing damage to *F. falcata* in Indonesia since 1993 (Rahayu et al. 2010). It is also present in other countries of Southeast Asia, including Malaysia and Philippines (Rahayu et al. 2010, 2018; Lacandula et al. 2017; Palma et al. 2020; Calunsag et al. 2022).

The pathogen causing gall rust of *F. falcata* is *Uromycladium falcatarium* Doung-

sa-ard, McTaggart & Shivas (Dounsa-ard et al. 2014, Suharti et al. 2019, Rahayu et al. 2020). Dounsa-ard et al. (2014) mentioned that the morphology of *U. falcatarium* and *U. tepperianum* (Sacc.) McAlpine, which is previously reported as caused of gall rust, was similar, but *U. falcatarium* had fewer striae (25–32) than *U. tepperianum* (30–45). In addition, Rahayu et al. (2020) reported that *U. falcatarium* from areas surrounding volcano mountain was more virulent than others.

Gall rust can attack plants at all stages of growth, from seedlings in the nursery to mature stands in the field (Rahayu et al. 2020). Corryanti and Novitasari (2015) suggested that gall rust may cause up to 90 % mortality of *F. falcata*. Moreover, Lelana et al. (2024) mentioned that disease prevalence in *F. falcata*, which were planted around 100 – 500 m from inoculum source, reached 100 % seventh year after planted. According to Rahayu et al. (2018) development of gall rust is more intensive in environments with high relative humidity (≥ 90 %), low wind speed (about 30 to 50 km·h⁻¹), frequent fogs, usually in forest growing on steep slopes and surrounded by high and dense vegetation.

Several studies have been conducted on innovative methods for the control of gall rust. Provenance tests were carried out to determine whether high resistance to *U. falcatarium* occur in different populations of *F. falcata* (Charomaini and Ismail 2008, Baskorowati et al. 2012). Plant growth promoting rhizobacteria (PGPR) and mycorrhiza were tested to improve the vigour of *F. falcata* (Putri and Bramas-to 2017, Baskorowati et al. 2024). Silviculture practices, such as removing gall followed by tar smearing treatment, were conducted to control gall reformation (Cip-

ta et al. 2017). Furthermore, mix-planted forests were undertaken to manipulate the environment to reduce favourability for pathogen development (Lestari et al. 2013, Dendang and Sudomo 2020). Despite some effort looking for suitable management methods, inducible resistance of *F. falcata* against gall rust using plant extract elicitors has not been examined.

Induced resistance is a phenomenon that stimulates plant to activate resistance through the application of elicitors. It is wide-ranging and effective in managing infections, as numerous resistance triggers disease control ranging from 20 % to 85 % (Walters et al. 2005). In response to elicitors, plants release chemical compounds, such as phenolics, anthocyanins, and flavonoids as a defence mechanism against pathogen attack (Aguilar et al. 2023). Furthermore, Putri et al. (2014) reported that *F. falcata* seedlings attacked by pathogens produced higher concentrations of total phenolics than those that were uninfected.

Hanudin et al. (2016) showed that extract of *Salix* sp. effectively suppressed white rust disease on *Chrysanthemum* sp. flowers caused by *Puccinia horiana* Henn. Besides, Pandawani et al. (2022) reported that leaf extract of *Clerodendrum paniculatum* L. successfully inhibited zucchini yellow mosaic virus in *Cucurbita pepo* L. These extracts, therefore, can be examined in eliciting systemic resistance of *F. falcata* seedlings against gall rust, particularly at the seedling stage, where *F. falcata* is more susceptible to *U. falcatarium* infection. Therefore, the aim of the research was to determine the effects of plant-derived extracts of *Salix babylonica* L. and *Clerodendrum paniculatum* when applied to *F. falcata* exposed to gall rust.

Material and Methods

Experimental design

Experiments were conducted for seven months in the nursery of the Vocational College, Universitas Gadjah Mada. The experiment was laid out in a completely randomized design (CRD) with three factors, elicitor (*S. babylonica* or *C. paniculatum*), extract concentration (diluted or undiluted), and inoculation time of *U. falcatarium*'s teliospores (inoculated one day or seven days after elicitor application). In total, there were 8 treatment combinations, i.e. diluted *S. babylonica* extract, inoculated one day after extract application (DS1); undiluted *S. babylonica* extract, inoculated one day after extract application (US1); diluted *S. babylonica* extract, inoculated seven days after extract application (DS7); undiluted *S. babylonica* extract, inoculated seven days after extract application (US7); diluted *C. paniculatum* extract, inoculated one day after application extract (DC1); undiluted *C. paniculatum* extract, applied one day after application (UC1), diluted *C. paniculatum* extract, inoculated seven days after application extract (DC7); undiluted *C. paniculatum* extract, inoculated seven days after application (UC7). Each treatment and control (control, without extract application) were replicated 28 times, 25 plants for disease observation and 3 plants for total phenolic content measurement.

Extraction of plant

Extractions were carried out following the methods of Duriat (2008) and Hanudin et al. (2016). Briefly, *S. babylonica* and *C. paniculatum* fresh mature leaves were crushed into 0.01 M phosphate buffer pH 7.0. The leaves to buffer ratio for diluted

extract was 1: 1 (w/v, 100 g per 100 ml), while for undiluted 2: 1 (w/v, 200 g per 100ml). Leaf extracts were stored at < 10 °C until required.

Inoculation of seedlings

Teliospores of *U. falcatarium* were collected from the community forest of Yogyakarta (7°37'06.6" S 110°27'30.5" E). Six weeks old healthy seedlings of *F. falcata* were inoculated with teliospores of *U. falcatarium* using a suspension-drop technique where 3 mL of spore suspension was applied onto each seedling at terminal shoot and leaves using a pipette. Inoculum density was $2.46 \cdot 10^6 \cdot \text{mL}^{-1}$. Treated seedlings were later placed in plastic shade for one month to maintain high humidity.

Analysis of total phenolic contents

To understanding changes in total phenolic contents after application of elicitor extracts, host plant tissues were analysed at 1, 3, 5, and 7 days after application. The leaf of host plant was separated from the twigs and was air dried for about seven days at room temperature. As much as 1 g air dried sample was extracted with methanol (30 mL) for three days at room temperature. The solution was then filtered using Whatman No. 2. Prior the analysis, 0.5 mL of methanol extract was reacted with 2.5 mL of Folin-Ciocalteu reagent diluted tenfold. The sample then was allowed to stand for 2 min at room temperature. To the solution, 2 mL of Na_2CO_3 solution (7.5 %) was added and the reaction was stood for 30 min. The absorbance of the solution was recorded at 765 nm using a visible spectrophotometer (model SP-3000 Nano, Optima, Tokyo, Japan). Total phenolic contents were calculated using

gallic acid standard as curve calibration in unit of mg gallic acid equivalents (GAE) per g air dried sample (Diouf et al. 2009).

Statistical analyses

Data were subjected to multi-way analysis of variance (ANOVA) followed by HSD tests to determine significant treatments effects. All analyses were conducted in R with agricolae package.

Result and Discussion

Total phenolic content differed significantly with type of elicitor treatment ($P < 0.01$), whereas concentration of elicitor and time of application had no significant effect. The highest concentration of total phenolics was found in control seedlings. Total phenolic content in seedlings treated with *C. paniculatum* extract were significantly lower compared to other treatments ($P < 0.01$). Phenolic concentration in seedlings control, treated by extracts of *S. babylonica* and *C. paniculatum*, were 4.71, 4.25, and 3.44 mg GAE·g⁻¹, respectively (Fig. 1). The higher concentration of phenolics in control seedlings compared to those treated with *C. paniculatum* and *S. babylonica* extracts suggests that the untreated plants may rely more on phenolic-based defences as a general stress response (Putri et al. 2014), while the elicitor treatments likely activate alternative defence pathways, potentially resulting in different resistance or susceptibility to gall rust disease. Previously, it was reported that addition the elicitor to the seedlings or plants could affect to the number of bioactive compounds or secondary metabolites, such as phenolics (Shein et al. 2003, Al-Khayri and Naik 2020, Santos et al. 2023). For example, free proanthocyani-

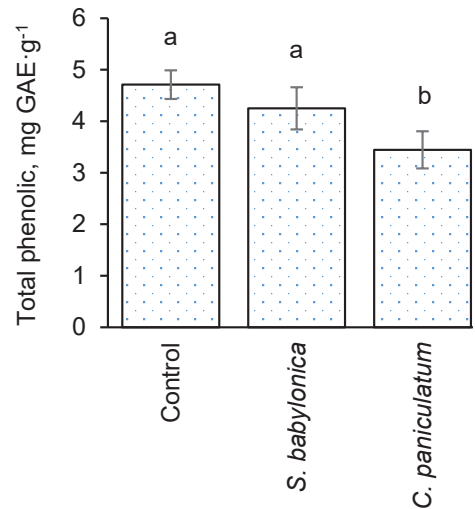


Fig. 1. Total phenolic of *F. falcata* treated by extract of *S. babylonica* and *C. paniculatum*.

din decreased in *Pinus sylvestris* L. seedling after treating by mycelium extract of *Fusarium* (Shein et al. 2003), total phenolic and total flavonoid contents of *Phoenix dactylifera* cell decreased after the addition of pectin, yeast extract, salicylic acid, cadmium chloride, and silver nitrate elicitor (Al-Khayri and Naik 2020), and total phenolic content of *Cereus hildmannianus* K.Schum. callus cultures decreased after 8% sucrose treatment (Santos et al. 2023). Hence, the decreasing of the total phenolic contents in this study were in agreement with those reported in previous studies. In the phenylpropanoid pathway, phenolics and flavonoids are made, starting an important enzyme process that produce bioactive compounds (Manivanan et al. 2016). However, the addition of elicitor with high concentration might inhibit the production of these bioactive compounds (Ali et al. 2015). Furthermore, the addition of elicitor that rich in phenolics or antioxidants could inhibit the secretion of phenolic compounds (Titov et al. 2006).

These facts suggest that the reduction of total phenolic content in this study might be due to high concentration of secondary metabolites, such as saponins, alkaloids, flavonoids, and terpenoids in *C. paniculatum* extracts (Hafiz et al. 2019, Hebbar et al. 2022, Khairuddin et al. 2022).

Total phenolic contents in *F. falcata* seedlings fluctuated over the first week after treatment with elicitor extracts (Fig. 2). Generally, total phenolic contents decreased from the first to fifth days after application of extracts but increased thereafter. Application of both diluted and undiluted extracts of *C. paniculatum* led to lower phenolic compound concentrations than found in other treatments ($P < 0.01$).

Antibiotic compounds in plants take an important role for defence mechanisms against pathogen attack (Chester 1933). Phenolic compounds may be amongst the preformed chemicals responsible for defence (Putri et al. 2014, Mahawer et al. 2022). Based on the result of this study, it appeared that total phenolic contents of *F. falcata* seedlings reduced following

treatment with *C. paniculatum* extracts, compared to other treatments. This reduction in phenolic concentrations may be a reason for earlier development of gall rust symptoms compared to plants in other treatments. Singh et al. (1998) mentioned that germination of *Ascochyta rabiei* (Pass.) Labr., pathogen that causes blight disease at chickpea, is decelerated at higher concentration of malic acid, one form of phenolic compounds. Likewise, Cagirgan et al. (2011) reported that the resistant genotype of chickpea contains higher concentration of malic acid than the susceptible one. Therefore, the response of total phenol content against disease in this study agreed with previous studies (Singh et al. 1998, Cagirgan et al. 2011, Putri et al. 2014, Mahawer et al. 2022, Misra et al. 2023, Khanday et al. 2024).

Gall rust symptoms appeared 5 months after inoculation (figs 3 and 4). The symptoms only emerged at seedling, which were applied by diluted and undiluted extract of *C. paniculatum*. The part of seedlings infected by *U. falcatarium* were stiff

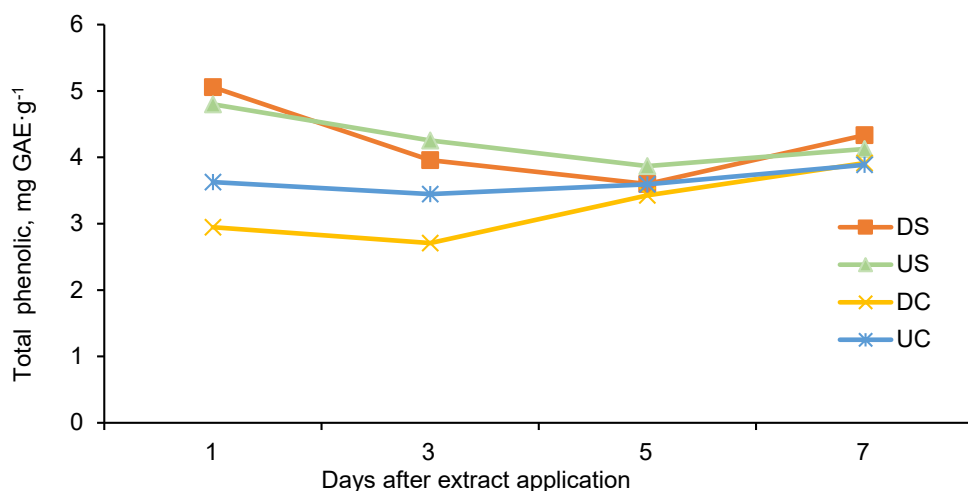


Fig. 2. Trend total phenolic of *F. falcata* after application of elicitors extract.

Note: DS – diluted extract of *S. babylonica*, US – undiluted extract of *S. babylonica*, DC – diluted extract of *C. paniculatum*, UC – undiluted extract of *C. paniculatum*.



Fig. 3. Early symptom at seedling which treated by diluted extract of *C. paniculatum*: (a) stiff and bent shoot, (b) stiff and slightly bent branch and white stripe on the infected branch surface.

and bent. A white strip appeared on the surface of infected branches. Small galls formed on the main stem. The symptoms observed in this study were similar to those reported by Rahayu et al. (2010). Moreover, Rahayu et al. (2010) explained that infection was indicated by cellular changes including misshapen periderm and phloem and distorted xylem cells. The gall that formed in our research has a green colour, and teliospores of *U. falcatarium* did not appear, indicating that the infection is in the early stage. In the next stage, the gall colour and shape might change due to the tumour surface being covered with active reddish-brown spores (Rahmawati et al. 2019) and varying from round to irregular shapes (Anggraeni 2009). In addition, we found that fungal hyphae were also visible between the wood cells of *F. falcata* seedlings. According to Rahmawati et al.

(2019), microscopic observation revealed that the structure of wood tissue affected by tumour rust disease was scattered and irregular.

Conclusions

In the present study, the effects of plant-derived extracts of *S. babylonica* and *C. paniculatum* to *F. falcata* seedling resistance against gall rust disease were evaluated. The total phenol content and gall rust growth were also discussed. Total phenol content of *F. falcata* control ($4.71 \text{ mg GAE} \cdot \text{g}^{-1}$) and treated by extracts of *S. babylonica* ($4.25 \text{ mg GAE} \cdot \text{g}^{-1}$) were significantly higher than treated by extracts of *C. paniculatum* ($3.44 \text{ mg GAE} \cdot \text{g}^{-1}$). In addition, the gall rust symptoms including stiff and bent shoots, stiff and slightly

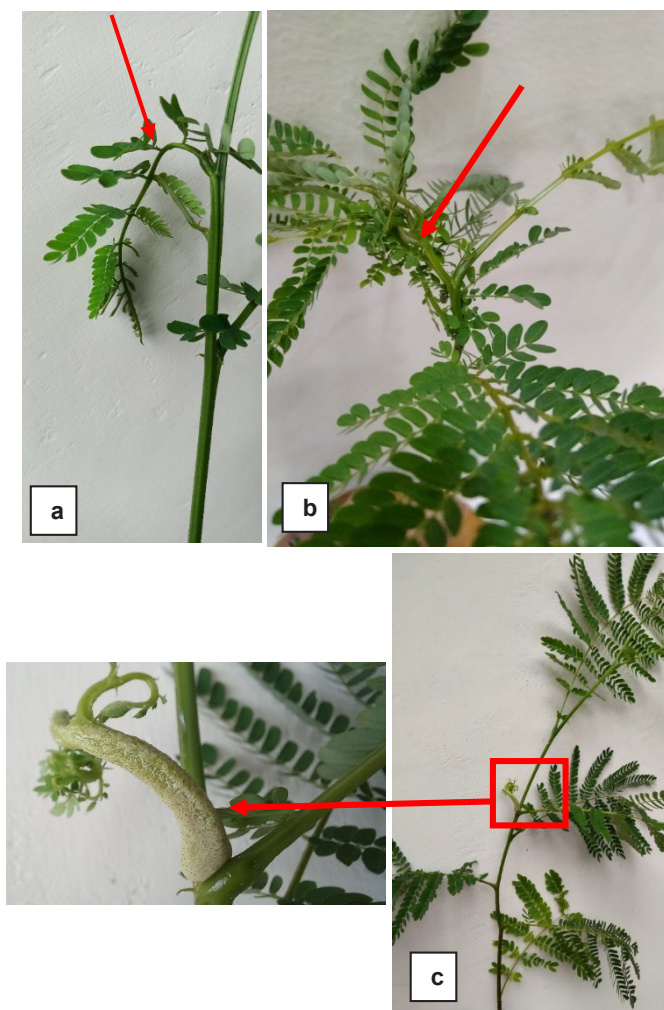


Fig. 4. Early symptom at seedling treated by undiluted extract of *C. paniculatum*: (a) stiff and slightly bent leaf stalk, (b) stiff and slightly bent shoot, (c) gall formation.

bent branches with white stripes, stiff and slightly bent leaf stalks, and gall formation, were observed only in seedlings treated with *C. paniculatum* extract five months after infection. In conclusion, the use of plant extract elicitors in this study did not appear to induce resistance in *F. falcata*, particularly with *C. paniculatum* extract.

Acknowledgements

The authors acknowledge the financial support of Universitas Gadjah Mada under research grant programme 'Peningkatan Kapasitas Peneliti Dosen Muda', under contract No. 2258/UN1.P.III/DIT-LIT/PT/2021.

References

- AL-KHAYRI J.M., NAIK P.M. 2020. Elicitor-Induced Production of Biomass and Pharmaceutical Phenolic Compounds in Cell Suspension Culture of Date Palm (*Phoenix dactylifera* L.). *Molecules* 25(20), 4669. 10 p. <https://doi.org/10.3390/molecules25204669>
- ALI M., ABBASI B.H., ALI G.S. 2015. Elicitation of antioxidant secondary metabolites with jasmonates and gibberellic acid in cell suspension cultures of *Artemisia absinthium* L. *Plant Cell, Tissue and Organ Culture* 120: 1099–1106. <https://doi.org/10.1007/s11240-014-0666-2>
- ANGGRAENI I. 2009. Gall Rust Disease on Sengon (*Paraserianthes falcataria* (L.) Nielsen) in Glenmore Plantation, Banyuwangi, East Java. [Penyakit Karat Tumor Pada Sengon (*Paraserianthes falcataria* (L.) Nielsen) di Perkebunan Glenmore Banyuwangi, Jawa Timur.] *Jurnal Penelitian Hutan Tanaman* 6(5): 311–321 (in Indonesian).
- AGUILAR N.A.S., FUENTES J.A.G., AGUILAR L.A.V., PÉREZ M.G.L., MACIAS J.M., MENDOZA A.B., MORALES S.G. 2023. Effect of elicitors and biostimulants on the content of bioactive compounds in raspberry fruits. *Horticultural Science (Prague)* 50(2): 101–111. doi: 10.17221/98/2021-HORTSCI
- BASKOROWATI L., SUSANTO M., CHAROMAINI M. 2012. Genetic Variability in Resistance of (Miq.) Barneby & J. W. Grimes to gall rust disease *Falcataria moluccana*. *Journal of Forestry Research* 9(1): 1–9. doi: 10.20886/ijfr.2012.9.1.1-9
- BASKOROWATI L., WIRABUANA P.Y.A.P., HENDRATI R.L., NURTJAHJANINGSIH I.L.G., SETIADI D., MASHUDI, SUSANTO M., PUDJIONO S., SUMARDI, SULISTIADI H.B.S., GUNAWAN 2024. Early boosting of genetically improved *Falcataria moluccana* with mycorrhiza for better growth and disease tolerance. *Forest Science and Technology* 20(2): 124–135. <https://doi.org/10.1080/21580103.2024.2314709>
- CALUNSAG R.G., ROJO M.J.A., MEDINA M.A.P., MARIN R.A. 2022. Farmers' perception on falcata (*Falcataria moluccana* (miq.) Barneby & j.w.grimes) gall rust disease in kiorao, kibawe, Bukidnon, Philippines. *Journal of Biodiversity and Environmental Sciences* 21(2): 43–49.
- CAGIRGAN M.I., TOKER C., KARHAN M., AKSU M., ULGER S., CANCI H. 2011. Assessment of Endogenous Organic Acid Levels in Ascochyta Blight [*Ascochyta rabiei* (Pass.) Labr.] Susceptible and Resistant Chickpeas (*Cicer arietinum* L.). *Turkish Journal of Field Crops* 16(2): 121–124.
- CHAROMAINI M., ISMAIL 2008. Preliminary indication of resistant on sengon (*Falcataria moluccana*) from Papua provenances to gall rust disease [Indikasi awal ketahanan sengon (*Falcataria moluccana*) provenan Papua terhadap jamur *Uromykladium tepperianum* penyebab penyakit karat tumor (gall rust)]. *Jurnal Pemuliaan Tanaman Hutan* 2(2): 203–209 (in Indonesian).
- CHESTER K.S. 1933. The Problem of Acquired Physiological Immunity in Plants. *The Quarterly Review of Biology* 8(3): 275–324. <https://doi.org/10.1086/394440>
- CIPTA H., RAHAYU S., NUGROHO W.D. 2017. Effects of Tar Smearing Treatment on *Falcataria Moluccana* Infected by Gall Rust Disease. *Journal of Tropical Forest Science* 29(1): 10–18. <https://www.jstor.org/stable/44028270>
- CORRYANTI, NOVITASARI D. 2015. Sengon and gall rust disease [Sengon dan Penyakit Karat Puru]. *Puslitbang Perum Perhutani Cepu*. 29 p. (in Indonesian).
- DENDANG B., SUDOMO A. 2020. Growth performance of *Falcataria moluccana* in the mixed cropping pattern and its severity from Gall-rust disease: A case study in Ciamis, West Java. *IOP Conference Series: Earth and Environmental Science*. IOP Publishing 533, 012044. 8 p. doi: 10.1088/1755-1315/533/1/012044
- DIOUF P.N., STEVANOVIC T., CLOUTIER A. 2009. Antioxidant properties and polyphenol contents of Trembling aspen bark extracts. *Wood Science Technology* 43(4): 457–470. <https://doi.org/10.1007/s00226-009-0240-y>
- DOUNGSA-ARD C., McTAGGART A.R., GEERING A.D.W., DALISAY T.U., RAY J., SHIVAS R.G. 2014. *Uromykladium falcatarium* sp. nov.,

- the cause of gall rust on *Paraserianthes falcataria* in south-east Asia. *Australasian Plant Pathology* 44(1): 25–30. <https://doi.org/10.1007/s13313-014-0301-z>
- DURIAT A.S. 2008. The Influence of Plant Extract for Inducing Resistance of Chili Pepper Plant Against Pathogen and Vector of Yellow Leafcurl Disease [Pengaruh ekstrak bahan nabati dalam menginduksi ketahanan tanaman cabai terhadap vektor dan penyakit kuning keriting]. *Jurnal Hortikultura* 18(4): 446–456 (in Indonesian). doi: 10.21082/jhort.v18n4.2008.p%p
- HANUDIN, NURYANI W., MARWOTO B. 2016. Resistance Induction of Chrysanthemum Plant to *Puccinia horiana* P. Henn Using Elicitor Plant Extracts [Induksi Resistensi Tanaman Krisan terhadap *Puccinia horiana* P. Henn. dengan Menggunakan Ekstrak Tanaman Elisitor]. *Jurnal Hortikultura* 26(2): 245–256 (in Indonesian). doi: 10.21082/jhort.v26n2.2016.p245-256
- HAFIZ H, GINTING M., YUERMAILENI 2019. Antioxidant Activity of Pagoda Flower (*Clerodendrum paniculatum* L.) Ethanol Extract using Visible Spectrophotometric Method. *Indonesian Journal of Pharmaceutical and Clinical Research* 2(2): 14–19. <https://doi.org/10.32734/ijpcr.v2i2.2060>
- HEBBAR D.R., DEVIKA M., RASHMI G.N., NALINI M.S. 2022. Phytochemicals and Antioxidant Activity of *Clerodendrum paniculatum* (L.) Leaf and Flower Extracts. *Asian Journal of Pharmaceutical and Clinical Research* 15(1): 31–34. <https://doi.org/10.22159/ajpcr.2022.v15i1.43361>
- KHAIRUDDIN T.M., ETIKA S.B., MULIA M. 2022. Phytochemical Test of Methanol Extract of Pagoda Flower Plant (*Clerodendrum Paniculatum* L.) [Uji Fitokimia Ekstrak Metanol Bunga Tumbuhan Bunga Pagoda (*Clerodendrum Paniculatum* L.)]. *Periodic* 11(3): 6–8 (in Indonesian). <https://doi.org/10.24036/p.v11i3.114971>
- KHANDAY A.H., BADROO I.B., WAGAY N.A., RAFIQ S. 2024. Role of Phenolic Compounds in Disease Resistance to Plants. In: Lone R., Khan S., Mohammed Al-Sadi, A. (Eds), *Plant Phenolics in Biotic Stress Management*. Springer, Singapore: 455–479. https://doi.org/10.1007/978-981-99-3334-1_19
- LACANDULA L.F., ROJO M.J.A., PUNO G.R., CASAS J.V. 2017. Geospatial analysis on the influence of biophysical factors on the gall rust prevalence in falcata (*Paraserianthes falcataria* L. Nielsen) plantation in Gingoog city, Philippines. *Journal of Biodiversity and Environmental Sciences* 11(4): 18–24. <https://ssrn.com/abstract=3588102>
- LELANA N.E, DARMAWAN U.W., NURONIAH H.S., PUSPITANINGTYAS D.M., IRIANTO R.S.B. 2024. Rapid spread and high prevalence of the gall rust pathogen *Uromycladium falcatariae* in stands of *Falcataria falcata*. *Forest Science and Technology*: 1–7. <https://doi.org/10.1080/21580103.2024.2388607>
- LESTARI P., RAHAYU S., WIDIYATNO 2013. Dynamics of gall rust disease on sengon (*Falcataria moluccana*) in various agroforestry patterns. *Procedia Environmental Sciences* 17: 167–171. <https://doi.org/10.1016/j.proenv.2013.02.025>
- MAHAWER S.K., ARYA S., KABDAL T., KUMAR R., PRAKASH O., CHITARA M.K., KOLI P. 2022. Plant defense systems: mechanism of self-protection by plants against pathogens. In: Soni R., Suyal D.C., Goel R. (Eds). *Plant Protection: From Chemicals to Biologicals*. Walter de Gruyter GmbH, Berlin/Boston: 115–140. <https://doi.org/10.1515/9783110771558-006>
- MANIVANNAN A., SOUNDARARAJAN P., PARK Y.G., JEONG B.R. 2016. Chemical Elicitor-Induced Modulation of Antioxidant Metabolism and Enhancement of Secondary Metabolite Accumulation in Cell Suspension Cultures of *Scrophularia kakudensis* Franch. *International Journal of Molecular Sciences* 17(3), 399. 13 p. <https://doi.org/10.3390/ijms17030399>
- MISRA D., DUTTA W., JHA G., RAY P. 2023. Interactions and Regulatory Functions of Phenolics in Soil-Plant-Climate Nexus. *Agronomy* 23(280): 1–18. <https://doi.org/10.3390/agronomy13020280>
- NANDINI R., SUSILA I.W.W., AGUSTARINI R., SAMAWANDANA G. 2023. Evaluating agroforestry patterns to increase land productivi-

- ty of *Falcataria moluccana* private forests in Central Lombok Regency, West Nusa Tenggara. *Forest and Society* 7(2): 247–262. <https://doi.org/10.24259/fs.v7i2.25752>
- PALMA R.A., TIONGCO L.E., CANENCIA O.P., BONIAO R.D., FLORIDA E.J., DAGONIO J.Y. 2020. Gall rust disease incidence of *Falcataria* (*Paraserianthes falcataria* (L.) Nielsen) in Falcata – Based agroforestry systems in Misamis Oriental, Philippines. *IOP Conference Series: Earth and Environmental Science* 449, 012035. 7 p. doi: 10.1088/1755-1315/449/1/012035
- PANDAWANI N.P., LISTIHANI, WIDNYANA I.K., ARIATI P.E.P., SELANGGA D.G.W. 2022. High impact of *Clerodendrum paniculatum* leaf extract to suppress zucchini yellow mosaic virus infection in zucchini plants. *Biodiversitas* 23(6): 2914–2919. <https://doi.org/10.13057/biodiv/d230618>
- PUTRI A.I., NA'EM M., INDRIOKO S., RAHAYU S., INDRANTO A. 2014. In Vitro Screening of *Falcataria moluccana* (Miq.) with Gall Rust (*Uromycladium tepperianum* (Sacc.) Filtrate as Media Selection. *Indonesian Journal of Biotechnology* 19(2): 111–120. <https://doi.org/10.22146/ijbiotech.9301>
- PUTRI K.P., BRAMASTO Y. 2017. The Control of Fungus *Uromycladium tepperianum* on Seedling of Sengon (*Falcataria moluccana* (Miq.) Barneby & J.W.Grimes) in a nursery. [Pengendalian Cendawan *Uromycladium tepperianum* Pada Bibit Sengon (*Falcataria moluccana* (Miq.) Barneby & J.W. Grimes) di Persemaian]. *Jurnal Perbenihan Tanaman Hutan* 5(1): 13–22 (in Indonesian). <https://doi.org/10.20886/bptph.2017.5.1.13-22>
- RAHAYU S., LEE S.S., SHUKOR N.A.A. 2010. *Uromycladium tepperianum*, the gall rust fungus from *Falcataria moluccana* in Malaysia and Indonesia. *Mycoscience* 51(2): 149–153. <https://doi.org/10.1007/S10267-009-0022-2>
- RAHAYU S., SEE L.S., SHUKOR N.A.A., SALEH G. 2018. Environmental factors related to gall rust disease development on *Falcataria moluccana* (Miq.) Barneby & J. W. Grimes at Brumas estate, Tawau, Sabah, Malaysia. *Applied Ecology and Environmental Research* 16(6): 7485–7499. http://dx.doi.org/10.15666/aeer/1606_74857499
- RAHAYU S., WIDIYATNO, ADRIYANTI D.T. 2020. Pathogenesis of gall-rust disease on *Falcataria moluccana* in areas affected by mount merapi eruption in Indonesia. *Biodiversitas* 21(4): 1310–1315. <https://doi.org/10.13057/biodiv/d210406>
- RAHMAWATI D., KHUMAIDA N., SIREGAR U.J. 2019. Morphological and phytochemical characterization of susceptible and resistant sengon (*Falcataria moluccana*) tree to gall rust disease. *Biodiversitas* 20(3): 907–913. <https://doi.org/10.13057/biodiv/d200340>
- SANTOS E.S, CABRAL M.R.P., SILVA T.F.O., OLIVEIRA A.J.B., MACHADO M.F.P.S., MANGOLIN C.A., GONCALVES R.A.C. 2023. Improvement of phenolic compounds production in callus cultures of *Cereus hildmannianus* (K.) Schum. by elicitation. *Plant Cell, Tissue and Organ Culture* 153(1): 37–51. <https://doi.org/10.1007/s11240-022-02438-7>
- SHEIN I.V., ANDREEVA O.N., POLYAKOVA G.G., ZRAZHEVSKAYA G.K. 2003. Effect of Pine Callus Elicitation by the *Fusarium* Strains of Various Pathogenicity on the Content of Phenolic Compounds. *Russian Journal of Plant Physiology* 50(5): 634–639. <https://doi.org/10.1023/A:1025688023862>
- SINGH P.J., PAL M., DEVAKUMAR C. 1998. Role of Malic Acid in Pycnidiospore Germination of *Ascochyta rabiei* and chickpea blight resistance. *Indian Phytopathology* 51(3): 254–257.
- SUHARTI T., PUTRI K.P., BRAMASTO Y. 2019. The Endurance of Sengon (*Falcataria moluccana* (Miq.) Barneby & J.W. Grimes) Seedling against *Uromycladium falcatarium* Fungus Based on Seed Source and Controller Agent [Ketahanan Bibit Sengon (*Falcataria moluccana* (Miq.) Barneby & J.W. Grimes) terhadap Cendawan *Uromycladium falcatarium* Berdasarkan Asal Benih dan Jenis Pengendali. *Jurnal Perbenihan Tanaman Hutan* 7(2): 101–111 (in Indonesian). doi: 10.20886/bptph.2017.5.2.101-111
- TITOV S., BHOWMIK S.K., MANDAL A., ALAM M.S., UDDIN S.N. 2006. Control of Phe-

- nolic Compound Secretion and Effect of Growth Regulators for Organ Formation from *Musa* spp. cv. Kanthali Floral Bud Explants. *American Journal of Biochemistry and Biotechnology* 2(3): 97–104. <https://doi.org/10.3844/ajbbsp.2006.97.104>
- WALTERS D., WALSH D., NEWTON A., LYON G. 2005. Induced Resistance for Plant Disease Control: Maximizing the Efficacy of Resistance Elicitors. *Phytopathology* 95(12): 1368–1373. <https://doi.org/10.1094/PHYTO-95-1368>
- YUNITA R.S., RINIARTI M., HIDAYAT W., NISWATI A., PRASETIA H., HASANUDIN U., BANUWA I.S., YUNITA E., RIZKASUMARTA F. 2023. Improvement of *Falcataria moluccana* Root Growth by Giving Empty Palm Oil Fruit Bunches (EFB) Biochar in Growing Media. *Journal of Sylva Indonesiana* 6(1): 10–18. <https://doi.org/10.32734/jsi.v6i01.7670>

Molecular markers vs. phylogeographic memory dilemma: an example of length-dependent mutation processes

Review paper

Krassimir D. Naydenov^{1,3}, Michel K. Naydenov², Alexander Alexandrov³,
Todor Gurov^{4*}, Georgi Hinkov³, Sofiya Ivanovska⁴, Veselka Gyuleva³,
Silvi-Maria Gurova⁴, Makech Balakumar⁵, and Biljana Nikolic⁶

¹Ministry of National Defence – CAF, 25 Grand-Bernier, St-Jean-sur-Richelieu, QC, J0J1R0, Canada. E-mails: KrassimirDN@gmail.com, KrassimirDN@hotmail.com

²UN Secretariat – UNOHR | DMSPC/ GSPD/ STMS/ ODS, Headquarters, 405 E 42nd St., New York, NY 10017, USA. E-mails: michel.naydenov@un.org, michel92kn@gmail.com

³Forest Research Institute, Bulgarian Academy of Sciences, 132 Kliment Ochridskii Blvd., Sofia 1756, Bulgaria. E-mails: Alexandrov_38@abv.bg, gjuleva33v@abv.bg, georgihi@abv.bg

⁴Institute of Information and Communication Technologies, Bulgarian Academy of Sciences, Acad. G. Bonchev Str., Bl. 25-A, 1113 Sofia, Bulgaria. E-mails: todir.gurov@iict.bas.bg, sofia@parallel.bas.bg, smgurova@parallel.bas.bg

⁵Department of Botany, G-Venkataswamy Naidu College, Kovilpatti-628502, India. E-mail: bala.Makeshkumar@gvncollege.edu.in

⁶Institute of Forestry, Kneza Višeslava 3, 11000 Belgrade, Serbia. E-mail: smikitis@gmail.com

§ In Memory of Irena Naydenova

Received: 14 August 2024 / Accepted: 17 October 2024 / Available online: 22 October 2024



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

Abstract

In this research, we focused on the following question: What element can be used for phylogeography and phylogenetic studies for all species using results of the genome-wide analysis (GWA) of numerous model organisms (e.g., *Homo sapiens*, *Mus musculus*, *Drosophila melanogaster*)? We especially paid attention to the average mutation rate variation in the DNA fragment size across alleles from diverse loci (i.e., related to length-dependent mutation processes). Over the past 30 years, all molecular markers have been developed from the fundamentally different mechanisms of four mutations: single-nucleotide polymorphisms (SNPs), simple sequence repeats (SSRs), insertions–deletions (INDELs), and chromosome aberrations. The challenge is to accurately fix the molecular clock for size-variant DNA marker data to uncover the phylogeographic histories of many plants and animals. In this paper, we provided a lot of examples from a *Homo sapiens* to a forest tree from *Pinus* genus, illustrating the importance of differentiating between molecular markers, their origins, and the locus molecular size to better calibrate the molecular clock for back-in-time simulation analyses.

Key words: genome analysis, length-dependent mutation processes, molecular clock, phylogeography.

Introduction

Over the past 20–25 years, genome-wide analysis (GWA) has enabled the collection of high-quality genome assemblies of diverse species (Rhie et al. 2021). The millions of sequences of nucleotide data obtained with overall good, effective depth and high resolution have been object of intensive investigations related to the principal, fundamentally different mechanisms underlying four mutations: single-nucleotide polymorphisms (SNPs), simple sequence repeats (SSRs), insertions–deletions (INDELs), and chromosome aberrations. This has, to some extent, changed the definition, models, meaning, and mutation significance for species evolution. These molecular markers have been used for numerous practical applications, such as forensics (Ruitberg et al. 2001), paternity testing (Thomson et al. 1999), personal medicine (Sturzeneker et al. 2000), and determination of the time of divergence between populations (Goldstein and Clark 1995, Stumpf and Goldstein 2001). The initial traits of genomic data of scientific and practical interest are the density, frequency, allele size, and mutation rate of molecular markers. DNA sequence changes are often studied using their chromosome position and length-dependent frequency. The average mutation rate per base pair (μ_{bp}) is observed to be reciprocally proportional to the genome size (G) in the base pair (bp), as reported by Drake (1991), Drake et al. (1998), Lynch (2010), Sanjuan et al. (2010), and Sung et al. (2012). In addition, the between-species genomic differences in all mechanisms underlying principal mutations have been confirmed (Kruglyak et al. 1998, Dieringer and Schlötterer 2003). The results show the following differences and similarities: a significant

difference in the molecular marker density and mutation rate between species; and a significant observable similarity related to length-dependent mutation processes among species. Often, genomic studies focus on SNPs and from two different mutation mechanisms, microsatellites and short INDELs. For SNPs, due to the nature of DNA change, length-dependent mutation processes are not directly applicable. We decided to focus on the similarities between genomic sequence data with free access. Next, we present the results obtained by different researchers.

Short tandem repeats (STRs) or SSRs, known as microsatellites, are repeats of 1–6-nucleotide motifs. These could be *mono-*, *di-*, *tri-*, *tetra-*, *penta-*, and *hexa-*nucleotides. A microsatellite can be *perfect* (or uninterrupted), *imperfect* (or interrupted), or *isolated* (Calabrese and Durrett 2003). Strong evidence suggests that the mutation rates of SSR/STR loci depend on the length of a repeat unit (Weber and Wong 1993; Chakraborty et al. 1997; Schug et al. 1997; Kruglyak et al. 1998, 2000; Sibily et al. 2001, 2003; Calabrese and Durrett 2003; Dieringer and Schlötterer 2003; Lai and Sun 2003; Whitaker et al. 2003; Verbiest et al. 2023). This dependency has been confirmed in different organisms, such as humans, mice, the fruit fly, and yeast. The length-dependent density of SSRs is often related to point mutations, which break up long repeats; long microsatellite repeats are the result of mutation robustness at the genomic level (Kruglyak et al. 1998). Additional features of this DNA change include: (1) the number of repeat motifs is more abundant in *noncoding* DNA (i.e., non-genic region) than in *coding* DNA (i.e., genic region), (2) the microsatellite density differs between chromosome pairs, (3) between intergenic versus intronic sequences (Toth et al.

2000, Morgante et al. 2002), and (4) between sex chromosomes and autosomes (Bachtrog et al. 2000), and (5) the microsatellite frequency decreases from short to large repeat motifs (Calabrese and Durrett 2003, Dieringer and Schlötterer 2003). Another particularity of microsatellites is that mutation robustness depends on the nucleotide repeat motif composition (Schlötterer and Tautz 1992, Chakraborty et al. 1997, Bachtrog et al. 2000). Furthermore, SSR *interrupted* alleles mutate less than *perfect* alleles at the same fragment/allele size (Brinkmann et al. 1998). In human paternity testing (pedigree analysis), Brinkmann et al. (1998) and Makova et al. (2024) also demonstrated statistically significant sex differences in mutations on the X and Y chromosomes for nine loci. Similar results have been reported for humans and other animals by Weber and Wong (1993), Ellegren and Fridolfsson (1997), and McVean (2000). Regarding locus evolution, Garza et al. (1995) showed that microsatellites have a '*target length*', that is, short microsatellites have a mutation bias-up, whereas longer ones have a mutation bias-down. This finding was later supported by Wierdl et al. (1997), Harr and Schlötterer (2000), and Bhargava and Fuentes (2010). Additionally, for genome species evolution, *in silico* analysis have shown that microsatellites of a minimum thresholded size exist for slippage mutations (Rose and Falush 1998). Some of the more popular microsatellite mutation mechanisms include: (1) the stepwise mutation model (SMM; Ohta and Kimura 1973); (2) the continuous-time Markov chain, which incorporates length-dependent slippage events, also known as proportional slippage (PS; Kruglyak et al. 1998); (3) the constant exponential model (ConExp; Xu et al. 2000); and (4) slippage occurs only when the

length exceeds some threshold K (PSwK; Calabrese et al. 2001). In addition, Calabrese and Durrett (2003) proposed four additional mutation models: (5) piecewise linear bias (PLBias), (6) the asymmetric quadratic model (AsyQuad), (7) the asymmetric linear model (AsyLin), and (8) the multinomial model. It is widely accepted that the SSR/STR mutation mechanism is complex (Lai and Sun 2003).

The second more popular mutation mechanism studied in genomic data is INDELs. This DNA change consists of specific insertions or deletions of genome bases, from 1 to 10,000 nucleotides. Short INDELs include single bases, *monometric* bases, and multi-bp expansions of 2–15 bp repeat units (i.e., *dimetric*, *trimetric*, *tetrametric*, *pentrametric*, *hexametric*, *heptametric*, *octametric*, *nonametric*, and *decametric*), as shown by Mills et al. (2006). INDELs containing random DNA sequences of more than 50 bases are classified as structural variants (SVs; Mahmoud et al. 2019, Ebert et al. 2021). Short INDELs can be compared to point mutations and microsatellites. The three mutations SNPs, SSRs/STRs, and INDELs result from fundamentally different mechanisms (Buettner et al. 1999, Hill et al. 2003, Yan et al. 2014). Generally, genomic data indicate that for all species, long INDELs (SVs) are less abundant than short INDELs, microsatellites, and SNPs. Studies on genetic variation in *Homo sapiens*, *Drosophila melanogaster*, and *Caenorhabditis elegans* have shown that SVs and chromosome aberrations are formed by strong length-dependent mutation processes, similar to the aforementioned microsatellites (Berger et al. 2001, Wicks et al. 2001, Mills et al. 2006, Rhie et al. 2023, Hallast et al. 2023).

A database from a large geographic region comprises more than 6000 gene

disorders and chromosome aberrations in humans. Known also as abnormalities, on average, a frequency of 7.4 per 10,000 births is responsible for the large numbers of phenotypic and congenital anomalies (Wellesley et al. 2012). The frequency of gene disorders is significantly lower compared to INDELs, SSRs, and SNPs. Here, the mutation load of gene disorders is higher than the mutation changes for INDELs, SSRs, and SNPs. The high mutation load in this example of gene disorders is the result of a large DNA fragment size with affected coding sequences. For example, Zuberi (2013) reported the following chromosome aberrations related to length-dependent mutation processes: partial terminal zone deletion chromosome (1p36), whose frequency is 2 per 10,000 live births, followed by partial chromosome arm deletion with a frequency of 1.86 per 10,000 live births; a duplication rate with a frequency of 0.70 per 10,000 live births; a marker chromosome with a frequency of 0.43 per 10,000 live births; Wolf-Hirschhorn syndrome (4p-) with a frequency of 0.20 per 10,000 live births; and, if the mutation is in a high-density coding DNA region, a frequency of 0.03 per 10,000 live births, as observed for Miller-Dieker syndrome (del 17p13.3). In this example, a gradual decline of surviving frequency is observed for partial chromosome aberration, which results from a combination of coding sequencing density and chromosome arm fragment size DNA. The mutation load's lethal effect in this example is proportional to the affected chromosome fragment size and its coding DNA density.

Another example of length dependent mutation process are *aneuploidy* and *polyploidy*. Aneuploidy is an abnormal number of chromosomes in a cell, that is, cells have one or more chromosomes missing

or present in surplus. A good example of aneuploidy (a karyology phenomenon in humans) is the trisomy of chromosome 13 (Patau syndrome), with a frequency of 1 per 10,000–20,000 live births, followed by chromosome 18 (Edwards syndrome), with a frequency of 1 per 3600–8500 live births, and chromosome 21 (Down syndrome), with a frequency of 1 per 800 live births (Greene and Benjamin 2023). In aneuploidy example here, the total extra chromosome size gradually decreases from chromosomes N13 through N18 up to N21, while the lethal effect decreases. When extra complete sets of chromosomes are found, the condition is called polyploidy (high mutation charge). In humans, polyploidy is dangerous; embryo development is observed for a few days or weeks, but finally, pregnancy is terminated by abortion or surgical intervention to protect the woman from dangerous complications. The condition is also known as a *partial molar pregnancy* or a *partial hydatidiform mole*, with a frequency of 1 per 1000–1200 births at the zygote stage and zero chances of survival (Mahdieh and Rabbani 2013, De Franciscis et al. 2019, Al Ghadeer et al. 2022). The mutation load is high, with a lethal effect. Polyploidy is found in amphibians, such as salamanders, frogs, and leeches, and in invertebrates, such as clams. In more developed animals, only sterile *triploid* fish, nonsterile *tetraploid* Salmonidae fish, and only one *tetraploid* mammal, the plains viscacha rat (*Tympanoctomys barrerae*), have survived. In contrast to humans and other animals, plants support aneuploidy and polyploidy relatively better. For example, some successful cultivars in agriculture and forest practice are *triploid* (seedless watermelon, banana, and some *Populus* cultivars). In reality, the initial random mutation pattern is under constant selection

pressure from day 1 to reproductive age and death. The change in the genetic/genomic structure follows important steps: prezygotic, prenatal, natal, and classes of ages. For example, in support of constant selection pressure in the population, Korf et al. (2019) reported that in human gametes, abnormality rates of 4–5 % in sperm and 12–15 % in oocytes have been observed, in significant contrast with an abnormality rate of 0.07 % in new births. The postnatal survival rates in humans are inversely related to the affected chromosome fragment. Selection pressure is proportional to the DNA fragment size under mutation and explains part of mutation robustness at the population level.

Over the past 30 years, molecular geneticists' laboratories have developed numerous molecular markers from the three principal, fundamentally different mutation mechanisms (SNPs, SSRs, INDELs), which are specific DNA fragments associated with certain nucleotide patterns, fragment size and locations within the genome (Grover and Sharma 2016). These molecular markers include restriction fragment length polymorphisms, simple sequence length polymorphisms (SSLPs), amplified fragment length polymorphisms, random amplifications of polymorphic DNA (RAPDs), variable number tandem repeats (VNTRs), SSR microsatellite polymorphisms, SNPs, STRs, single-feature polymorphisms, diversity array technology, restriction-site-associated (RAD) DNA markers, allele-specific associated primers, inverse sequence-tagged repeats, inter-retrotransposon amplified polymorphisms (IRAPs), and sequence-tagged sites. More popular existing classifications are: (1) variations at the DNA level, such as nucleotide changes, including deletion, duplication, inversion, and/or insertion; (2) modes of inheritance, that is, dominant/

recessive and codominant; (3) *allosomal* and *autosomal*; and (4) plastids and chromosomes. For example, the four principal mutation mechanisms in the human genome include ~10 million SNPs, ~0.5 million SSRs, ~0.5 million short INDELs (single, mono-metric and multi-bp nucleotide repeat expansions), and less than 0.02 million SVs (long INDELs). Chromosome aberrations, full or partial, have a low frequency. The densities of SNPs, SSRs, short INDELs, and SVs have been confirmed for numerous organisms (Mills et al. 2006, Galindo et al. 2009).

We focused on the question, what element can be used for phylogeography and phylogenetic studies for all species using WGA results? We especially focused on the average mutation rate variation in the DNA fragment size (bp) across alleles from diverse loci from SSRs/STRs, short INDELs, SVs, and chromosome aberrations. First, we analyzed how the length-dependent mutation processes are manifested in real genomic data. Second, we focused on where the length-dependent mutation processes could be used for molecular clock calibration for size-variant DNA data, such as SSRs, short INDELs, and SVs, in phylogenetic and phylogeographic studies. The mutation frequency is a well-known fundamental factor in evolution studies. However, the concept of molecular clock calibration for size-variant DNA is poorly understood. In this study, we proposed a simple model for the molecular clock mutation rate list of universal principles and discussed how it helps compare different molecular clock speeds from different molecular markers. The forest trees have been less studied at genome level generally do to their huge total genome size. They have low migration speed and distance compared to animals. That allows us to make back-time

phylogeographic simulation more interesting (Naydenov et al. 2016). More advanced analyses are from deferent species of genera *Pinus*, *Picea*, and *Populus* (Kovach et al. 2010, Nystedt et al. 2013, Gonzalez-Ibeas et al. 2016, Christenhusz et al. 2024). The obtained results have shown similar length-dependent mutation processes. We also presented a short comparative example of empirical data with three species: *P. nigra* Arn., *P. sylvestris* L., and *P. halepensis* Mill. from the *Pinus* genus (Fig. 1).

Can length-dependent mutation processes in population genetics improve the precision of phylogenetic and phylogeographic hypotheses?

An overview of empirical data on DNA mutation frequency, specifically regarding length-dependent mutation processes in organisms, reveals that each organism's genome contains various mutations with differing frequencies. These mutations can be roughly categorized into different groups at the population level. This categorization could be used to create a more accurate molecular clock for each mutational group, significantly enhancing the accuracy of future predictions in phylogenetics and phylogeography. Below are some suggestions we believe could be valuable for future research.

Specific molecular markers and molecular clock calibration

Two principal factors are involved in computer data simulations for forward and backward molecular clock simulation for evolution, speciation, and phylogenetic and phylogeographic questions: (1) mutation frequency (Lynch 2010, Bergeron et al. 2023, Lynch et al. 2023) and (2) time

mark molecular clock fixing. For more information, see Rogers and Harpending (1992), Sanderson (1997, 2003), Ho et al. (2015), O'Reilly et al. (2015), and Donoghue and Yang (2016).

Mutation frequency

Each of the molecular markers (SNPs, SSRs, and long INDELs) has specific strengths and weaknesses, so knowledge of these molecular markers is necessary before using them. For phylogenetic and phylogeographic studies, it is important to determine the mutation rate (μ) of the molecular marker used. The mutation rate depends on multiple factors, some of which are general, while others are specifically related to the species biology. The more important general factors are the molecular marker's size (bp; i.e., the molecular mass of the DNA fragments), the nucleotide fragment order as the *coding* or *noncoding* DNA mutation mechanism, and the origin of the molecular marker (chromosome, mitochondrion, ribosome, or chloroplast; Schug et al. 1997; Dieringer and Schlötterer 2003; Sibly et al. 2001, 2003; Verbiest et al. 2023). Based on the cell structure and morphology, we proposed four universal principles with the limit of one species and/or one genus:

(1) Long fragments (chromosome, locus, allele) have a proportionally lower mutation rate than short fragments (Chakraborty et al. 1997, Calabrese and Durrett 2003, Whittaker et al. 2003, Makova et al. 2024).

(2) *Coding* DNA fragments have a lower mutation rate than *noncoding* DNA fragments of the same size (Weber and Wong 1993; Kruglyak et al. 1998, 2000; Lai and Sun 2003).

(3) Molecular markers with a plastid origin generally have a lower mutation rate

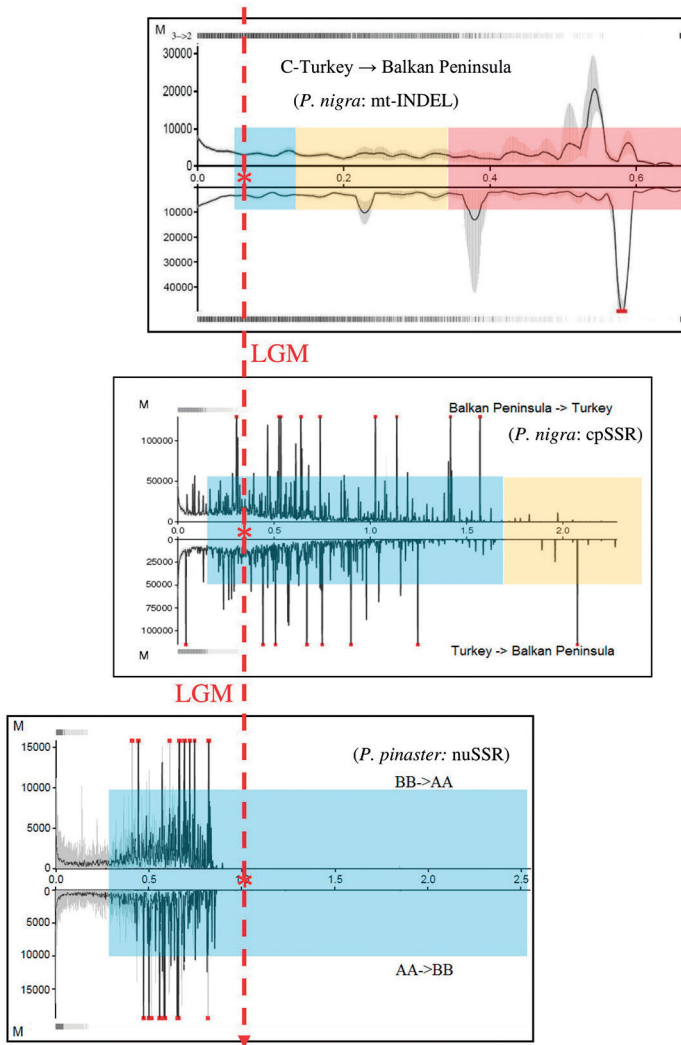


Fig. 1. An example of the phylogenetic memory of three of the most frequently used molecular markers from phylogeographic studies on pines.

Note: The horizontal axis for each chart is time by mutation rate. The time units are different for the different molecular markers, and the average time span for each migration wave shows a different number of generations for each chart. The results are taken from Naydenov et al. (2014, 2017, 2023); YBP – years before present; MY – millions of years before present. Figure 1 also shows a comparison of the asymmetric migration patterns of the mitochondrial INDELs, chloroplast SSRs, and nuclear SSRs for two Mediterranean pines (*P. nigra* and *P. pinaster* Aiton). The red dashed line connecting the red asterisks is the time mark for the Last Glacial Maximum (LGM ≈ 27,000 YBP). The horizontal, colored bar in the middle of each chart represents the geological time grid: white – Holocene epoch (up to 0.0117 MY), light blue – Pleistocene epoch (between 0.0117 and 1.806 MY), yellow – Pliocene epoch (between 1.806 and 5.332 MY), and orange – Miocene epoch (≥ 5.332 MY). The pine seed radiation molecular markers, INDEL (top) and

nuSSR (bottom), show a low average migration intensity of approximately 10,000 individuals per migration wave, but the pollen radiation marker, cpSSR (middle), shows a high average migration intensity of approximately 50,000 individuals per migration wave. The three molecular markers used show different phylogenetic memories: that of mt-INDEL is the longest, followed by cpSSR, and that of nuSSR is the shortest.

than chromosomes of the same size due to the plastids' double membranes in plants and animals (Toth et al. 2000, Morgante et al. 2002). The principal plastids are mitochondria and chloroplasts for plants and mitochondria and ribosomes for animals. In plant and animal genetics, cell plastids are different organelles in the cytoplasm and transfer genetic material, which is known as cytoplasmic inheritance. Some of the genetic material is strictly maternal or paternal, but species with mixed sex exist, too (Reboud and Zeyl 1994, Xu 2005, Munasinghe and Agren 2023, Sakamoto and Takami 2023).

(4) Among species from different genera up to a high taxonomic level, specific fluctuations in the mutation rate of the same molecular marker are different (Drake 1991, Drake et al. 1998, Lynch 2010, Sanjuan et al. 2010, Sun and Lind 2022, Lynch et al. 2023). These results are due to differences in the genome size and probably karyological specificity (chromosome number fluctuations and size difference). Generally, for the same origins and DNA fragment size, species with large genome sizes have lower mutation rates than species with small genomes. The molecular marker ranking is important for computer simulations for the aforementioned markers, for high-performing wide genome analysis (WGA) developed in the past 20 years, and for future developments.

Time mark molecular clock fixing

For time mark molecular clock calibration, it is necessary to match the aforemen-

tioned universal principles with a time mark, such as climatic fluctuations, tectonic history maps, or paleo-records (Rogers and Harpending 1992; Sanderson 1997, 2003; Ho et al. 2015; O'Reilly et al. 2015; Donoghue and Yang 2016). Time mark molecular clock fixing is closely related to the molecular marker ranking. For example, it is impossible for molecular markers with a high molecular mass difference (bp difference) and/or different origins to refer to the same historical period. In this context, postglacial migration routes with molecular markers with a high mutation rate difference (i.e., the mutation class, order, and origin [MCOO] profile difference) cannot be described. It is also important to mention that paleo-records must be used with precaution (Schoonmaker and Foster 1991, Carrion and Scott 1999, Charles et al. 2003, Rohde and Muller 2005), as false-positive paleo-botanical artifacts could be pollen (Naydenov et al. 2014, 2017, 2023).

Technically, molecular clock theory is well developed, and robust computer programs, such as LAMARC (Kuhner 2006) and MIGRATE (Beerli 1998), exist for phylogeographic simulations. These programs offer numerous hypothetical scenarios, often including population sizes, migration rates, growth rates, recombination rates, bottlenecks, and isolation-level fluctuations. Multiple rigorous publications involving paleo-map projects are available for tectonic history (Stampfli and Borel 2002; Stampfli et al. 2002a, 2002b; Blakey 2008). We used those developed by Dr. Ron Blakey from Colorado Plateau Geosystems (USA; Blakey 2008). For

molecular clock calibration for phylogenetic analysis, the BEAUti and BEAST 1.7 (Drummond et al. 2012) and CladeDate (Claramunt 2022) programs are used more often.

Example: Forest trees and molecular markers

Over the past 30 years, many studies have discussed molecular-based phylogeography using numerous molecular markers and the postglacial colonization routes of forest trees through the temperate zones to the boreal and tundra regions (Jaramillo-Correa et al. 2004, Godbout et al. 2005, Naydenov et al. 2007). The main question is whether all molecular markers (SNPs, SSRs, and large INDELs) can describe postglacial migration. The simple answer is no. In this paper, we showed that, first, the mutation rate significantly differs between molecular markers by locus/allele length-dependent mutation processes and that, second, the DNA mutation process in plastids versus chromosomes differs. For example, in the *Pinus* genus, the mitochondrial genome is transmitted maternally, while that of chloroplasts is transmitted paternally, that is, by pollen (Neale and Sederoff 1989). In addition, based on our studies on the *Pinus* genus, we considered maternally inherited molecular markers to be more conservative than paternal ones of the same size (Naydenov et al. 2014, 2017, 2023). Various interacting factors directly impact the mutation rate μ . We abbreviated the molecular marker ranking as MCOO. In short, the molecular mutation–rated difference carries a different phylogenetic memory; that is, for different contrasting ranges of molecular markers, it is impossible to describe the same historical migration pattern and phylogeographic structures.

For molecular clock calibration for forest tree phylogeography and phylogenetic analysis, the time mark we must assume is that species have a large genome size and reproductive age. Conifers have a genome that is more than three times that of humans, and the reproductive age of conifers starts from 20 years and reaches its maximum effect at 50–60 years for *P. nigra* and *P. sylvestris* (Dobrinov et al. 1982, Alexandrov et al. 1988). Based on the mutation rate, the time marks to fix the molecular clock could be well-known global climate change records and tectonic history events. For example, in some places in the world, the tectonic history is more dynamic and has been well studied, such as the Mediterranean basin, which allows researchers to try using different time marks to fix the molecular clock back in time. For coniferous species, the most interesting geological period is between 0.01 and 8 million years (Fig. 1). For the *Pinus* genus, we proposed that mitochondrial SNPs (mtSNPs) and nuclear SSRs (nuSSRs) should be used for the Pleistocene epoch, chloroplast SSRs (cpSSRs) for the Pliocene epoch, and mitochondrial INDELs (mtINDELs) for the late Miocene epoch (Burban and Petit 2003; Naydenov et al. 2014, 2017, 2023). For places where it is difficult to find a sufficiently credible time mark, it is possible to use a time mark comparable to those proposed here for coniferous species with similar genome sizes. In the future, an open access data set must be created with the mutation rates for each molecular marker by species and genus.

Conclusion

The mutation rate ranking, and the principles cited before reflecting that different

genome elements have different speeds of evolution and phylogeographic memory, which is important to consider for phylogeographic research. Phylogenetic and phylogeographic memories are valuable for research in various fields, including plants, animals, and humans. For example, understanding the phylogeography of forest trees helps identify historical mutation events and their connections to population migration dynamics, climate change, and the conservation and management of biodiversity. In agriculture and livestock, these insights can determine the origin and period of domestication and guide conservation strategies for important genetic lines, which are crucial for a sustainable economy. In personalized medicine for humans, phylogeographic memory is important for identifying diseases, understanding resistance and parasite vectors, tracing evolutionary timelines, and analyzing their relationships with geographic distribution and social factors. This knowledge will aid in supporting future health programs and developing new medicines.

Acknowledgements

We would like to thank Irena M. Naydenova for her technical assistance. The work of authors (T. Gurov and S. Ivanovska) was carried out using the infrastructure purchased under the National Roadmap for RI, financially coordinated by the MES of the Republic of Bulgaria (Grant No. DO1-325/01.12.2023). The work of author S.-M. Gurova was partly supported by the National Geoformation Centre (part of the National Roadmap of RIs) under grant No. D01-321/30.11.2023.

Declarations

Conflict of interest: None declared.

References

- AL GHADEER H.A., AL KISHI N., ALGURINI K.H., ALBESHER A.B., ALGHADEER M.R., ALSALMAN A.A., BUBSHAIT A.A., ALKISHI B.M. 2022. Partial Molar Pregnancy with Normal Karyotype. *Cureus* 14(10), e30934. doi: 10.7759/cureus.30934
- ALEXANDROV A., RAFAILOV G., NEDELIN G., TSANOV K., BOGDANOV B., SPASOV S. 1988. Coniferous forest in Bulgaria. *Zemizdat*, Sofia, Bulgaria. 152 p. (in Bulgarian).
- BACHTROG D., AGIS M., IMHOF M., SCHLÖTTERER C. 2000. Microsatellite variability differs between dinucleotide repeat motifs – evidence from *Drosophila melanogaster*. *Molecular Biology and Evolution* 17(9): 1277–1285. <https://doi.org/10.1093/oxfordjournals.molbev.a026411>
- BEERLI P. 1998. Estimation of migration rates and population sizes in geographically structured populations. *NATO ASI Series a Life Sciences* 306: 39–54.
- BERGER J., SUZUKI T., SENTI K.-A., STUBBS J., SCHAFFNER G., DICKSON B.J. 2001. Genetic mapping with SNP markers in *Drosophila*. *Nature Genetics* 29: 475–481. <https://doi.org/10.1038/hg773>
- BERGERON L.A., BESENBACHER S., ZHENG J., LI P., BERTELSEN M.F., QUINTARD B., HOFFMAN J.I., LI Z., LEGER J.St., SHAO C., STILLER J., GILBERT M.T.P., SCHIERUP M.H., ZHANG G. 2023. Evolution of the germline mutation rate across vertebrates. *Nature* 615: 285–291. <https://doi.org/10.1038/s41586-023-05752-y>
- BHARGAVA A., FUENTES F.F. 2010. Mutational dynamics of microsatellites. *Molecular Biotechnology* 44(3): 250–266. doi: 10.1007/s12033-009-9230-4
- BLAKEY R.C. 2008. Gondwana paleogeography from assembly to breakup – A 500 m.y.

- odyssey. Overview. In: Fielding C.R., Frank T.D., and Isbell J.L. (Eds), *Resolving the Late Paleozoic Ice Age in Time and Space*. Geological Society of America. Special Paper 441: 1–28.
- BRINKMANN B., KLINTSCHAR M., NEUHUBER F., HÜHNE J., ROLF B. 1998. Mutation rate in human microsatellites: influence of the structure and length of the tandem repeat. *American Journal of Human Genetics* 62(6): 1408–1415. doi: 10.1086/301869
- BUETTNER V.L., HILL K.A., HALANGODA A., SOMMER S.S. 1999. Tandem-base mutations occur in mouse liver and adipose tissue preferentially as G:C to T:A transversions and accumulate with age. *Environmental and Molecular Mutagenesis* 33(4): 320–324. doi: 10.1002/(sici)1098-2280(1999)33:4<320::aid-em9>3.0.co;2-s
- BURBAN C., PETIT R.J. 2003. Phylogeography of maritime pine inferred with organelle markers having contrasted inheritance. *Molecular Ecology* 12(6): 1487–1495. doi: 10.1046/j.1365-294x.2003.01817.x
- CALABRESE P., DURRETT R. 2003. Dinucleotide Repeats in the *Drosophila* and Human Genomes Have Complex, Length-Dependent Mutation Processes. *Molecular Biology and Evolution* 20(5): 715–725. https://doi.org/10.1093/molbev/msg084
- CALABRESE P.P., DURRETT R.T., AQUADRO C.F. 2001. Dynamics of microsatellite divergence and proportional slippage/point mutation models. *Genetics* 159(2): 839–852. https://doi.org/10.1093/genetics/159.2.839
- CARRION J.S., SCOTT L. 1999. The challenge of pollen analysis in paleoenvironmental studies of hominid beds: the record from Sterkfontein caves. *Journal of Human Evolution* 36(4): 401–408. https://doi.org/10.1006/jhev.1998.0276
- CHAKRABORTY R., KIMMEL M., STIVERS D.N., DEKA R. 1997. Relative mutation rates at di-, tri-, and tetranucleotide microsatellite loci. *PNAS* 94(3): 1041–1046. https://doi.org/10.1073/pnas.94.3.1041
- CHARLES H.W., OSTERLOFF P.L., MOHIUDDIN U. 2003. Fragments of the Earliest Land Plants. *Nature* 42(6955): 282–285. https://doi.org/10.1038/nature01884
- CHRISTENHUSZ M.J.M., BASTIAANSE H.; ROYAL BOTANIC GARDENS KEW GENOME ACQUISITION LAB; PLANT GENOME SIZING COLLECTIVE; DARWIN TREE OF LIFE BARCODING COLLECTIVE; WELLCOME SANGER INSTITUTE TREE OF LIFE MANAGEMENT, SAMPLES AND LABORATORY TEAM; WELLCOME SANGER INSTITUTE SCIENTIFIC OPERATIONS: SEQUENCING OPERATIONS; WELLCOME SANGER INSTITUTE TREE OF LIFE CORE INFORMATICS TEAM; TREE OF LIFE CORE INFORMATICS COLLECTIVE; DARWIN TREE OF LIFE CONSORTIUM. 2024. The genome sequence of black poplar, *Populus nigra* subsp. *betulifolia* L., 1753 (Salicaceae). Wellcome Open Research 9, 228. 16 p. https://doi.org/10.12688/wellcomeopenres.21300.1
- CLARAMUNT S. 2022. CladeDate: Calibration information generator for divergence time estimation. *Methods in Ecology and Evolution* 13(11): 2331–2338. https://doi.org/10.1111/2041-210X.13977
- DE FRANCISCIS P., SCHIATTARELLA A., LABRIOLA D., TAMMARO C., MESSALLI E.M., LA MANTIA E., MONTELLA M., TORELLA M. 2019. A partial molar pregnancy associated with a fetus with intrauterine growth restriction delivered at 31 weeks: a case report. *Journal of Medical Case Reports* 13, 204. 5 p. https://doi.org/10.1186/s13256-019-2150-4
- DIERINGER D., SCHLÖTTERER C. 2003. Two distinct modes of microsatellite mutation processes: evidence from the complete genomic sequences of nine species. *Genome Research* 13(10): 2242–2251. http://www.genome.org/cgi/doi/10.1101/gr.1416703
- DOBRINOV I., DOYKOV G., GAGOV V. 1982. Forest genetic pool in Bulgaria. Zemizdat, Sofia, Bulgaria. 258 p. (in Bulgarian).
- DONOGHUE P.C., YANG Z. 2016. The evolution of methods for establishing evolutionary timescales. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences* 371(1699), 20160020. https://doi.org/10.1098/rstb.2016.0020
- DRAKE J.W. 1991. A constant rate of spontaneous mutation in DNA based microbes.

- PNAS 88(16): 7160–7164. <https://doi.org/10.1073/pnas.88.16.7160>
- DRAKE J.W., CHARLESWORTH B., CHARLESWORTH D., CROW J.F. 1998. Rates of spontaneous mutation. *Genetics* 148(4): 1667–1686. <https://doi.org/10.1093/genetics/148.4.1667>
- DRUMMOND A.J., SUCHARD M.A., XIE D., RAMBAUT A. 2012. Bayesian phylogenetics with BEAUti and the BEAST 1.7. *Molecular Biology and Evolution* 29(8): 1969–1973. <https://doi.org/10.1093/molbev/mss075>
- EBERT P., AUDANO P.A., ZHU Q., RODRIGUEZ-MARTIN B., PORUBSKY D. ET AL. 2021. Haplotype-resolved diverse human genomes and integrated analysis of structural variation. *Science* 372, 6537. 13 p. <https://doi.org/10.1126/science.abf7117>
- ELLEGRAN H., FRIDOLFSSON A.-K. 1997. Male driven evolution of DNA sequences in birds. *Nature Genetics* 17: 182–184. <https://doi.org/10.1038/ng1097-182>
- GALINDO C.L., MCLIVER L.J., MCCORMICK J.F., SKINNER M.A., XIE Y., GELHAUSEN R.A., NG K., KUMAR N.M., GARNER H.R. 2009. Global Microsatellite Content Distinguishes Humans, Primates, Animals, and Plants. *Molecular Biology and Evolution* 26(12): 2809–2819. <https://doi.org/10.1093/molbev/msp192>
- GARZA J.C., SLATKIN M., FREIMER N.B. 1995. Microsatellite allele frequencies in humans and chimpanzees, with implications for constraints on allele size. *Molecular Biology and Evolution* 12(4): 594–603. <https://doi.org/10.1093/oxfordjournals.molbev.a040239>
- GODBOUT J., JARAMILLO-CORREA J.P., BEAULIEU J., BOUSQUET J. 2005. A mitochondrial DNA minisatellite reveals the postglacial history of jack pine (*Pinus banksiana*), a broad-range North American conifer. *Molecular Ecology* 14(11): 3497–3512. <https://doi.org/10.1111/j.1365-294X.2005.02674.x>
- GOLDSTEIN D.B., CLARK A.G. 1995. Microsatellite variation in North American populations of *Drosophila melanogaster*. *Nucleic Acids Research* 23(19): 3882–3886. <https://doi.org/10.1093/nar/23.19.3882>
- GONZALEZ-IBEAS D., MARTINEZ-GARCIA P.J., FAMULA R.A., DELFINO-MIX A., STEVENS K.A., LOOPSTRA C.A., LANGLEY C.H., NEALE D.B. 2016. Assessing the Gene Content of the Megagenome: Sugar Pine (*Pinus lambertiana*). *G3 (Bethesda)* 6(12): 3787–3802. <https://doi.org/10.1534/g3.116.032805>
- GREENE E., BENJAMIN R. 2023. Pediatric disorders of stature. In: Halpern-Felsher B. (Ed.), *Encyclopedia of Child and Adolescent Health* 1: 336–351. <https://doi.org/10.1016/B978-0-12-818872-9.00132-1>
- GROVER A., SHARMA P.C. 2016. Development and use of molecular markers: past and present. *Critical Reviews in Biotechnology* 36(2): 290–302. <https://doi.org/10.3109/07388551.2014.959891>
- HALLAST P., EBERT P., LOFTUS M., YILMAZ F., AUDANO P.A. ET AL. 2023. Assembly of 43 human Y chromosomes reveals extensive complexity and variation. *Nature* 621: 355–364. <https://doi.org/10.1038/s41586-023-06425-6>
- HARR B., SCHLÖTTERER C. 2000. Long microsatellite alleles in *Drosophila melanogaster* have a downward mutation bias and short persistence times, which cause their genome-wide underrepresentation. *Genetics* 155(3): 1213–1220. <https://doi.org/10.1093/genetics/155.3.1213>
- HILL K.A., WANG J., FARWELL K.D., SOMMER S.S. 2003. Spontaneous tandem-base mutations (TBM) show dramatic tissue, age, pattern, and spectrum specificity. *Mutation Research* 534(1–2): 173–186. [https://doi.org/10.1016/S1383-5718\(02\)00277-2](https://doi.org/10.1016/S1383-5718(02)00277-2)
- HO S.Y., TONG K.J., FOSTER C.S., RITCHIE A.M., LO N., CRISPAL M.D. 2015. Biogeographic calibrations for the molecular clock. *Biology Letters* 11(9), 20150194. <https://doi.org/10.1098/rsbl.2015.0194>
- JARAMILLO-CORREA J.P., BEAULIEU J., BOUSQUET J. 2004. Variation in mitochondrial DNA reveals multiple distant glacial refugia in black spruce (*Picea mariana*), a transcontinental North American conifer. *Molecular Ecology* 13(9): 2735–2747. <https://doi.org/10.1111/j.1365-294X.2004.02258.x>
- KORF B.R., PYERITZ R.E., GRODY W.W. 2019.

- 3 – Nature and Frequency of Genetic Disease In: Pyeritz R.E., Korf B.R., Grody W.W. (Eds), Emery and Rimoin's Principles and Practice of Medical Genetics and Genomics (Seventh edition), Academic Press: 47–51. <https://doi.org/10.1016/B978-0-12-812537-3.00003-2>
- KOVACH A., WEGRZYŃ J.L., PARRA G., HOLT C., BRUENING G.E., LOOPSTRA C.A., HARTIGAN J., YANDELL M., LANGLEY C.H., KORF I., NEALE D.B. 2010. The *Pinus taeda* genome is characterized by diverse and highly diverged repetitive sequences. BMC Genomics 11, 420. 14 p. <https://doi.org/10.1186/1471-2164-11-420>
- KRUGLYAK S., DURRETT R., SCHUG M.D., AQUADRO C.F. 2000. Distribution and Abundance of Microsatellites in the Yeast Genome Can Be Explained by a Balance Between Slippage Events and Point Mutations, Molecular Biology and Evolution 17(8): 1210–1219. <https://doi.org/10.1093/oxfordjournals.molbev.a026404>
- KRUGLYAK S., DURRETT R.T., SCHUG M.D., AQUADRO C.F. 1998. Equilibrium distributions of microsatellite repeat length resulting from a balance between slippage events and point mutations. PNAS 95(18): 10774–10778. <https://doi.org/10.1073/pnas.95.18.10774>
- KUHNER M.K. 2006. LAMARC 2.0: maximum likelihood and Bayesian estimation of population parameters. Bioinformatics 22(6): 768–770. <https://doi.org/10.1093/bioinformatics/btk051>
- LAI Y., SUN F. 2003. Microsatellite mutations during the polymerase chain reaction: mean field approximations and their applications. Journal of Theoretical Biology 224(1): 127–137. [https://doi.org/10.1016/S0022-5193\(03\)00155-3](https://doi.org/10.1016/S0022-5193(03)00155-3)
- LYNCH M. 2010. Evolution of the mutation rate. Trends in Genetics 26(8): 345–352. <https://doi.org/10.1016/j.tig.2010.05.003>
- LYNCH M., ALI F., LIN T., WANG Y., NI J., LONG H. 2023. The divergence of mutation rates and spectra across the Tree of Life. EMBO reports 24, 10. <https://doi.org/10.15252/embr.202357561>
- MAHDIEH N., RABBANI B. 2013. An overview of mutation detection methods in genetic disorders. Iranian Journal of Pediatrics 23(4): 375–388.
- MAHMOUD M., GOBET N., CRUZ-DÁVALOS D.I., MOUNIER N., DESSIMOZ C., SEDLAZECK F.J. 2019. Structural variant calling: the long and threshold of it. Genome Biology 20, 246. 14 p. <https://doi.org/10.1186/s13059-019-1828-7>
- MAKOVA K.D., PICKETT B.D., HARRIS R.S., HARTLEY G.A., CECHOVA M. ET AL. 2024. The complete sequence and comparative analysis of ape sex chromosomes. Nature 630: 401–411. <https://doi.org/10.1038/s41586-024-07473-2>
- MCVEAN G. 2000. Evolutionary genetics: What is driving male mutation? Current Biology 10(22): R834–R835. [https://doi.org/10.1016/S0960-9822\(00\)00787-9](https://doi.org/10.1016/S0960-9822(00)00787-9)
- MILLS R.E., LUTTIG C.T., LARKINS C.E., BEAUCHAMP A., TSUI C., PITTARD W.S., DEVINE S.E. 2006. An initial map of insertion and deletion (INDEL) variation in the human genome. Genome Research 16(9): 1182–1190. <http://www.genome.org/cgi/doi/10.1101/gr.4565806>
- MORGANTE M., HANAFEY M., POWELL W. 2002. Microsatellites are preferentially associated with nonrepetitive DNA in plant genomes. Nature Genetics 30(2): 194–200. <https://doi.org/10.1038/ng822>
- MUNASINGHE M., AGREN J.A. 2023. When and why are mitochondria paternally inherited? Current Opinion in Genetics & Development 80, 102053. 8 p. <https://doi.org/10.1016/j.gde.2023.102053>
- NAYDENOV K.D., ALEXANDROV A., MATEVSKI V., VASILEVSKI K., NAYDENOV M.K., GYULEVA V., CARCAILLET C., WAHID N., KAMARY S. 2014. Range-wide genetic structure of maritime pine predates the last glacial maximum: evidence from nuclear DNA. Hereditas 151(1): 1–13. <https://doi.org/10.1111/j.1601-5223.2013.00027.x>
- NAYDENOV K.D., NAYDENOV M., ALEXANDROV A., GUROV T., GYULEVA V. ET AL. 2023. Speciation and historical migration pattern interaction: examples from *P. nigra* and *P. sylvestris* phylogeography. European Journal of Forest Research 142: 1–26. <https://doi.org/10.1007/s10342-023-01555-5>

- doi.org/ 10.1007/ s10342-022-01513-0
- NAYDENOV K.D., NAYDENOV M.K., ALEXANDROV A., VASILEVSKI K., GYULEVA V. ET AL. 2016. Ancient split of major genetic lineages of European Black Pine: evidence from chloroplast DNA. *Tree Genetics and Genomes* 12, 68. <https://doi.org/10.1007/s11295-016-1022-y>
- NAYDENOV K.D., NAYDENOV M.K., ALEXANDROV A., VASILEVSKI K., HINKOV G. ET AL. 2017. Ancient genetic bottleneck and Plio-Pleistocene climatic changes imprinted the phylogeography of European Black Pine populations. *European Journal of Forest Research* 136(5–6): 767–786. <https://doi.org/10.1007/s10342-017-1069-9>
- NAYDENOV K.D., SENNEVILLE S., BEAULIEU J., TREMBLAY F., BOUSQUET J. 2007. Glacial vicariance in Eurasia: mitochondrial DNA evidence from Scots pine for a complex heritage involving genetically distinct refugia at mid-northern latitudes and in Asia Minor. *BMC Evolutionary Biology* 7, 233. 12 p. <https://doi.org/10.1186/1471-2148-7-233>
- NEALE D.B., SEDEROFF R.R. 1989. Paternal inheritance of chloroplast DNA and maternal inheritance of mitochondrial DNA in loblolly pine. *Theoretical and Applied Genetics* 77(2): 212–216. <https://doi.org/10.1007/BF00266189>
- NYSTEDT B., STREET N., WETTERBOM A., ZUCOLO A., LIN Y.-C. ET AL. 2013. The Norway spruce genome sequence and conifer genome evolution. *Nature* 497: 579–584. <https://doi.org/10.1038/nature12211>
- OHATA T., KIMURA M. 1973. A model of mutation appropriate to calculate the number of electrophoretically detectable alleles in a genetic population. *Genetical Research* 22(2): 201–204. doi: 10.1017/s0016672300012994
- O'REILLY J.E., DOS REIS M., DONOGHUE P.C.J. 2015. Dating Tips for Divergence-Time Estimation. *Trends in Genetics* 31(11): 637–650. <https://doi.org/10.1016/j.tig.2015.08.001>
- REBOUD X., ZEYL C. 1994. Organelle inheritance in plants. *Heredity* 72: 132–140. <https://doi.org/10.1038/hdy.1994.19>
- RHIE A., MCCARTHY S.A., FEDRIGO O., DAMAS J., FORMENTI G. ET AL. 2021. Towards complete and error-free genome assemblies of all vertebrate species. *Nature* 592: 737–746. <https://doi.org/10.1038/s41586-021-03451-0>
- RHIE A., NURK S., CECHOVA M., HOYT S.J., TAYLOR D.J. ET AL. 2023. The complete sequence of a human Y chromosome. *Nature* 621: 344–354. <https://doi.org/10.1038/s41586-023-06457-y>
- ROGERS A.R., HARPENDING H. 1992. Population growth makes waves in the distribution of pairwise genetic differences. *Molecular Biology and Evolution* 9(3): 552–569. <https://doi.org/10.1093/oxfordjournals.molbev.a040727>
- ROHDE R.A., MULLER R.A. 2005. Cycles in fossil diversity. *Nature* 434: 208–210. <https://doi.org/10.1038/nature03339>
- ROSE O., FALUSH D. 1998. A threshold size for microsatellite expansion. *Molecular Biology and Evolution* 15(5): 613–615. <https://doi.org/10.1093/oxfordjournals.molbev.a025964>
- RUITBERG C.M., REEDER D.J., BUTLER J.M. 2001. STRBase: a short tandem repeat DNA database for the human identity testing community. *Nucleic Acids Research* 29(1): 320–322. <https://doi.org/10.1093/nar/29.1.320>
- SAKAMOTO W., TAKAMI T. 2023. Plastid inheritance revisited: emerging role of organelle DNA degradation in angiosperms. *Plant and Cell Physiology* 65(4): 484–492. <https://doi.org/10.1093/pcp/pcad104>
- SANDERSON M. 1997. A nonparametric approach to estimating divergence times in the absence of rate constancy. *Molecular Biology and Evolution* 14(12): 1218–1231. <https://doi.org/10.1093/oxfordjournals.molbev.a025731>
- SANDERSON M.J. 2003. r8s: inferring absolute rates of molecular evolution and divergence times in the absence of a molecular clock. *Bioinformatics* 19(2): 301–302. <https://doi.org/10.1093/bioinformatics/19.2.301>
- SANJUAN R., NEBOT M.R., CHIRICO N., MANSKY L.M., BELSHAW R. 2010. Viral mutation

- rates. *Journal of Virology* 84(19): 9733–9748. <https://doi.org/10.1128/jvi.00694-10>
- SCHLOTTERER C., TAUTZ D. 1992. Slippage synthesis of simple sequence DNA. *Nucleic Acids Research* 20(2): 211–215. <https://doi.org/10.1093/nar/20.2.211>
- SCHOONMAKER P.K., FOSTER D.R. 1991. Some Implications of Paleoecology for Contemporary Ecology. *Botanical Review* 57(3): 204–245. <https://www.jstor.org/stable/4354170>
- SCHUG M.D., MACKAY T.F., AQUADRO C.F. 1997. Low mutation rates of microsatellite loci in *Drosophila melanogaster*. *Nature Genetics* 15: 99–102. <https://doi.org/10.1038/ng0197-99>
- SIBLY R.M., MEADE A., BOXALL N., WILKINSON M.J., CORNE D.W., WHITTAKER J.C. 2003. The structure of interrupted human AC microsatellites. *Molecular Biology and Evolution* 20(3): 453–459. <https://doi.org/10.1093/molbev/msg056>
- SIBLY R.M., WHITTAKER J.C., TALBOT M. 2001. A maximum-likelihood approach to fitting equilibrium models of microsatellite evolution. *Molecular Biology and Evolution* 18(3): 413–417. <https://doi.org/10.1093/oxfordjournals.molbev.a003817>
- STAMPFLI G.M., BOREL G.D. 2002. A plate tectonic model for the Paleozoic and Mesozoic constrained by dynamic plate boundaries and restored synthetic oceanic isochrons. *Earth and Planetary Science Letters* 196(1–2): 17–33. [https://doi.org/10.1016/S0012-821X\(01\)00588-X](https://doi.org/10.1016/S0012-821X(01)00588-X)
- STAMPFLI G.M., MOSAR J., FAVRE P. ET AL. 2002a. The paleotectonic atlas of the Peri-Tethyan Domain (electronic resource). European Geophysical Society, CD-ROM.
- STAMPFLI G.M., VON RAUMER J.F., BOREL G.D. 2002b. Palaeozoic evolution of pre-Variscan terranes: From Gondwana to the Variscan collision. In: Martinez-Catalan R., Hatcher R.D., Arenas R., Diaz Garcia F. (Eds), *Variscan Appalachian dynamics: the building of the Upper Paleozoic basement*. Geological Society of America, Special Paper 364: 263–280.
- STUMPF M.P., GOLDSTEIN D.B. 2001. Genealogical and evolutionary inference with the human Y chromosome. *Science* 291(5509): 1738–1742. doi: 10.1126/science.291.5509.1738
- STURZENNEKER R., BEVILACQUA R.A.U., HADDAD LA, SIMPSON A.J.G., PENA S.D.J. 2000. Microsatellite instability in tumors as a model to study the process of microsatellite mutations. *Human Molecular Genetics* 9(3): 347–352. <https://doi.org/10.1093/hmg/9.3.347>
- SUN T.A., LIND P.A. 2022. Distribution of mutation rates challenges evolutionary predictability. *bioRxiv* 12, 518962. 45 p. <https://doi.org/10.1101/2022.12.12.518962>
- SUNG W., ACKERMAN M.S., MILLER S.F., LYNCH M. 2012. Drift-barrier hypothesis, and mutation-rate evolution. *PNAS* 109(45): 18488–18492. <https://doi.org/10.1073/pnas.1216223109>
- THOMSON J.A., PILOTTI V., STEVENS P., AYRES K.L., DEBENHAM P.G. 1999. Validation of short tandem repeat analysis for the investigation of cases of disputed paternity. *Forensic Science International* 100(1–2): 1–16. [https://doi.org/10.1016/S0379-0738\(98\)00199-6](https://doi.org/10.1016/S0379-0738(98)00199-6)
- TOTH G., GASPARI Z., JURKA J. 2000. Microsatellites in different eukaryotic genomes: Survey and analysis. *Genome Research* 10(7): 967–981. doi: 10.1101/gr.10.7.967
- VERBIEST M., MAKSIMOV M., JIN Y., ANISIMOVA M., GYMREK M., SONAY T.B. 2023. Mutation and selection processes regulating short tandem repeats give rise to genetic and phenotypic diversity across species. *Journal of Evolutionary Biology* 36(2): 321–336. doi: 10.1111/jeb.14106
- WEBER J.L., WONG C. 1993. Mutation of human short tandem repeats. *Human Molecular Genetics* 2(8): 1123–1128. <https://doi.org/10.1093/hmg/2.8.1123>
- WELLESLEY D., DOLK H., BOYD P.A., GREENLEES R., HAEUSLER M., NELEN V., GARNE E., KHOSHNOOD B., DORAY B., RISSMANN A., MULLANEY C., CALZOLARI E., BAKKER M., SALVADOR J., ADDOR M.C., DRAPER E., RANKIN J., TUCKER D. 2012. Rare chromosome abnormalities, prevalence and prenatal diagnosis rates from population-based congenital anomaly regis-

- ters in Europe. *European Journal of Human Genetics* 20(5): 521–526. <https://doi.org/10.1038/ejhg.2011.246>
- WHITTAKER J.C., HARBORD R.M., BOXALL N., MACKAY I., DAWSON G., SIBLY R.M. 2003. Likelihood-based estimation of microsatellite mutation rates. *Genetics* 164(2): 781–787. <https://doi.org/10.1093/genetics/164.2.781>
- WICKS S.R., YEH R.T., GISH W.R., WATERSTON R.H., PLASTERK R.H.A. 2001. Rapid gene mapping in *Caenorhabditis elegans* using a high-density polymorphism map. *Nature Genetics* 28: 160–164. <https://doi.org/10.1038/88878>
- WIERDL M., DOMINSKA M., PETES T.D. 1997. Microsatellite instability in yeast: dependence on the length of the microsatellite. *Genetics* 146(3): 769–779. <https://doi.org/10.1093/genetics/146.3.769>
- XU J. 2005. The inheritance of organelle genes and genomes: patterns and mechanisms. *Genome* 48(6): 951–958. <https://doi.org/10.1139/g05-082>
- XU X., PENG M., FANG Z., XU X. 2000. The direction of microsatellite mutation is dependent upon allele length. *Nature Genetics* 24(4): 396–399. <https://doi.org/10.1038/74238>
- YAN Y., YI G., SUN C., QU L., YANG N. 2014. Genome-Wide Characterization of Insertion and Deletion Variation in Chicken Using Next Generation Sequencing. *PLoS ONE* 9(8), e104652. 11 p. <https://doi.org/10.1371/journal.pone.0104652>
- ZUBERI S.M. 2013. Chapter 57 – Chromosome disorders associated with epilepsy. In: Dulac O., Lasseonde M., Sarnat H.B. (Eds), *Handbook of Clinical Neurology*. Elsevier 111: 543–548, <https://doi.org/10.1016/B978-0-444-52891-9.00057-9>

Review of satellite-based platforms and algorithms for near real-time monitoring of wildfires

Antoaneta Frantzova^{*}, Nikolai Dobrev^{}, Plamen Ivanov^{},
Miroslav Krastanov^{}, and Boyko Berov^{}

Geological Institute at Bulgarian Academy of Sciences, 24 Acad. Georgi Bonchev Srt., 1113
Sofia, Bulgaria. ^{*}E-mail: afrantzova@gmail.com

Received: 19 September 2024 / Accepted: 23 October 2024 / Available online: 31 October 2024



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

Abstract

The article deals with the methodology for detecting and monitoring of wildfires with remote sensing data. The development's purpose is to demonstrate the ways and methods of using free satellite data, as well as their practical application. We selected NASA's largest fire monitoring platform, which offers free access and data from the European Space Agency's Sentinel 2 satellites, for this purpose. This paper presents an overview of the physical basis for forest fire detection and provides a comparative study of the application of various satellite systems and equipment in the process of managing forest fire risks.

Key words: Earth observation, forest fire detection, free of charge satellite data.

Introduction

Remote sensing data related to fires is one of the main contributions to scientific and applied research covering various scientific disciplines. Fire is an important process in most terrestrial biomes. The release of gases and aerosols during biomass burning is a major factor in a number of chemical reactions and physical processes occurring in the atmosphere. Fires are a significant and persistent factor in the ecology of savannas, tundra, tropical, and boreal forests and play a central role in deforestation in tropical and subtropical regions. Strong and large-scale fires also

occur in a number of temperate biomes, such as forests, grasslands, etc.

Fires change the physical state of vegetation, releasing a number of greenhouse gases into the atmosphere. Despite the uncertainty associated with calculations and modelling to determine the amount of greenhouse gases released into the atmosphere, it is assumed that the amount of net annual carbon released into the atmosphere due to deforestation and conversion of tropical forests to agricultural land is about 30 % of the net annual increase in CO₂ concentration in the atmosphere (Jin et al. 2021).

Due to the distinct attributes of forest

fires (elevated temperatures, release of smoke and gasses, and the generation of clouds over the affected region), they are readily observable and detectable by satellite technologies. The primary aim of the study is to outline a methodology for the detection, monitoring, and damage assessment of forest fires using satellite technologies in near real time. The paper primarily examines complimentary data accessible on official NASA and European Commission websites as well as Google Earth. Frantzova (2010, 2012, 2014) outlines the operational approaches employed by satellite ground receiving stations in Bulgaria.

Material and Methods

The physical basis for thermal anomaly detection

The law of Planck's function determines the significantly increased amount of radiation in the mid-infrared region of the electromagnetic spectrum for the characteristic temperatures of the fire, providing the physical basis for detecting thermal anomalies. According to Wien's displacement law, the wavelength of maximum electromagnetic radiation for a body with an average temperature in the range of about 700–800 K is about 3.6–4.1 μm . The different phases of the fire (burning, smoldering) are characterised by different intensity, temperature, and amount of gases released into the atmosphere. According to Planck's law, thermal energy radiation reaches its maximum value at temperatures ranging from 500 K for smoldering fires to over 1000 K for burning fires. Fire intensity affects the fire temperature and the spatial extent of the hot zone. Measurements in the infrared range

of the electromagnetic spectrum can distinguish the processes of smoldering and burning, as the temperature of combustion significantly varies between these two stages. Based on data from Lobert and Warnatz (1993), Marchetti (2020) the temperature in the active fire is between 800 and 1200 K, possibly reaching 1800 K. The smoldering process has a temperature range of about 850 K and above.

The mid-infrared region of the electromagnetic spectrum is most suitable for detecting fires, but the high sensitivity of the channels of the measuring devices in this range of the spectrum also leads to the problem of so-called 'false alarms' when detecting fires. Many anthropogenic objects (factories, industrial enterprises, thermal power plants, mines, etc.) and natural formations under suitable conditions (high temperature of the earth's surface, zenith angle of the sun) have the physical characteristics and radiative properties of fire. The elimination of 'false alarms' is carried out after their localisation and expert judgment. Fire detection by satellite methods and tools depends not only on the fire temperature but also on the size of the fire and the resolution of the instrumentation. A fire may occupy a pixel with areas not burned, areas smoldering, and areas blazing. In low- or medium-resolution satellite imagery, fires can have varying temperatures within a single pixel, resulting in enormous differences in radio-brightness temperature between pixels. To 'see' a fire of small dimensions, its temperature must be extremely high (and vice versa). However, due to the high sensitivity of the channels in the region of the peak of electromagnetic radiation for the characteristic temperatures of the fire, and most importantly, the extremely high difference between the fire and the ambient temperature, it is possible to detect

thermal anomalies with dimensions smaller than the equipment's resolution (Marchetti 2020).

The use of satellite systems to detect fires began in early 1980. Theoretically, a way to record temperatures in 3.7 and 11 μm channels was first introduced in 1981 (Dozier 1981). The first AVHRR attempts to find fires used fixed targets in a known area. The same year saw the first use of nighttime images from NOAA-6 to detect high-temperature industrial sources in Detroit and (ignited) gas plumes from oil fields in the Persian Gulf (Matson and Dozier 1981). Thus, it becomes possible to detect ignited gas plumes associated with North Sea oil fields using NOAA-6 daytime images (Muirhead and Cracknell 1984). As a result of these studies based on fixed targets, the AVHRR radiometer (on board NOAA satellites) began to be used to detect forest and field fires using thermal imaging in the 3.7–3.9 μm range of the electromagnetic spectrum.

Near real time detection and monitoring of wildfires using the Fire Information for Resource Management System (FIRMS)

The Fire Information for Resource Management System (FIRMS) provides near real-time access to satellite imagery and data on active fires and hotspots. This system helps identify the location, extent, and intensity of wildfire activity. It was developed by NASA's Earth Science Data and Information System (ESDIS) project. The platform uses polar-orbiting and geostationary satellite.

FIRMS uses data from the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Visible Infrared Imaging Radiometer Suite (VIIRS) to deliver this information within three hours of satellite observation

Table 1 displays satellite platforms, fire monitoring and detection devices, together with their associated resolutions appli-

Table 1. Satellite platforms, fire monitoring and detection devices.

Product	Sensor (Platform)	Source	Spatial resolution	Coverage
Polar orbiting Active Fire Detections	MODIS (Terra/Aqua)	NASA LANCE	1 km	<3 hours (Global)
Polar orbiting Active Fire Detections	VIIRS (Suomi NPP/NOAA-20)	NASA LANCE	375 m	<3 hours (Global)
Polar orbiting Active Fire Detections	VIIRS (Suomi NPP/NOAA-21)	NASA LANCE	375 m	<3 hours (Global)
True/False Colour Composite Imagery	MODIS (Terra/Aqua)	NASA GIBS	250 m	<3 hours (Global)
True/False Colour Composite Imagery	VIIRS (Suomi NPP/NOAA-20)	NASA GIBS	250 m	<3 hours (Global)

cable for Bulgaria (FIRMS).

FIRMS interface is presented below in advance mode (Fig. 1). Every point on the map symbolises a thermal anomaly discovered by the associated sensor (satellite), and it is displayed with the colour that corresponds to it (red or yellow). The

detection of fires by satellite observation depends not only on the temperature of the fire but also on the area affected by the fire – the higher the temperature, the smaller the area required for its detection (smaller spatial resolution).

Daily gridded hotspot according to the

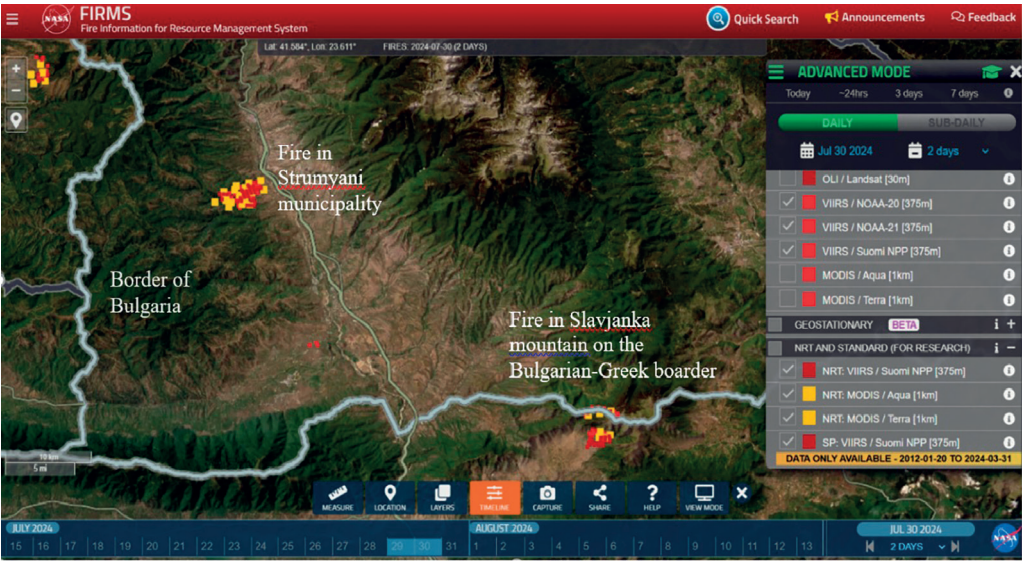


Fig. 1. FIRMS image, 30 Jul 2024. Advanced mode, daily coverage.

Note: 375 m spatial resolution: NOAA-20, NOAA-21, Suomi NPP (red); 1 km spatial: resolution Terra, Aqua (yellow).

global coverage is around 35 for one satellite, as can be seen on Figure 2; respectively – 120 detected hot spots daily from 3 satellite with 374 m. resolution (Fig. 3 and Table 2).

Coordinates link each grid hotspot, enabling its visualisation on any platform or map. According to the FIRMS, the platform is particularly useful for natural resource managers, firefighters, and any-



Fig. 2. NOAA-20/ VIIRS, Daily gridded hotspot, spatial resolution – 375 m, July 30 2024.

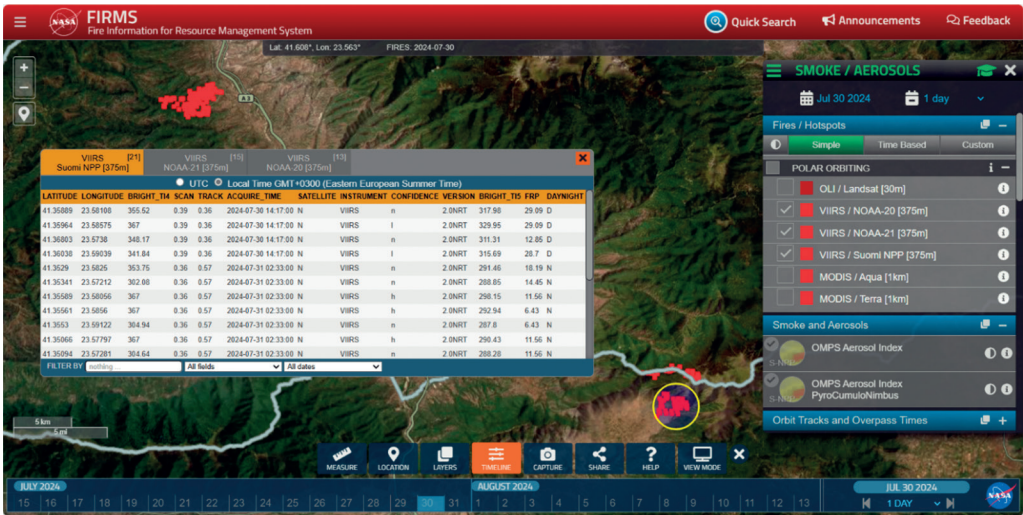


Fig. 3. Daily detected hot spots daily from 3 satellite with 374 m resolution.

one involved in monitoring and managing wildfire activity. It offers tools like global fire maps, email alerts, and downloadable data to support decision-making and resource management.

Row satellite images from different

Table 2. Daily orbits

Satellite Orbits	Suomi NPP 21 orbits	NOAA-22 15 orbits	NOAA-20 13 orbits
------------------	------------------------	----------------------	----------------------

platform and sensors are available via NASA Worldview platform (Fig. 4).

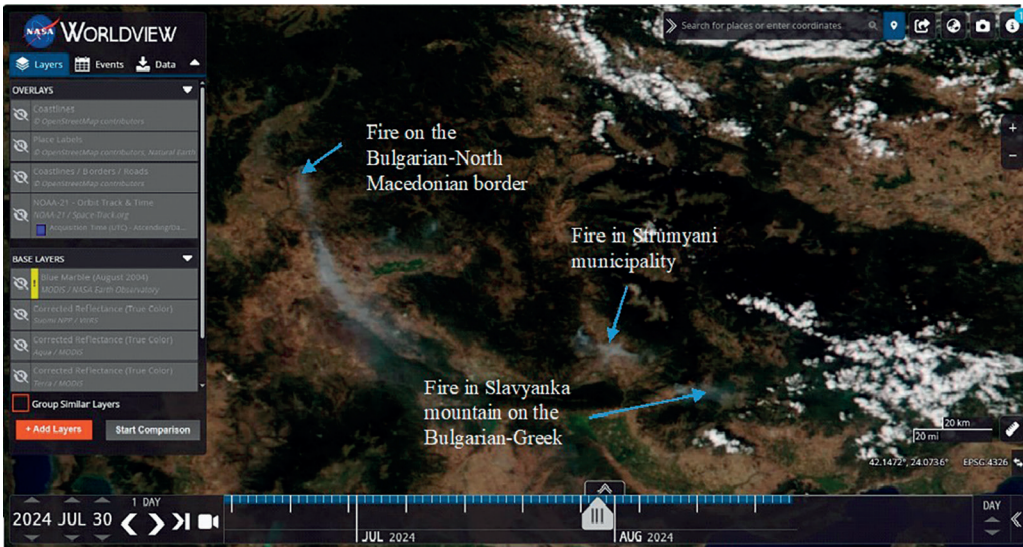


Fig. 4. VIIRS True colour, corrected reflectance, row image, July 30 2024, NOAA-21.

Note: We acknowledge the use of imagery from NASA Worldview application (<https://worldview.earthdata.nasa.gov>), part of NASA ESDIS.

Sentinel-2, Copernicus Programme

Sentinel-2 is a part of the European Space Agency's Copernicus Programme, designed for Earth observation. The mission consists of three satellites, Sentinel-2A and Sentinel-2B, Sentinel-2C, which provide high-resolution optical imagery. These satellites capture images in 13 spectral bands, ranging from visible to shortwave infrared, with spatial resolutions of 10, 20, and 60 m.

The Sentinel-2 satellite passes over Bulgaria approximately two to three times per week (about 2 to 3 orbits). Each orbit allows the satellite to capture high-resolution images of different parts of the country.

Sentinel's orbit and technological characteristics make it unsuitable for detecting forest fires in contrast with NOAA satel-

lites. It has great applicability in the monitoring and damage assessment.

When working with Sentinel-2 images, extremely important activities are those related to the analysis, and analysis and interpretation of the satellite image. The data in the platform FIRMS does not need to be analysed and interpreted. They are provided ready-made, bound with the corresponding coordinates.

For effective wildfire monitoring, it is essential to differentiate between a flaming smoldering fire and areas that have burnt or not. Tasks of this nature need specialised knowledge in the field of remote sensing, and the interpretation of images is based on the problem, as outlined in the material and methodology. Examples of such are shown in the figures 5 and 6.

Analysys and interpretation of satellite images

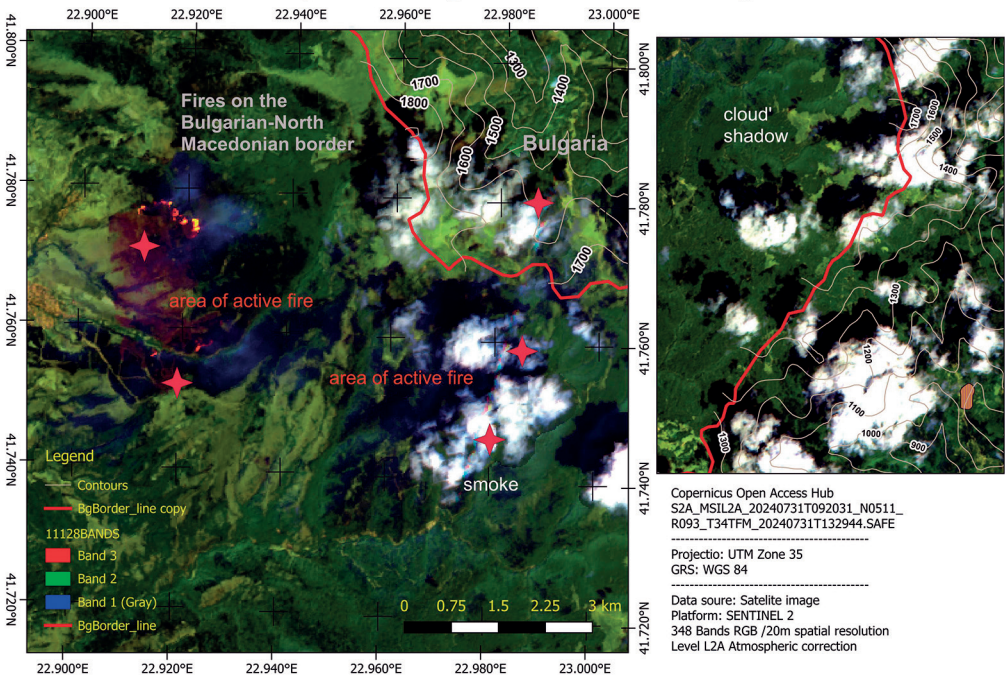


Fig. 5. Forest fires at Bulgarian-North Macedonia boarder.

Note: Sentilel-2, Band 3, 4, 8; 20 m spatial resolution (active fires are depicted with red sign).

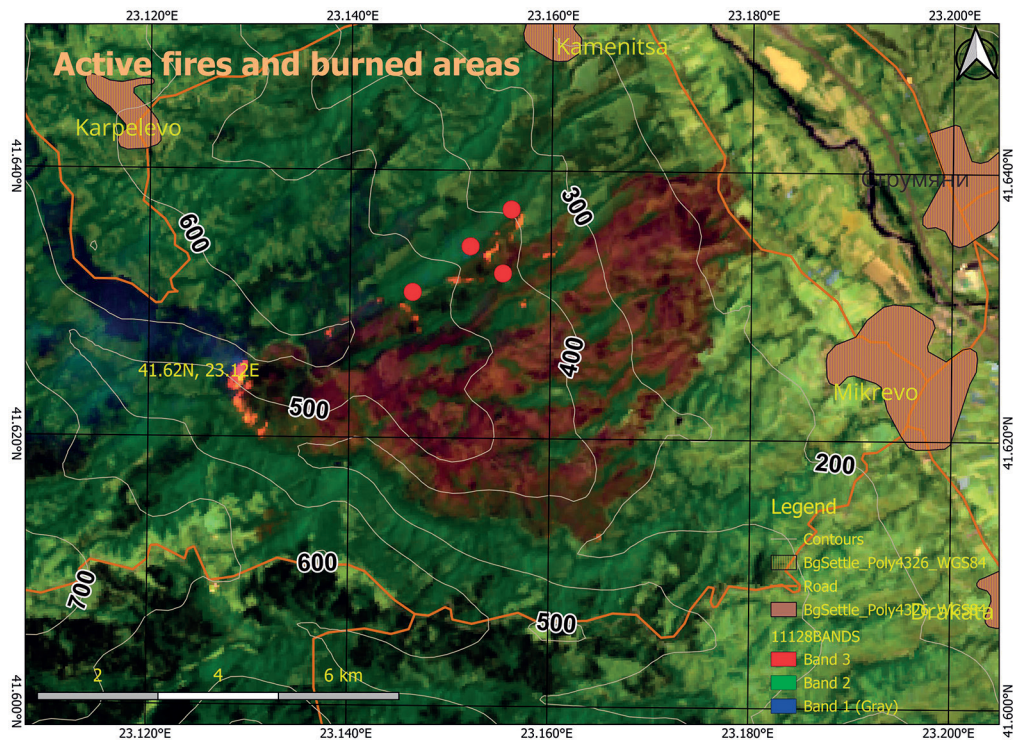


Fig. 6. Forest fires in Strumyani municipality – image from Sentinel-2, band 8, 11, 12.
Note: Active fires are depicted with red dots, burns areas are visible in brown.

Finally, one can assess damage with very high precision using Google Earth (figs 7 and 8).

Table 3 summarises the applicability of various satellite platforms in various stages of risk management process.

Table 3. Applicability of different satellites platforms to different stages of risk management process.

Satellite	Instrument	Before	During	After	Resolution
NOAA-20	VIIRS	1	3	1	375 m
NOAA-21	VIIRS	1	3	1	375 m
Suomi-NPP	VIIRS	1	3	1	375 m
Aqua	MODIS	1	2	2	1 km
Terra	MODIS	1	2	2	1 km
Sentinel-2	MSI	3	3	3	10, 20, 60 m

Note: 1 – low applicability, 2 – medium applicability, 3 – high applicability. Before – preparedness, risk assessment; During – detecting, monitoring and localizing during the emergency response; After – damage assessment, recovery.

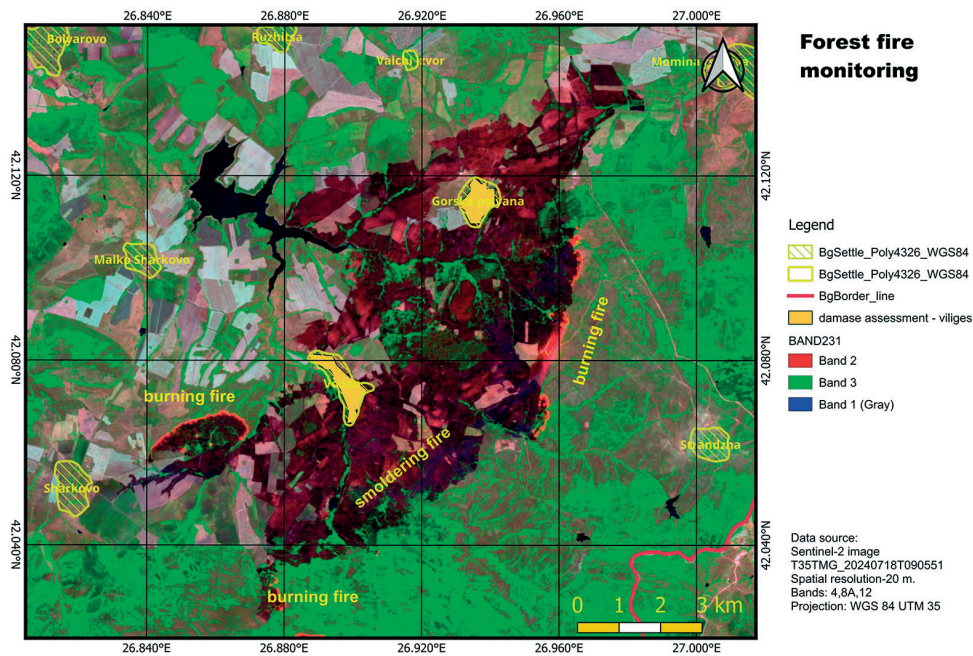


Fig. 7. Forest fires in Strumyani municipality.

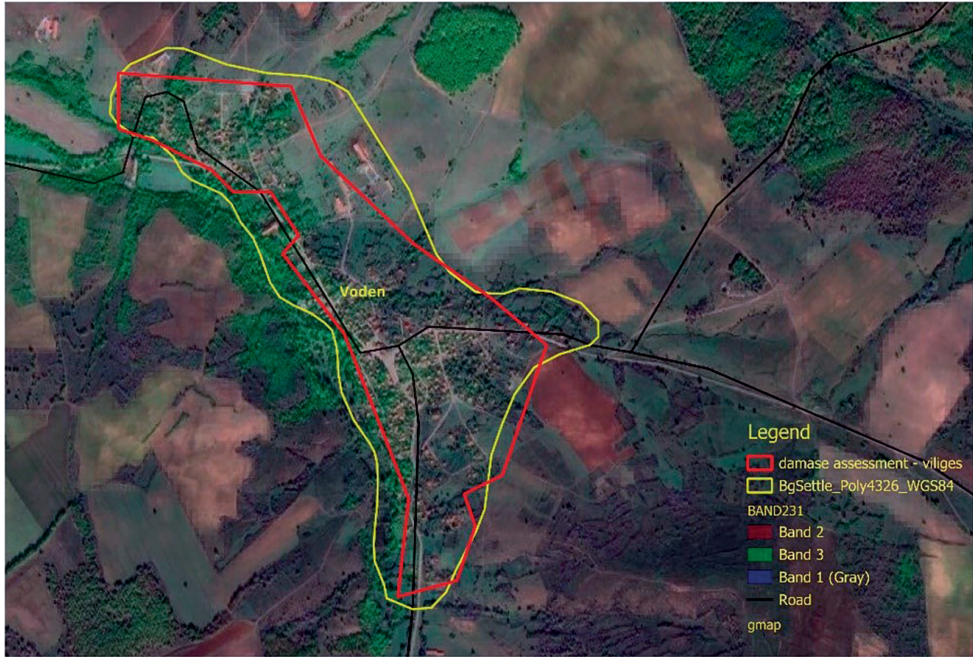


Fig. 8. Forest fires in Strumyani municipality, damage in Voden village, satellite image – Goggle Earth.

Conclusions

As the resolution of a satellite improves, the acquisition of satellite pictures becomes less frequent. Hence, the orbital properties of meteorological satellites (NOAA), together with the technical attributes of the associated sensor (equipment), make them very appropriate for detecting forest fires. In contrast, 375 m high-resolution satellites are specifically designed for the purposes of monitoring, evaluating damage, and implementing preventive measures. Consequently, for optimal use of remote sensing images for detecting and monitoring forest and field fires, it is necessary to employ several satellite types together with appropriate onboard equipment of varying resolutions.

Acknowledgments

This work is supported by the project 'National Geoinformation Center (NGIC)' funded by Contract D01-404/18.12.2020 with the Ministry of Education and Science of Bulgaria.

References

- DOZIER J. 1981. A method for satellite identification of surface temperature fields of subpixel resolution. *Remote Sensing of Environment* 11: 221–229. [https://doi.org/10.1016/0034-4257\(81\)90021-3](https://doi.org/10.1016/0034-4257(81)90021-3)
- FRANTZOVA A. 2010. Remote Sensing, GIS and Disaster Management. Third International Conference on Cartography and GIS. Nessebar, 15–20 June 2010 Bulgaria. Seminar with EU cooperation on Early Warning and Disaster/Crisis Management: 72–82.
- FRANTZOVA A. 2012. Detecting and monitoring of wildfires with remote sensing data. *South-Eastern European Journal of Earth Observation and Geomatics* 1(2): 13–25.
- FRANTZOVA A. 2014. Remote sensing application in disaster management of natural hazards. 5th International Conference on Cartography and GIS Proceedings, 15–20 June 2014, Riviera, Bulgaria, vol. 1 & 2: 715–725. https://cartography-gis.com/docsbca/5ICC&GIS_Proceedings_LQ.pdf
- JIN X., ZHU Q., COHEN R.C. 2021. Direct estimates of biomass burning NO_x emissions and lifetimes using daily observations from TROPOMI. *Atmospheric Chemistry and Physics* 21(20): 15569–15587. <https://doi.org/10.5194/acp-21-15569-2021>
- LOBERT J.M., WARNATZ J. 1993. Fire in the Environment: The Ecological, Atmospheric, and Climatic Importance of Vegetation Fires. Edited by Crutzen P.J. and Goldammer J.G. John Wiley & Sons Ltd: 15–37. https://expertonmold.com/wp-content/uploads/2023/08/Wildfire_Overview_Vegetation-Fires_Lobert.Warnatz.Wiley_.1993.pdf
- MATSON M., DOZIER J. 1981. Identification of Subresolution High Temperature Sources Using a Thermal IR Sensor. *Photogrammetric Engineering and Remote Sensing* 47(9): 1311–1318. https://www.asprs.org/wp-content/uploads/pers/1981journal/sep/1981_sep_1311-1318.pdf
- MARCHETTI L.J. 2020. Fire Dynamics Series: Estimating Fire Flame Height and Radiant Heat Flux from Fire. Chapter 5. Estimating Radiant Heat Flux from Fire to a Target Fuel. 58 p. <https://pdhonline.com/courses/m312/Radiant%20Flux.pdf>
- MUIRHEAD K., CRACKNELL A.P. 1984. Identification of gas flares in the North Sea using satellite data. *International Journal of Remote Sensing* 5(1): 199–212. <https://doi.org/10.1080/01431168408948798>

Growth characteristics and flowering stage of some *Digitalis purpurea* L. cultivars and *Gaillardia* sp. Foug. in the agro-ecological conditions in Kosovo

Nexhat Balaj¹, Hyzer Rizani^{1*}, Zenel Hajrizi², Adnan Gajtani²,
Nol Dedaj¹, and Lavdim Lepaja³

¹Faculty of Agriculture and Environment Engineering, University of Business and Technology, Lagjja Kalabria p.n., 10000 Prishtina, Kosovo. E-mails: nexhat.balaj@ubt-uni.net, hyzer.rizani@ubt-uni.net^{*}, nol.dedaj@ubt-uni.net

²South East European University-Tetovo, 335 Ilindenska Str., 1200 Tetovo, North Macedonia. E-mails: zenelhajrizi20@gmail.com, adnanigajtani100@gmail.com

³Department Horticulture, Faculty of Agriculture, University of Prishtina, 10000 Prishtina, Kosovo. E-mail: lavdim.lepaja@uni.edu.pr

Received: 10 June 2024 / Accepted: 22 October 2024 / Available online: 31 October 2024



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

Abstract

Perennial flowering plants are important parts of the urban green spaces with their beautiful flowers, colours and foliage. The purpose of the study was to evaluate the blooming stage and vegetative growth parameters for 12 perennials flowering taxa of *Digitalis purpurea* and *Gaillardia* sp. in the agro-ecological conditions of Kosovo. During the 2022–2023 growing periods, the object of research in our experimental field were totally 12 taxa. The experiment was 'Randomized block' type with four replications and 200 plants for each cultivar. All taxa were studied for: beginning and end of the flowering stage, features of petal fusion/ligules per flower head, flower opening stage, colour of flowers, dynamic of growth in length of flower stems, diameter of flower stems, number of flower stems per plant, fragrance of flowers. *Digitalis* cultivars and *Gaillardia* sp. have demonstrated high ornamentally and long period with flowers, good growing, leaves and flowers of different colours. Because of their good performance, studied taxa deserve more important place in public green spaces in the context of greater sustainability in urban landscape and should be included in the design and planting structure in Kosovo.

Key words: *Gaillardia aristata*, *Gaillardia pulchella*, *Gaillardia* × *grandiflora*, perennial flowering plants, vegetative growth parameters.

Introduction

Green spaces are becoming more important for the cities due to the increasing pressures of urbanization and climate change. Along with trees, shrubs and lawns, flower

beds are an important part of urban green spaces. Most flower beds in public spaces consist of annual, biennial and perennial flower species (Poje et al. 2023).

The improvement of living standard in the last two decades in the Republic

of Kosovo and the great development of various fields of construction (various social-cultural objects, city squares, residential houses, etc.), have influenced the increase in the demand for ornamental plants and implementing a modern landscape architecture (Balaj et al. 2022).

Most of the flower beds in public spaces in Kosovo consist of one-year and two-year flowers with beautiful colours, but to keep their aesthetic view during the summer, they require a lot of maintenance (Lushi et al. 2009).

Perennial flowering plants are used in the design of parks, flower gardens, private gardens, green spaces in cities, residential houses, etc. This group includes plants that in the climatic conditions of Kosovo are of high ornamental value, such as *Gaillardia aristata* Pursh, *Digitalis purpurea* L., *Antirrhinum majus* L., *Lavandula angustifolia* Mill., *Astilbe* × *arendsii* Arends, *Solidago virgaurea* L. (Dinga 1988).

Perennial flowering plants are important parts of green spaces with their beautiful flowers, colours and foliage (Almas and Conway 2016). They have a wide variety of colours and growth sizes and adapt to almost any landscape situation (Witting 1998).

The advantages of the combination of perennial plants depend on the diversity and heterogeneity, to have a beautiful appearance in the spaces of the parks, as well as to be attractive to their visitors (Lindemann-Matthies et al. 2010).

Digitalis purpurea is a member of Plantaginaceae family and is short-lived *perennial* plant growing 1 to 1.5 m in height, with bell-shaped flowers that hang down, with pink, red, white colours. The flowering period starts from late spring to mid-autumn. This species is used in gardens combined with several types of ornamental plants.

It is one of the most important medicinal plants in the world and is also favoured as a garden plant or cut flowers (Qualtrocchi 2000).

Genus *Gaillardia* Foug. is a member of Asteraceae family *G. aristata* is native to North and South America. Among the flowers used for domestic market, *gaillardia* is one of the important commercial flowers. Inflorescences are mono and bi-coloured in red, yellow and rusty brown, etc. It is used in the decoration of gardens in flower borders combined with other types of flowers (Wunderlin 1998).

Gaillardia pulchella Foug. is a short-lived perennial native to North America (Eastern and South-central US and Mexico). Corollas are usually reddish to purplish proximally, yellow to orange distally, rarely yellow, reddish, or purplish throughout. It prefers sandy or calcareous soils, often disturbed places, mostly in grasslands or open places, in the range 0–1800 m a.s.l. Cultivars of *G. pulchella* or of hybrids between *G. pulchella* and *G. aristata* are used horticulturally (Flora of North America 2024).

Gaillardia × *grandiflora* hort. ex Van Houtte is a tetraploid hybrid resulting from a cross between perennial *G. aristata* and *G. pulchella*, inheriting its perennial habit from the former and its long flowering period and rapid growth rate from the latter. It is perennial but generally short-lived. The stems and leaves are densely hairy. The flowers are often bicoloured and daisy-like in a wide variety of colour arrangements, but usually featuring yellow to orange to red rays with maroon to orange banding at the petal bases and dark burgundy centre disks. There are several cultivars available to extend the colour and height availability (North Carolina State University 2024).

The purpose of the study was to evaluate the blooming stage and vegetative

growth parameters for 12 perennials flowering taxa of *Digitalis purpurea* and *Gaillardia* sp. in the agro-ecological conditions of Kosovo.

Materials and Methods

During the 2022–2023 growing periods, the object of research in our experimental field were the following 12 perennial flowering taxa: six cultivars of *Digitalis purpurea* ('Polkadot Polly', 'Illumination Flame', 'Mountains Mixed', 'Rose Shades', 'Pam's Choice', and 'Excelsior Mix'); three cultivars of *Gaillardia aristata* ('Oranges and Lemons', 'Arizona Apricot', and 'Arizona Sun'); two hybrids – *Gaillardia* × *grandiflora* 'Summer Kiss' and *G. × grandiflora* hort.; and *Gaillardia pulchella*. Plans of all these 12 taxa were studied for the main growth characteristics and flowering stage: beginning and end of flowering stage, features of petal fusion based on number of protrusions on the corolla edge; flower opening stage, colour of flowers; dynamic of growth in length of flower stems (in cm, average value); diameter of flower stalk (in mm, average value), number of flower stems per plant (average) and fragrance of flowers. The results of the study are presented as an average for two growing periods (2022–2023).

The distillation method was used to determine the fragrance of flowers. The distillation method is a process used to extract the aromatic essence from flowers and plants. This method involves evaporating water, which extracts the essential oils from the plant materials, and then condensing the steam to separate the distilled oils from the water (Tisserand 2004).

The experiment was 'Randomized block' type with four replications and 200 plants for each cultivar. Plant seedlings

were produced in greenhouses and then planted in the ground in April 2022. Plant seedlings were 10 cm tall and had 3–4 leaves, without flower buds. The planting distance between the plants was 30 cm, while between the rows was 80 cm. The plants were planted in sandy soil and irrigated during the growth period by drip irrigation system.

The average monthly temperature during the growing period was in April (12.2 °C), May (17.7 °C), June (19.9 °C), July (23.0 °C), August (21.9 °C) and in September the average temperature was 18.9 °C. The precipitation amount during the growing period was 27.3 mm in April, 83.0 mm in May, 99.0 mm in June, 60.0 mm in July, 42.9 mm in August and in September the average of precipitation was 32.5 mm (HMIK 2022).

For all data, an analysis of variance was applied using the statistical package, Systat, Genstat, further analysed using rang test with a critical level (*P*-value) of 5% (Gomez and Gomez 1984).

The study was carried out in the urban space in Prizren, Republic of Kosovo, in two growing periods from April 2022 to October 2023, in an area 1200 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 municipality of Prizren has an area of 627 km² (5.94 % of the territory of Kosovo), which is located in the southwest of Kosovo with 76 settlements with about 175,000 inhabitants. The Prizren plain is located at an altitude of 400 m a.s.l., where some peaks of Sharri Mountain exceed the height of 2000 m a.s.l.

The climate of the city is moderate but extremely diverse in its different parts. In the lowlands, due to the influence of the

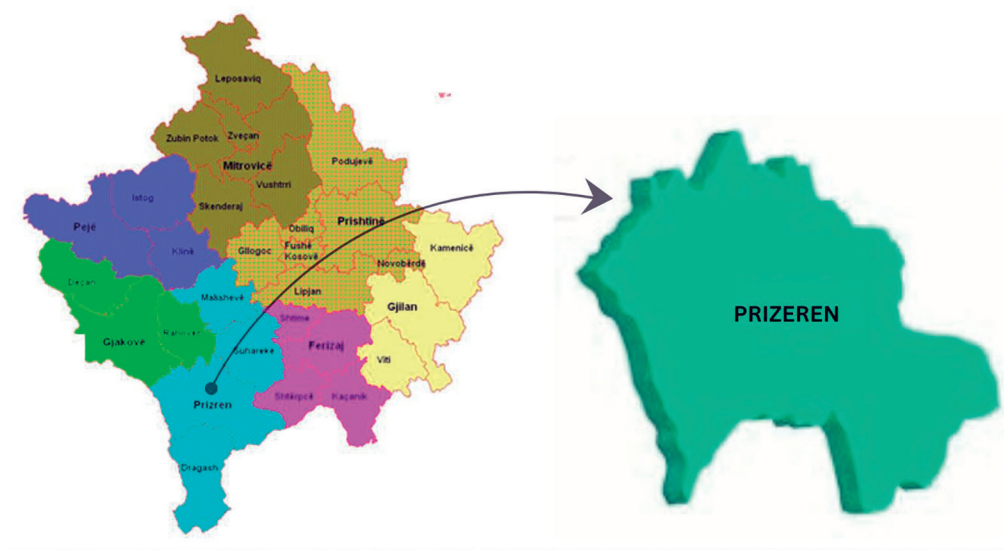


Fig. 1. Study area.

Mediterranean, there are very hot summers, with an average temperature of 28–32 °C during July and August and the harvests are among the first in South-Eastern Europe. In the mountainous regions, the climate of the Alps dominates, for this reason snow caps on peaks are visible until June.

Results and Discussion

The average results from the two years of the study (2022–2023) are shown below.

Flowering stage of *Digitalis purpurea* cultivars

The beginning and duration of flowering were different in the two years of the study, this was influenced by different meteorological parameters (temperatures and precipitation, which were different in the two growing periods). Dynamics of flowering stage of *Digitalis purpurea* cultivars during the May–October period was

analysed. For all studied cultivars flowering stage starts in mid of May and varies depending on cultivars. There is also a different number of flowers: 5–8 for each plant. Number of flowers in May was different depending on the cultivars. The highest was achieved at the cultivar 'Rose Shades' with 8 flowers per plant. The lowest, with 5 flowers was at the cultivar 'Illumination Flame'. Number of flowers per plant in this study begins to increase in June and the highest is achieved at the cultivar 'Polkadot Polly', 23 flowers per plant, while the lowest at the cultivar 'Illumination Flame' – 17 flowers per plant (Fig. 2).

Maximum number of flowers is achieved in July, depending on the cultivars. The peak was achieved at the cultivar 'Rose Shades' with 48 flowers per plant, whereas the lowest number of flowers – 44 was observed at the cultivar 'Pam's Choice'. The flowering period ends in late October depending on the decrease of temperature. The smallest number of flowers was achieved at the 'Illumination

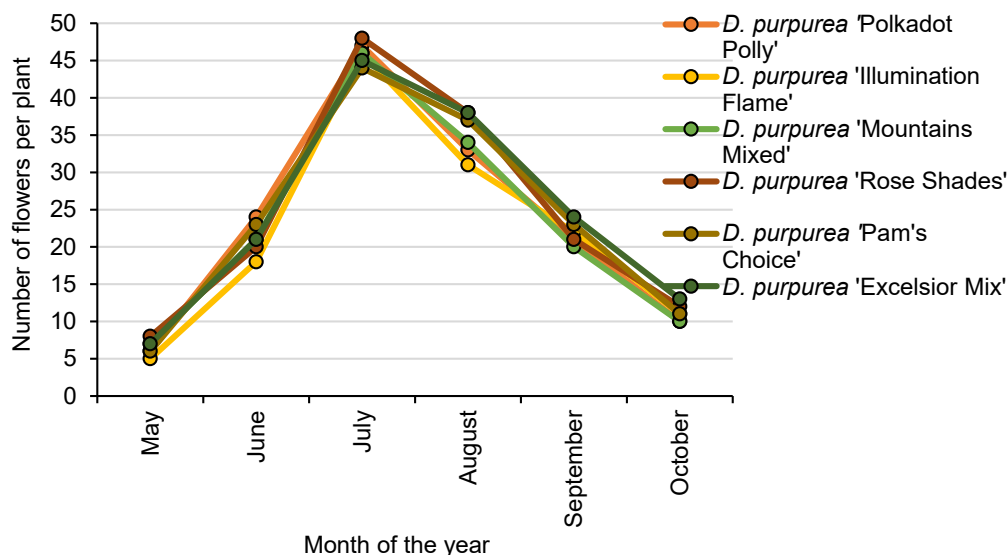


Fig. 2. Dynamic of flowering stage for the *Digitalis purpurea* cultivars.

Flame' with 10 flowers per plant and the highest at cultivar 'Excelsior Mix' with 13 flowers per plant.

Similar results concerning the number of flowers per plant were reported by Parkinson (2003), Pokorný et al. (2005), Bretzel and Pezzarossa (2010), Crespel et al. (2014).

Similar results were reported by Wolff et al. (2024), for the cultivar 'Rose Shades' which is famous cultivar for beautiful flowers. The author describes it as a tall plant that can reach up to 80–120 cm height and produces striking purple or pink flowers on tall spikes.

Flowering stage of *Gaillardia* sp.

The beginning and duration of flowering stage were different in the two growing periods (2022–2023), which were influenced by different meteorological factors, such as temperatures and precipitation. The flowering stage for all taxa in the study starts in the mid of May, the number

of flower heads was different depending on the cultivar. The highest was achieved at the cultivar *G. aristata* 'Oranges and Lemons' with 8 flower heads per plant. The lowest with 5 flower heads at the *G. aristata* 'Arizona Apricot'. The number of flower heads per plant begins to increase in June and the highest is achieved at the cultivar *G. aristata* 'Arizona Sun' 18, while the lowest one is observed at *G. pulchella*: 14 flowers per plant. The highest was achieved at the *G. × grandiflora* hort. with 32 flower heads per plant, the lowest one with 28 flower heads at *G. pulchella* (Fig. 3).

Flowering ends in late October depending on the decrease of temperature. The smallest number of flowers was achieved at the *G. × grandiflora* 'Summer Kiss' with 3 flower heads per plant and the highest at cultivar *G. aristata* 'Oranges and Lemons' with 5 flower heads per plant.

The results of the study for the flowering phase of *G. aristata* cultivars are in accordance with the studies of other au-

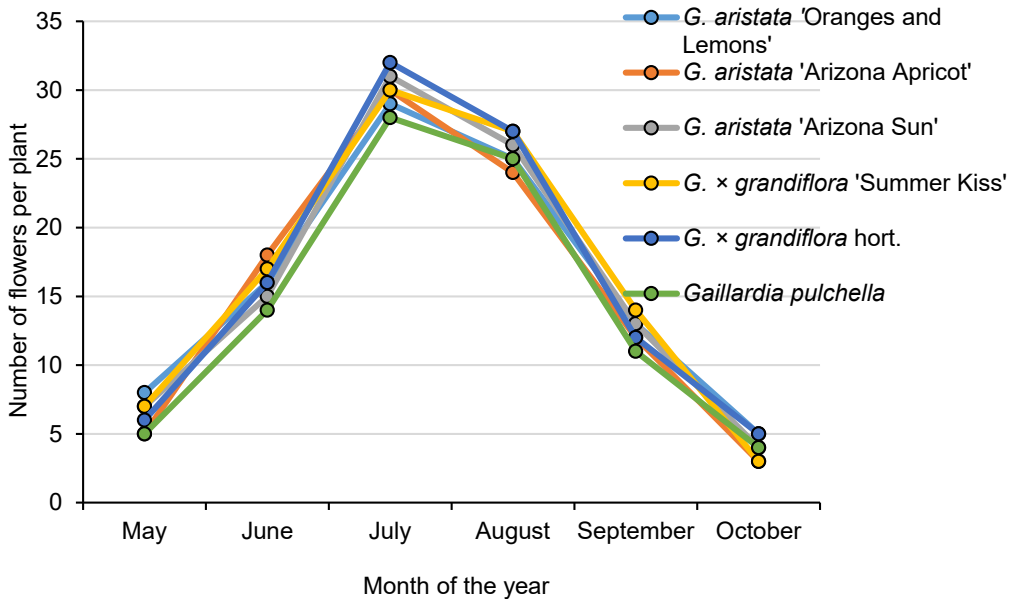


Fig. 3. Dynamic of flowering stage for the *Gaillardia* sp.

thors (Opler and Cranshaw 2008, Süle et al. 2023). The flower heads of *G. aristata* 'Arizona Sun' are radiating, showy, slightly solitary, with an outer series of ray florets and an inner set of disc florets. There are usually 13–17 flowers with yellow rays (belt-shaped), with a purple base (eFloras 2011).

Structure of petal fusion (number of protrusions on the corolla edge), flower colour and fragrance of *Digitalis purpurea* cultivars

Table 1 shows the visible protrusions on the corolla edge, colour and fragrance of flowers according to cultivars. Largest number of them per flower was recorded from the cultivar 'Rose Shades' (6.18) followed by 'Polkadot Polly' (5.18) and low number of petals was recorded from 'Pam's Choice' (4.11). This indicator is important especially when plants are perceived close up or used as a cut-flowers.

The colour of the flowers is different from white, red, pink, pink to white. The level of fragrance of the *Digitalis purpurea* cultivars was a low.

Number of ligules in the flower heads colour and fragrance of *Gaillardia* sp.

Table 2 shows the number of ligules (or ray flowers), flower colour and fragrance for the *Gaillardia* taxa in the study. Largest number of ligules per flower was recorded from the cultivar *G. aristata* 'Arizona Apricot' (25.45) followed by *G. x grandiflora* hort. (24.32) and low number of ligules was recorded from *G. x grandiflora* 'Summer Kiss' (19.34). The colour of the ligules is different from white, red, pink, pink to white. Three cultivars of *G. aristata* ('Orange and Lemon', 'Arizona Apricot' and 'Arizona Sun'), two hybrids – *G. x grandiflora* 'Summer Kiss' and *G. x grandiflora* hort., and *G. pulchella*, had fragrant flowers.

Table 1. Average number of petals, flower colour and fragrance of *Digitalis purpurea* cultivars.

<i>Digitalis purpurea</i> cultivars	Number of protrusions on the corolla edge	Flower colour	Fragrance of flowers
'Polkadot Polly'	5.23	Deep-pink apricot	Little fragrance
'Illumination Flame'	5.18	Orange and cream	Little fragrance
'Mountains Mixed'	4.26	Peach, rose, white	Little fragrance
'Rose Shades'	6.18	Rose-white	Little fragrance
'Pam's Choice'	4.11	White	Little fragrance
'Excelsior Mix'	5.45	Rose-white	Little fragrance

Table 2. Number of ligules, flower colour and fragrance of *Gaillardia* sp.

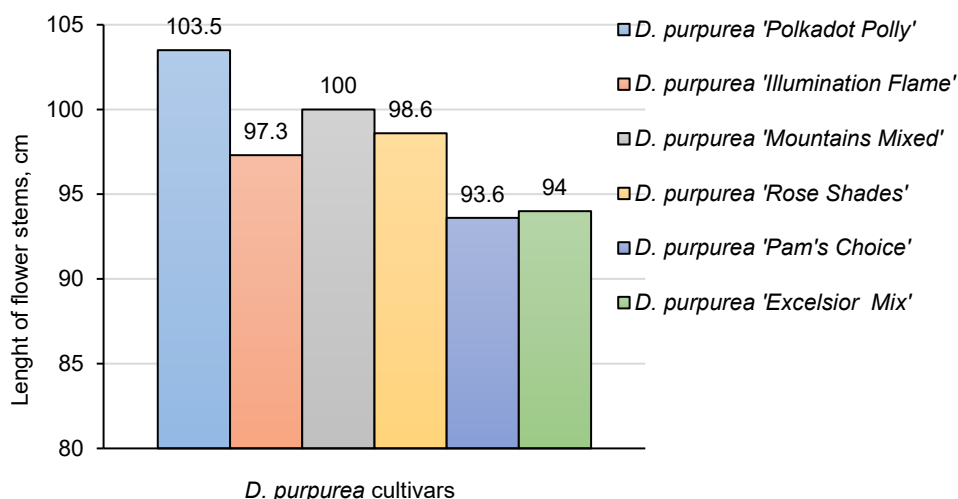
<i>Gaillardia</i> taxa	Number of ligules per flower heads	Flower ligules	Fragrance of flowers
<i>G. aristata</i> 'Oranges and Lemons'	23.33	Soft orange	With fragrance
<i>G. aristata</i> 'Arizona Apricot'	25.45	Apricot with yellow	With fragrance
<i>G. aristata</i> 'Arizona Sun'	22.21	Yellow-apricot	With fragrance
<i>G. × grandiflora</i> 'Summer Kiss'	19.34	Soft apricot-yellow	With fragrance
<i>G. × grandiflora</i> hort.	24.32	Yellow-apricot	With fragrance
<i>Gaillardia pulchella</i>	23.65	Apricot-yellow	With fragrance

Length and diameter of flower stems and number of leaves of *Digitalis purpurea* cultivars

The cultivar 'Polkadot Polly' produced the longest of flower stems (103.5 cm) fol-

lowed by 'Illumination Flame' (97.3 cm) and 'Pam's Choice' (93.6 cm) (Fig. 4).

The flower stems diameter with the highest values was recorded by 'Pam's Choice' (6.44 mm), followed by 'Illumina-

**Fig. 4. Length of flower stems of *Digitalis purpurea* cultivars.**

tion Flame’ (6.13 mm), while the lowest values were recorded in cultivar ‘Excelsior Mix’ (5.91 mm). The maximum number of leaves per shoots was recorded in ‘Polkadot Polly’ (22.57), followed by ‘Rose Shades’ (19.72) and the lowest number of leaves was recorded in ‘Mountains Mixed’ (15.39). Similar results were also

reported by (Willis et al. 2000, Niu et al. 2007).

Statistical results for two years (2022–2023) are presented in Table 3. Analysis of variance confirms that *D. purpurea* cultivars are statistically different regarding the length of flower stalk and number of flowers.

Table 3. Analysis of variance of *Digitalis purpurea* cultivars.

Sources of variation	Length of flower stalk		Number of flowers per plant	
	Value F	Probability	Value F	Probability
Year of study	1412.21	0.000	2431.23	0.000
Cultivar	1021.03	0.000	345.26	0.000
Cultivar × Year	23.11	0.000	11. 44	0.000

Length and diameter of flower stems and number of leaves of *Gaillardia* sp.

The cultivars *G. aristata* ‘Arizona Sun’ produced maximum of flower stems (60.52 cm) followed by *G. aristata* ‘Arizona Apricot’ (57.32 cm) and *G. pulchella* (51.64 cm). The flower stems diameter with the highest values was recorded by *G. aristata* ‘Arizona Apricot’ (3.58 mm), followed by *G. × grandiflora* ‘Summer Kiss’ (3.15 mm), while the lowest values

were recorded in *G. pulchella* (2.86 mm) diameter (Fig. 5).

The maximum number of leaves per shoots was recorded in *G. aristata* ‘Arizona Sun’ (14.21), followed by ‘Oranges and Lemons’ (12.25) and the lowest number of leaves was recorded in *G. × grandiflora* ‘Summer Kiss’ (11.21). Similar results were also reported by (Hermann 1996, Marlowe and Hufford 2007, Sonu et al. 2018, Xie et al. 2021, Zhuang et al. 2021) in gallardia. The *G. aristata* ‘Arizona Sun’ cultivar are

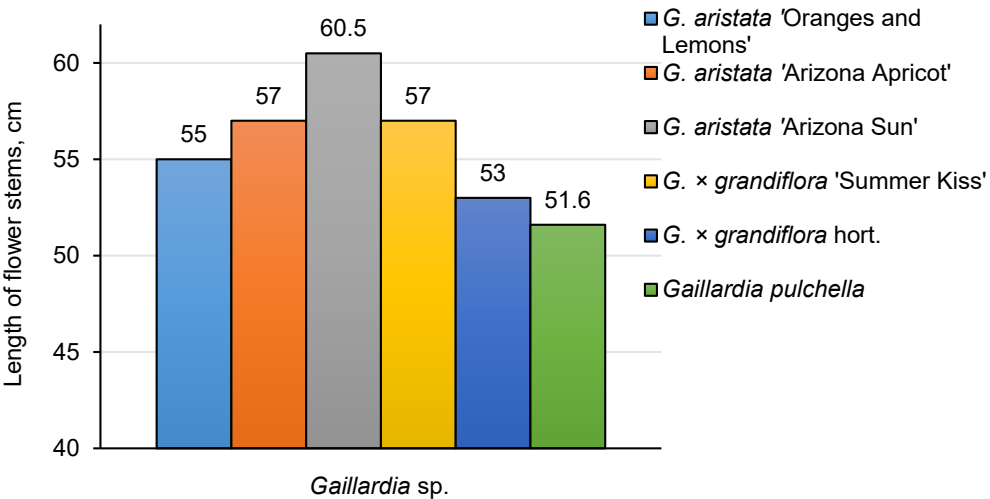


Fig. 5. Length of flower stems of *Gaillardia* sp.

reported to has masses of beautiful red daisy flowers with brick red eyes and yellow tips at the ends of the stems from early summer to mid fall, green leaves, which are most effective when planted in groupings (Kazemi and Jozay 2021).

Statistical results for two years (2022–2023) are presented in Table 4. Analysis of variance confirms that there are statistically differences regarding the length of flowerstalk and number of flowers of *Gaillardia* sp.

Table 4. Analysis of variance of *Gaillardia* sp.

Sources of variation	Length of flower stalk		Number of flowers per plant	
	F value	Probability	F value	Probability
Year of study	14351.41	0.000	2551.47	0.000
Cultivar	1033.22	0.000	324.38	0.000
Cultivar × Year	32.34	0.000	12.79	0.000

Conclusions

From the study and obtained results it is proved that the studied cultivars of *Digitalis purpurea* and *Gaillardia* sp. have a very good blooming and vegetative growth due to favourable climatic conditions in Kosovo, soil and moisture suitable for growth and development, which affected the growth, quality and colour of the flowers.

These perennial flowering plants and their cultivars deserve more important place in public green spaces, as their greater use is an important step towards greater sustainability in the urban landscape. The studied *Digitalis* cultivars and *Gaillardia* sp. differ from each other but all of them have demonstrated high ornamentality and long flowering period with flowers, steady growth, variety of leaves and flowers colouring (white, red, yellow, pink). The cultivars with the best performance are *D. purpurea* 'Rose Shades' and *G. aristata* 'Arizona Sun'.

Perennial flowering plants are more ecologically effective and less expensive to maintain, and are therefore more sustainable. For a good architecture and sustainability of the urban landscape, we recommend the studied cultivars to be

included in the design and planting structure in Kosovo.

Acknowledgements

All authors of this paper would like to express our great appreciation to Professor Agim Zajmi for his support during the work and the experiment phase of our study.

References

- ALMAS A.D., CONWAY T.M. 2016. The role of native species in urban forest planning a practice: A case study of Carolinian Canada. *Urban Forestry & Urban Greening* 17: 54–62. <https://doi.org/10.1016/j.ufug.2016.01.015>
- BRETZEL F., PEZZAROSSA B. 2010. Sustainable Management of Urban Landscapes with Wildflowers. *Acta Horticulturae* 881: 213–219. <https://doi.org/10.17660/Acta-Hortic.2010.881.27>
- BALAJ N., RIZANI H., ZAJMI A. 2022. An ecological perspective on cities: The benefit of urban vegetation and parks in Prishtina city, Kosovo. *Ecologia Balkanica* 14(1): 79–85. <http://web.uni-plovdiv.bg/mollov/EB/2022>
- CRSPEL L., LE BRAS C., RELION D., MOREL

- P. 2014. Genotype × year interaction and broad-sense herability of architectural characteristics of rose bush. *Plant Breeding* 133(3): 412–418. <https://doi.org/10.1111/pbr.12157>
- EFLORAS 2011. *Gaillardia*. Flora of North America, vol. 21, Asteraceae. Web site. http://www.efloras.org/florataxon.aspx?flora_id=1&taxon_id=113131
- FLORA OF NORTH AMERICA 2024. *Gaillardia pulchella* Fougeroux, 1788. Vol. 21: 421, 422, 425. http://www.efloras.org/florataxon.aspx?flora_id=1&taxon_id=200023953
- GOMEZ K.A., GOMEZ A.A. 1984. Statistical procedures for Agricultural Research. 2nd edn. John Wiley and Sons, New York. 680 p.
- DINGA L. 1988. Ornamental plants of the open field [Bimët zbukuruese të fushës]. Tirana Higher Agricultural Institute, Tirana. 123 p. (in Albanian).
- HERMANN F.J. 1966. Notes on Western Forbs. United States Department of Agriculture-Forest Service. Agriculture Handbook No. 293. U.S. 110 p.
- HMIK (HYDRO METEOROLOGICAL INSTITUTE OF Kosovo) 2022. Hydrometeorological Yearbook of Kosovo. Ministry of Environment and Spatial Planning, Prishtina, Kosovo. 31 p.
- KAZEMI F., JOZAY M. 2021. Characteristics of ornamental-medicinal species of balanket flower (*Gaillardia aristata*) under different mulch treatments in an arid climate region. *Crop Science Research in Arid Regions* 2(2): 267–279. doi: 10.22034/CS-RAR.2021.208943.1062
- LINDEMANN-MATTHIES P., JUNGE X., MATTHIES D. 2010. The Influence of Plant Diversity on People's Perception and Aesthetic Appreciation of Grassland Vegetation. *Biological Conservation* 143(1): 195–202. <https://doi.org/10.1016/j.biocon.2009.10.003>
- LUSHI I., BALAJ N., HAXHINASTO L., ZHITIA O. 2009. The study of some hybrids of tomatoes in sun greenhouses on Kosovo. *Acta Horticulturae* 830: 163–168. <https://doi.org/10.17660/ActaHortic.2009.830.21>
- MARLOWE K., HUFFORD L. 2007. Taxonomy and Biogeography of *Gaillardia* (Asteraceae): A Phylogenetic Analysis. *System Botany* 32(1): 208–226. <https://doi.org/10.1600/036364407780360229>
- NIU G., RODRIGUEZ D.S., AGUINIGA L. 2007. Growth and Landscape Performance of Ten Herbaceous Species in Response to Saline Water Irrigation. *Journal of Environmental Horticulture* 25(4): 204–210. <https://doi.org/10.24266/0738-2898-25.4.204>
- NORTH CAROLINA STATE UNIVERSITY 2024. *Gaillardia × grandiflora*. N.C. Cooperative Extension. Retrieved August 25, 2024. <https://plants.ces.ncsu.edu/plants/gaillardia-x-grandiflora>
- OPLER P.A., CRANSHAW W.S. 2008. Attracting Butterflies to the Garden. Online fact sheet no. 5.504. Colorado State University Extension, Fort Collins, Colorado, USA. <https://extension.colostate.edu/topic-areas/insects/attracting-butterflies-to-the-garden-5-504-2/>
- PARKINSON H. 2003. Landscaping with Native Plants of the Intermountain Region. Technical Reference No. 1730-3. USDI Bureau of Land Management, Boise, Idaho. 14 p. https://idahonativeplants.org/Guides/cover_p7.pdf
- POJE M., ŽIDOVEC V., PREBEG T., KUŠEN M. 2023. Does the Use of Perennials in Flower Beds Necessarily Imply Sustainability. *Plants* 12(24), 4113. 18 p. <https://doi.org/10.3390/plants12244113>
- POKORNY M.L., SHELEY R.L., ZABINSKI C.A., ENGEL R.E., SVEJCAR T.J., BORKOWSKI J.J. 2005. Plant functional group diversity as a mechanism for invasion resistance. *Restoration Ecology* 13(3): 448–459. <https://doi.org/10.1111/j.1526-100X.2005.00056.x>
- TISSERAD R. 2004. The Art of Aromatherapy. International Edition. C.W. Daniel. 320 p.
- QUALTROCCHI U. 2000. CRC world dictionary of plant names. CRC Press, New York, USA: 169–171.
- SONU K., SINGH A.K., SINGH A. 2018. Effect of plant growth regulators on growth and flowering characters of China aster (*Callistephus chinensis* L. Nees.) cv. Ostrich feather. *Journal of Pharmacognosy* 7(2): 3149–3153.
- SÜLE G., MIHOLCSA Z., MOLNÁR C., KOVÁCS-HOSTYÁNSZKI A., FENESI A., BAU-

- ER N., SZIGETI V. 2023. Escape from the garden: spreading, effects and traits of a new risky invasive ornamental plant (*Gaillardia aristata* Pursh). *NeoBiota* 83: 43–69. <https://doi.org/10.3897/neobiota.83.97325>
- WILLIS A.J., MEMMOTT J., FORRESTER R.I. 2000. Is there evidence for the post invasion evolution of increased size among invasive plant species? *Ecology Letters* 3(4): 275–283. <https://doi.org/10.1046/j.1461-0248.2000.00149.x>
- WITTING R. 1998. Flora und Vegetation. In: Sukopp H. and Wittig R. (Eds), *Stadtökologie*. Fischer, Stuttgart, Germany: 219–265.
- WOLFF K., FRIEDHOFF R., HORZ J.M., PUCKER B. 2024. Genome sequence of the medicinal and ornamental plant *Digitalis purpurea* reveals the molecular basis of flower color variation. *BioRxiv*, preprint server for Biology. 22 p. <https://doi.org/10.1101/2024.02.14.580303>
- WUNDERLIN R.P. 1998. *Guide to the vascular plants of Florida*. Gainesville, FL: University Press of Florida. 806 p.
- XIE J., LIU B., ELSADEK M. 2021. How Can Flowers and Their Colors Promote Individuals' Physiological and Psychological States during the COVID-19 Lockdown? *International Journal of Environmental Research and Public Health* 18(19), 10258. 15 p. <https://doi.org/10.3390/ijerph181910258>
- ZHUANG J., QUAO L., ZHANG X., SU Y., XIA Y. 2021. Effects of Visual Attributes of Flower Borders in Urban Vegetation Landscapes on Aesthetic Preference and Emotional Perception. *International Journal of Environmental Research and Public Health* 18(17), 9318. 13 p. <https://doi.org/10.3390/ijerph18179318>

Effect of the structural composition of a Saharan agricultural landscape on bird communities in the Algerian Northern Sahara

Oussama Bekakra¹, El-Yamine Guergueb^{2*}, Soumia Haddad²,
Yassine Noudjem³, Choayb Bounab², and Hichem Khammar⁴

¹Laboratory of Materials, Energy Systems, Technology and Environment,
University of Ghardaia, Ghardaia 47000, Algeria.

²Laboratory of Valorisation and Conservation of Arid Ecosystems (LVCAE), Faculty of Natural
Sciences, Life and Earth Sciences, University of Ghardaia, Ghardaia 47000, Algeria.

*E-mail: guergueb@univ-ghardaia.dz

³University of M'sila, University Pole, Road Bourdj Bou Arreiridj, M'sila 28000, Algeria.

⁴Laboratory of Functional Ecology and Environment, LFEE, University of Oum El Bouaghi,
Algeria.

Received: 18 September 2024 / Accepted: 26 October 2024 / Available online: 07 November 2024



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

Abstract

In this study, we examined the diversity of bird populations in an agricultural environment in Northern Algerian Sahara (Ghardaia province) over a period of 9 months. Using the point count technique, we collected data on birds at different levels of vertical stratification based on the number of cultivated plant species. An analysis of variance was used to assess the impact of plant strata number and cultivated species number on species richness and bird abundance. During this study, 35 bird species belonging to 7 orders and 18 families were identified. The highest values of Shannon-Wiener diversity index ($H' = 2.804$), Simpson index ($D = 0.913$), and Margalef index ($D = 4.761$) were observed in the most complex areas. The differences in the number of species and abundance were significant between the different levels of complexity in agricultural environments, with areas having three vertical plant strata (trees, shrubs, and herbaceous plants) and a greater number of cultivated plant species hosting the highest number of bird species and displaying high populations.

Key words: agroecosystem, arid environment, diversity index, Ghardaia, vertical stratification.

Introduction

Agroecosystems cover about 40 % of Earth's land surface (Allen et al. 2022) and cover almost half European Union's surface (Bakiş et al. 2021), forming one of

the most important terrestrial biomes (Foley et al. 2005). Such man-made ecosystems may comprise a variety of ecological conditions and habitats suitable havens for various living beings (Eriksson 2021).

The traditional agroecosystems in

the North African arid and semi-arid regions are the most biotically diversified in the world, the majority being constituted of small private gardens (Sellami 2008). These agricultural lands represent semi-natural ecosystems that may be very complex and include three layers of crops: date palm, fruit trees, and market gardening, surrounded by a harsh desert environment (Mellink 1991, Selmi 2007). The combination of layers of crops in these agricultural landscapes has been found to have a very peculiar and high level of fauna and flora (Tscharntke et al. 2011, Hagggar et al. 2019).

Agriculture is a driver decline in global biodiversity and ecosystem degradation than any other sector (Foley et al. 2005, Muñoz-Sáez et al. 2017), including birds (Mellink et al. 2016). According to IUCN data about 60 % of birds included in Red List are threatened by extinction (Johnson et al. 2011, Piratelli et al. 2019) and almost 39 % of farmland bird populations have declined (Gianpasquale and Alberto 2019, Mäkeläinen et al. 2019).

Birds use Saharan agroecosystems for resting and feeding during their trans-Saharan migrations (Lavee et al. 1991, Guezoul et al. 2013), and nesting and foraging during the breeding season (Mellink 1991, Johnson et al. 2011). They play a critical role in these ecosystems, including seed dispersal and pest control (Mulwa et al. 2012). Birds in agricultural environments are a bioindicator of agricultural sustainability (Kross et al. 2016, Muñoz-Sáez et al. 2017).

Several factors influence the structure of avian communities (richness and abundance) in Saharan agroecosystems, including landscape composition (Naidoo 2004, Muñoz-Sáez et al. 2017), habitat change (Shachak et al. 2005, Laube et al. 2008, Chillo et al. 2015) crop type

and their structural heterogeneity (Muñoz-Sáez et al. 2017).

The present study aims to establish the diversity of bird populations in an agricultural environment in Northern Algerian Sahara. To achieve the goal, we set ourselves the following 3 tasks: 1) to describe the avian diversity (species richness and abundance) of a Saharan agricultural landscape; 2) to assess the effects of crop change on the spatial distribution of bird species and their densities; and 3) the role of vertical stratification of vegetation (date palm, fruit trees, and market gardening) on the aggregation of bird populations.

Material and Methods

Study area

This study was carried out in El-Guerrara region (in Central Algeria, north of the Sahara, 600 km south of Algiers). This area is located within the geographical position of 32°45'70" to 32°46'30" northern latitudes and 04°27' to 04°33' eastern longitudes (Guergueb et al. 2024). The climate is arid, characterised by mild winters and hot, dry summers (mean annual temperature 23.27 °C, yearly mean rainfall 80.10 mm) (Bounab et al. 2024, Nedjar et al. 2024).

The study area is an agricultural landscape comprising a 200-hectare mosaic of small private fields (Fig. 1). The vegetation is dominated by date palms (*Phoenix dactylifera* L.), along with fruit trees such as olive, pomegranate, and orange trees. Market gardening is also common, featuring various vegetable crops, including tomatoes, peppers, and cucumbers. Additionally, spontaneous herbaceous plants grow naturally in the uncultivated spaces.

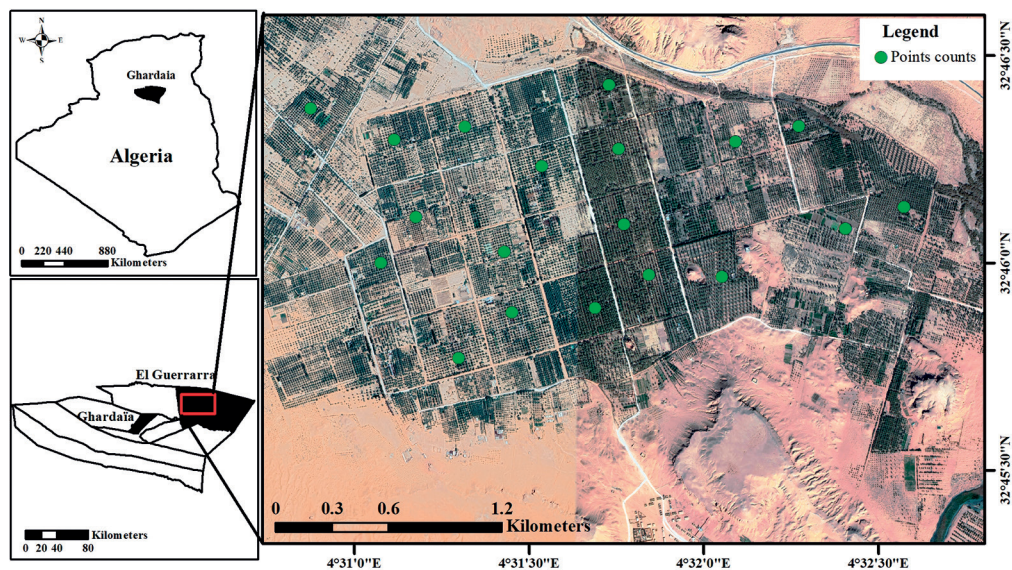


Fig. 1. Study area map with sampling locations.

Bird sampling

We collected our data between October 2022 and June 2023, and bird communities were estimated using the point-count sampling method (Bibby et al. 2000). Nineteen point count sites were randomly distributed to cover the entire study area (radius 50 m, each spaced 300 m apart) (dos Anjos et al. 2011, Hiron et al. 2013, Hamza and Hanane 2021). Each point has a bi-monthly visit, between 30 min before sunrise and 4 h after (Kang et al. 2015, Bouam et al. 2017) to coincide with periods when birds are most active (Terraube et al. 2016). Each point was surveyed for 10 min (Marsden et al. 2001, Jacoboski et al. 2016, Hanane et al. 2019). During this period we recorded all birds seen or heard (Sweeney et al. 2010, Boesing et al. 2018).

To assess the impact of the structural complexity of each habitat (defined by the number of cultivated species and number of vertical strata of vegetation) on avian

communities, it is necessary to conduct a comprehensive inventory of cultivated species within a 50 m radius around the observation points. These cultivated species should be categorised into three vertical strata: trees taller than 2 m (such as date palms), shrubs between 50 cm and 2 m (such as fruit trees), and ground cover under 50 cm (such as crops in market gardening).

Data analysis

We categorised the bird species based on their trophic guilds (Granivore, Insectivore, Omnivore, Carnivorous) following Svensson et al. (2012) and their phenological status (Wintering, Breeding, Migration) using the following sources: The Sibley Guide to Birds (Sibley 2014), and their conservation status was determined (LC: Least Concern), (IUCN 2023).

The diversity indices of species, such as Shannon-Weiner index (H') (Speller-

berg and Fedor 2003), Simpson index (D) (Simpson 1949), and Margalef index (D) (Magurran 1988) have been calculated to compare species diversity and abundance among the complexity levels of the vertical stratification of the agroecosystem using a one-way analysis of variance (ANOVA). In addition, a two-factor ANOVA was conducted to test the variations in bird richness and abundance based on the number of vegetation strata (one stratum, two or three strata) and the number of cultivated plant species. The R software was used for the analyses.

Results

Species diversity

During the nine months of study, a total of 35 species was encountered in the different surveyed habitats belonging to 7 orders, 18 families, and 27 genera. The order Passeriformes is the most represented with 12 families and 25 species, followed by Columbiformes with 4 species. The Coraciiformes have 2 species. The Pelecaniformes, Bucerotiformes, Falconiformes, and Strigiformes are weakly represented by one species each (Table 1).

Table 1. Bird phenology status, trophic guild, and conservation status of recorded species.

Family	Scientific name	Ecological status			Occupied habitats		
		PhS	TG	CS	low	medium	high
Ardeidae	<i>Bubulcus ibis</i> (Linnaeus, 1758)	M	I	LC	+	+	+
Falconidae	<i>Falco tinnunculus</i> (Linnaeus, 1758)	B	Cr	LC	+	-	+
Columbidae	<i>Columba livia</i> (Gmelin, JF, 1789)	B	G	LC	+	+	+
	<i>Streptopelia decaocto</i> (Frivaldsky, 1838)	B	G	LC	+	+	+
	<i>Streptopelia senegalensis</i> (Linnaeus, 1766)	B	G	LC	+	+	+
	<i>Streptopelia turtur</i> (Linnaeus, 1758)	B	G	VU	-	+	+
Tytonidae	<i>Tyto alba</i> (Scopoli, 1769)	B	Cr	LC	+	-	-
Meropidae	<i>Merops apiaster</i> (Linnaeus, 1758)	M	I	LC	-	-	+
	<i>Merops persicus</i> (Pallas, 1773)	B	I	LC	-	+	+
Upupidae	<i>Upupa epops</i> (Linnaeus, 1758)	B	I	LC	+	+	+
Alaudidae	<i>Ammomanes deserti</i> (Lichtenstein, MHC, 1823)	B	I	LC	+	-	-
	<i>Galerida cristata</i> (Linnaeus, 1758)	B	G	LC	+	-	+
	<i>Galerida theklae</i> (Brehm, AE, 1857)	M	G	LC	+	+	-
Hirundinidae	<i>Hirundo rustica</i> (Linnaeus, 1758)	W	I	LC	+	+	+
Motacillidae	<i>Anthus pratensis</i> (Linnaeus, 1758)	W	I	LC	-	+	+
	<i>Motacilla alba</i> (Linnaeus, 1758)	W	I	LC	-	-	+

Family	Scientific name	Ecological status			Occupied habitats		
		PhS	TG	CS	low	medium	high
Muscicapidae	<i>Cercotrichas galactotes</i> (Temminck, 1820)	B	I	LC	-	+	+
	<i>Ficedula hypoleuca</i> (Pallas, 1764)	M	I	LC	-	+	+
	<i>Muscicapa striata</i> (Pallas, 1764)	M	I	LC	-	+	+
	<i>Oenanthe leucopyga</i> (Brehm, 1855)	B	I	LC	+	+	+
	<i>Oenanthe leucura</i> (Gmelin, 1789)	M	I	LC	+	+	+
	<i>Phoenicurus moussieri</i> (Olphe-Galliard, 1852)	B	I	LC	-	+	+
Sylviidae	<i>Saxicola rubicola</i> (Linnaeus, 1766)	W	I	LC	-	+	-
	<i>Argya fulva</i> (Desf, 1789)	B	I	LC	+	+	+
	<i>Curruca melanocephala</i> (Gmelin, 1789)	W	I	LC	+	+	+
Acrocephalidae	<i>Iduna pallida</i> (Hemprich & Ehrenberg, 1833)	B	I	LC	-	+	+
Phylloscopidae	<i>Phylloscopus collybita</i> (Vieillot, 1817)	W	I	LC	-	+	+
	<i>Phylloscopus sibilatrix</i> (Bechst, 1793)	M	I	LC	-	+	+
	<i>Phylloscopus trochilus</i> (Linnaeus, 1758)	M	I	LC	-	+	+
Laniidae	<i>Lanius excubitor</i> (Linnaeus, 1758)	B	I	LC	+	+	+
	<i>Lanius meridionalis</i> (Temminck, 1820)	B	I	LC	-	-	+
Corvidae	<i>Corvus ruficollis</i> (Lesson, 1831)	B	O	LC	+	-	-
Passeridae	<i>Passer domesticus</i> (Linnaeus, 1758)	B	O	LC	+	+	+
Fringillidae	<i>Bucanetes githagineus</i> (Lichtenstein, MHC, 1823)	B	G	LC	+	+	+
Emberizidae	<i>Emberiza sahari</i> (Levaillant, 1850)	B	G	LC	+	+	+

Note: PhS: phenology status, B: breeding, W: wintering and M: migrant; TG: trophic guild, I: insectivorous, G: granivorous, O: omnivorous, Cr: carnivorous; CS: conservation status, LC: least concern, VU: vulnerable (IUCN 2023); -: absent species, +: present species.

In terms of species recorded by family, the most represented families are Muscicapidae with 18 % of the total number of species, followed by the family Columbidae with 12 %, the family Phylloscopidae and Alaudidae with 9 %. The families Sylviidae, Laniidae, Motacillidae and Meropidae, each account for 6 % of the species (Fig. 2).

The documented species as a whole

have different phenological statuses. Among them, 60 % are breeding, 23 % are migratory, and 17 % have a wintering status in the region.

Regarding trophic guilds, Insectivorous represented 65 % (23 species) of the total avifauna, Granivorous were listed with 8 species (23 %). Omnivorous and Carnivorous included 2 species, 6 % of all recorded birds.

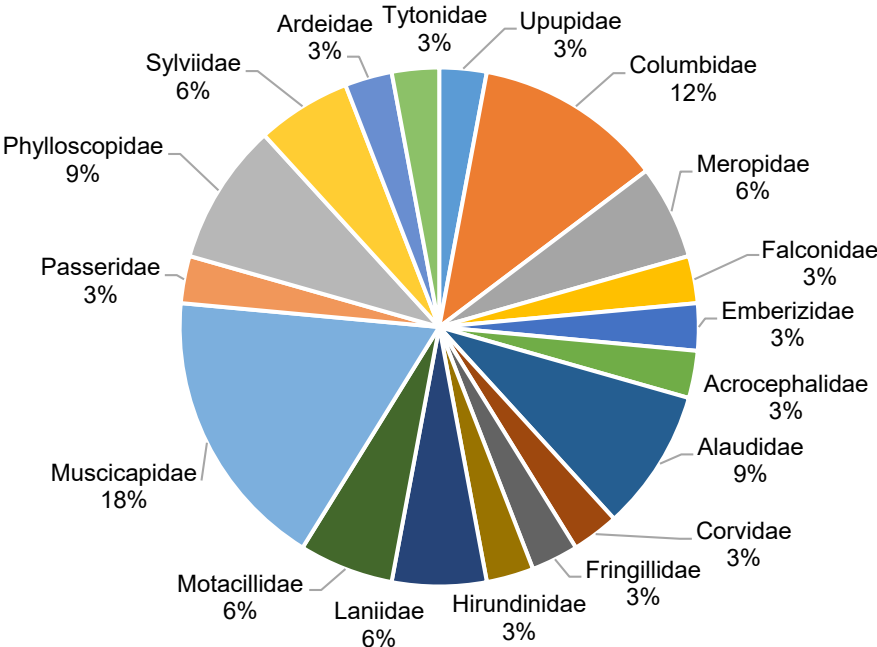


Fig. 2. Species richness and percentage of avian families recorded in El-Guerrara agroecosystem.

According to the BirdLife Red List (IUCN 2023), 97 % of reported species have a conservation status of LC (Least Concern) (Table 1).

Habitat richness

The results of the bird community composition parameters (Species richness) as well as the analysis of their diversity (Shannon-Wiener index, Margalef index, Simpson index, and evenness index) are represented in Table 2.

Among the 35 species identified in our

studied agroecosystems, only 20 species were observed in the least complex environments with a monoculture (one vegetation layer) during the study. Habitats with a more or less high level of complexity with two cultivated vegetation layers have a bird richness of 27 species. The sites with a high structural complexity, combining three vegetation layers and larger cultivated plant species, were the most visited, with a total of 30 species (Table 2).

A Venn diagram (Fig. 3) shows that, during our study period, three bird species were considered exclusive to low structur-

Table 2. Avian diversity among studied habitats.

Indicator	Low complexity	Medium complexity	High complexity
Number of taxa	20	27	30
Shannon-Wiener	2.284	2.591	2.804
Simpson	0.861	0.894	0.913
Margalef	3.458	4.192	4.761

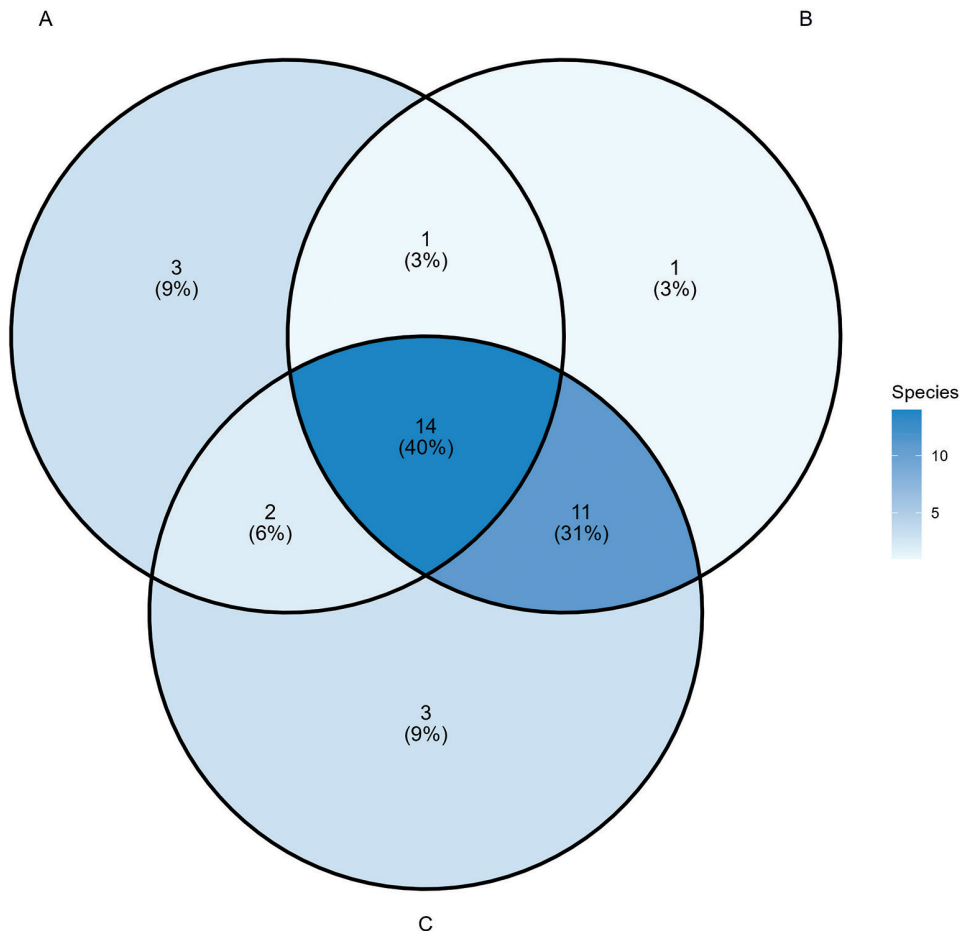


Fig. 3. Venn diagram of species richness among the three levels of crop complexity: A) low complexity, B) medium complexity, C) high complexity.

al complexity plots, one species to medium complexity plots, and three species in the most complex areas. High and medium complexity areas shared 11 species, or 31 % of all species encountered, while low complexity areas shared one species with medium complexity areas and two species with high complexity areas. Finally, 14 species (40 %) were present in all three levels of complexity.

In total, we recorded 1592 birds distributed across the studied zones, with the species having the largest numbers of in-

dividuals being the Rock Pigeon (*Columba livia* Gmelin, JF; $n = 369$), the House Sparrow (*Passer domesticus* L.; $n = 351$), the House Bunting (*Emberiza sahari* J. Levaillant; $n = 169$), and the Tawny Rock Thrush (*Argya fulva*; $n = 139$). However, the different studied habitats were dominated by the same species (Fig. 4).

The application of one-way ANOVA test showed highly significant differences for the number of species ($F = 12.47$, $p = 0.000013$) and for abundance ($F = 15.79$, $p = 0.000001$) among the three

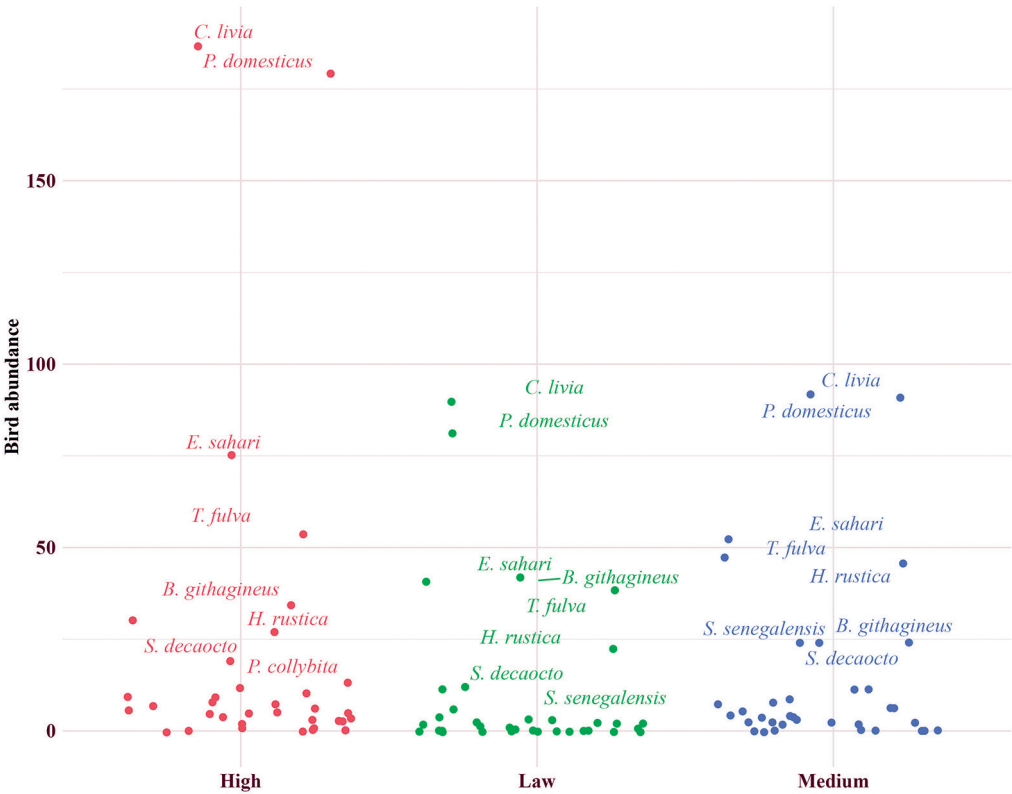


Fig. 4. Rank abundance plot, evidencing the most abundant bird species recorded.

studied habitats. In order to understand the effect of the number of layers and the number of cultivated plant species on bird richness and abundance, we conducted a two-factor ANOVA analysis. The number of layers has a highly significant effect on bird richness ($p=0.0000$) and on bird abundance ($p=0.0000$). The crops richness has a significant effect only on bird abundance ($p=0.006$), and the interaction (number of layers-crops richness) has no significant effect on either bird richness or abundance (Table 3).

Discussion

Our original results on the avian diversity of agricultural environments in a Saharan

region located in the middle of a rocky desert show that these environments and their structural complexity play a crucial role in the species richness, abundance, and spatio-temporal occupation of these habitats by breeding birds or trans-Saharan migrants, whether during their winter stay or their passage through the region.

A total of 35 bird species were recorded in the different levels of structural complexity of the agricultural landscape over the nine months, representing 10 % of the 350 species listed by Ledant et al. (1981), or 17.24 % of the total number of species documented by Chedad et al. (2023) after five years of study in the same region. These results are similar to those mentioned by Guerbouz et al. (2024) during their survey of bird populations in rural

Table 3. Two-way ANOVA testing variation of number of species and abundance according to layers, crops richness and their interaction.

Variable sources	Df	SS	MS	F	p
Species					
Layers	1	110.1	110.14	16.568	0.0000887
Crops richness	1	7.9	7.94	1.195	0.2767
Interaction	1	23.1	23.14	3.480	0.0648
Residuals error		731.2	6.65		
Abundance					
Layers	1	4098	4098	14.682	0.000212
Crops richness	1	2117	2117	7.584	0.006891
Interaction	1	496	496	1.778	0.185132
Residuals error	110	30704	279		

Note: Df is Degrees of Freedom, SS is Sum of Squares, MS is Mean Square.

habitats along an urban gradient in the city of Ghardaia, during the same period (38 species).

The avian richness recorded in our study area seems to be more or less comparable to that of other studied Saharan agroecosystems in Algeria. Guezoul et al. (2013) documented 47 species in the oases of Biskra in 2006, 44 species in the oases of Ouargla in 2008, and 33 species in the same habitats of Oued Souf region in 2009, with a total richness of 59 species in this region of the northeastern Algerian Sahara.

Ababsa et al. (2013), during their surveys in Ouargla region, mentioned that the total richness recorded in Mekhadema palm grove is 34 species, while only 28 species were inventoried at Hassi Ben Abdallah station, with a total richness of 43 species in the region.

Among the 35 species recorded in the surveyed agricultural environment, the species with reproductive status are the most abundant – 21. This represents over 50 % of the species with same status reported by Chedad et al. (2023), and similar to the results published by Guerbouz et al. (2024), collected during the same

period in the urban gradient of the city of Ghardaia. Eight species have a migratory status, using the region as a stopover during their trans-Saharan migration, and six species are wintering in the region.

In the present study, we report the dominance of Muscicapidae and Columbidae, representing 30 % of the total number of species recorded, with 7 and 4 species respectively. Furthermore, the order Passeriformes is the most represented in the study area, with 12 families and 25 species. The city of Ghardaia hosts 8 species from the Muscicapidae family and 4 species from the Columbidae family, accounting for 25 % of the species encountered (Guerbouz et al. 2024). In the same region, according to Chedad et al. (2021), the avian population of the Noumerat green belt is dominated by Muscicapidae (13 species) and Alaudidae (7 species), representing 46.51 % of the total number of species. In M'Zab region, Muscicapidae (22 species), Scolopacidae (17 species), and Anatidae (14 species) represent 26 % of all reported species (Chedad et al. 2023).

The structural complexity of habitats studied, due to the number of layers, has

a significant effect on species distribution and bird abundance. The results indicate that habitats with a high level of complexity, characterised by the presence of the three vertical layers of crops and a more or less high number of cultivated plant species (palms, fruit trees, and vegetable crops), host the greatest number of species, followed by moderately and weakly complex areas. These results confirm the general trends observed by Ababsa et al. (2013), who linked the high avian richness of Mekhadema station in Ouargla to the great plant heterogeneity of this station, as well as the work of Blondel et al. (1973) and Blondel (1975), which specified that the richness of the avian community is closely linked to the physiognomy, vegetation form, and number of plant layers.

Conclusion

In conclusion, this study on the avifauna of Saharan agricultural environments in relation to their structural complexity highlights the importance of these environments for nesting, wintering, and trans-Saharan migratory birds during their stops in the region. The significant presence of breeding species in these agricultural landscapes underscores the ecological interest of this type of ecosystem for birds. Furthermore, the diversity of bird species and their abundance are strongly influenced by plant heterogeneity and the structural complexity of agroecosystems in the Ghardaia region.

Agroecosystems play a crucial role in biodiversity conservation in Saharan environments by providing varied habitats for numerous species. By promoting sustainable agricultural practices, these systems can support local wildlife and flora while meeting the food needs of the population.

References

- ABABSA L., SEKOUR M., SOUTTOU K., GUEZOUL O., DOUMANDJI S. 2013. Some Aspects of the Avifauna in Two Palm Groves of the Northern Sahara (Algeria) [Quelques aspects sur l'avifaune dans deux palmeraies du sahara Septentrional (Algérie)]. *Algerian Journal of Arid Environment* 3(1): 59–67. <https://journals.univ-ouargla.dz/index.php/AJAE/article/download/56/42>
- ALLEN W.J., BUFFORD J.L., BARNES A.D., BARRATT B.I.P., DESLIPPE J.R., DICKIE I.A., GOLDSON S.L., HOWLETT B.G., HULME P.E., LAVOREL S., O'BRIEN S.A., WALLER L.P., TYLIANAKIS J.M. 2022. A network perspective for sustainable agroecosystems. *Trends in Plant Science* 27(8): 769–780. <https://doi.org/10.1016/j.tplants.2022.04.002>
- BAKIŞ A.L.-P., MACOVEI I., BARROS P., GOMES C., CARVALHO D., CABRAL J.A., TRAVASSOS P., TORRES L., ARANHA J., GALAŢCHI L. D., SANTOS M. 2021. Is biodiversity linked with farm management options in vineyard landscapes? A case study combining ecological indicators within a hybrid modelling framework. *Ecological Indicators* 121, 107012. 12 p. <https://doi.org/10.1016/j.ecolind.2020.107012>
- BIBBY C.J., BURGESS N.D., HILL D.A., MUSTOE S. 2000. Bird census techniques. Elsevier. 2nd Edition. 302 p.
- BLONDEL J. 1975. Analysis of Bird Communities: Elements of an Ecological Assessment I. The Progressive Frequency Sampling Method (PFS) [L'analyse des peuplements d'oiseaux, éléments d'un diagnostic écologique I. la méthode des échantillonnages fréquentiels progressifs (EFP)]. *Revue d'Écologie* 29(4): 533–589.
- BLONDEL J., FERRY C., FROCHOT B. 1973. Avifauna and Vegetation: an Attempt at Diversity Analysis [Avifaune et végétation. Essai d'analyse de la diversité]. *Alauda* 41(1–2): 63–84.
- BOESING A.L., NICHOLS E., METZGER J.P. 2018. Land use type, forest cover and forest edges modulate avian cross-habitat spillover. *Journal of Applied Ecology* 55(3): 1252–1264. <https://doi.org/10.1111/1365->

- 2664.13032
- BOUAM I., BACHIR A.S., KATAYAMA N. 2017. Variation in Bird Assemblages Along an Agricultural Intensification Gradient: a Case Study of Olive Orchards in North-Eastern Algeria. *Ornithological Science* 16(2): 147–157. <https://doi.org/10.2326/osj.16.147>
- BOUNAB C., GUERGUEB E.-Y., HADDAD S., ABED A., ZOUATINE O., BIAD R., NOUIDJEM Y. 2024. First urban breeding of Trumpeter Finch *Bucanetes Githagineus* in the Sahara desert in Algeria. *Natural Resources and Sustainable Development* 14(1): 1–10. <https://doi.org/10.31924/nrds.v14i1.145>
- CHEDAD A., BELADIS B., BOUZID A., BENDJOU-DI D., GUEZOU O. 2021. Avian Biodiversity in an Artificial Environment: Case of the Noumerate Green Band, (Ghardaïa, Algerian Sahara). *Revue des BioRessources* 11(2): 94–107. <https://dspace.univ-ouargla.dz/jspui/bitstream/123456789/27451/1/B110211.pdf> Give the French title as in other cases
- CHEDAD A., BOUZID A., BENDJOU-DI D., GUEZOU O. 2023. Avifauna of M'Zab region (Ghardaïa, Algerian Sahara): checklist and overview of the current status. *Zoology and Ecology* 33(1): 22–35. <https://doi.org/10.35513/21658005.2023.1.4>
- CHILLO V., OJEDA R.A., ANAND M., REYNOLDS J.F. 2015. A novel approach to assess livestock management effects on biodiversity of drylands. *Ecological Indicators* 50: 69–78. <https://doi.org/10.1016/j.ecol-ind.2014.10.009>
- DOS ANJOS L., COLLINS C.D., HOLT R.D., VOLPATO G.H., MENDONÇA L.B., LOPES E.V., BOÇON R., BISHEIMER M.V., SERAFINI P.P., CARVALHO J. 2011. Bird species abundance-occupancy patterns and sensitivity to forest fragmentation: Implications for conservation in the Brazilian Atlantic forest. *Biological Conservation* 144(9): 2213–2222. <https://doi.org/10.1016/j.biocon.2011.05.013>
- ERIKSSON O. 2021. The importance of traditional agricultural landscapes for preventing species extinctions. *Biodiversity and Conservation* 30(5): 1341–1357. <https://doi.org/10.1007/s10531-021-02145-3>
- FOLEY J.A., DEFRIES R., ASNER G.P., BARFORD C., BONAN G., CARPENTER S.R., CHAPIN F.S., COE M.T., DAILY G.C., GIBBS H.K., HELKOWSKI J.H., HOLLOWAY T., HOWARD E.A., KUCHARIK C.J., MONFREDA C., PATZ J.A., PRENTICE I.C., RAMANKUTTY N., SNYDER P.K. 2005. Global Consequences of Land Use. *Science* 309(5734): 570–574. <https://doi.org/10.1126/science.1111772>
- GIANPASQUALE C., ALBERTO M. 2019. The occurrence and density of three sympatric corvids in a Mediterranean agroecosystem explained by land use. *Journal of Ornithology* 160(4): 1133–1150. <https://doi.org/10.1007/s10336-019-01679-2>
- GUERBOUZ A., GUERGUEB E.-Y., HADDAD S., BOUNAB C., ZOUATINE O., BIAD R., NOUIDJEM Y. 2024. Diversity of avian species across urban landscape in Ghardaïa City (Algerian Sahara). *Revista Agrária Acadêmica* 7(3), Mai-Jun. In press. <https://agrariacad.com/edicoes-antiores-2/>
- GUERGUEB E.-Y., HADDAD S., ZOUATINE O., NOUIDJEM Y. 2024. Scorpions are Part of the Menu of the House Bunting *Emberiza sahari* Levaillant, 1850 (Passeriformes: Emberizidae) in Algerian Sahara. *Acta Zoologica Bulgarica* 76(3): 445–448. <https://www.acta-zoologica-bulgarica.eu/2024/002765>
- GUEZOU O., CHENCHOUNI H., SEKOUR M., ABABSA L., SOUTTOU K., DOUMANDJI S. 2013. An avifaunal survey of mesic man-made ecosystems 'Oases' in Algerian hot-hyperarid lands. *Saudi Journal of Biological Sciences* 20(1): 37–43. <https://doi.org/10.1016/j.sjbs.2012.10.001>
- HAGGAR J., PONS D., SAENZ L., VIDES M. 2019. Contribution of agroforestry systems to sustaining biodiversity in fragmented forest landscapes. *Agriculture, Ecosystems & Environment* 283, 106567. <https://doi.org/10.1016/j.agee.2019.06.006>
- HAMZA F., HANANE S. 2021. The effect of microhabitat features, anthropogenic pressure and spatial structure on bird diversity in southern Tunisian agroecosystems. *Annals of Applied Biology* 179(2): 195–206. <https://doi.org/10.1111/aab.12690>
- HANANE S., CHERKAOUI S.I., MAGRI N., YASSIN

- M. 2019. Bird species richness in artificial plantations and natural forests in a North African agroforestry system: assessment and implications. *Agroforestry Systems* 93(5): 1755–1764. <https://doi.org/10.1007/s10457-018-0281-z>
- HIRON M., BERG Å., EGGERS S., JOSEFSSON J., PÄRT T. 2013. Bird diversity relates to agri-environment schemes at local and landscape level in intensive farmland. *Agriculture, Ecosystems & Environment* 176: 9–16. <https://doi.org/10.1016/j.agee.2013.05.013>
- IUCN 2023. The IUCN Red List of Threatened Species. Version 2022-2. <https://www.iucnredlist.org>
- JACOBOSKI L.I., de MENDONÇA-LIMA A., HARTZ S.M. 2016. Structure of bird communities in Eucalyptus plantations: nestedness as a pattern of species distribution. *Brazilian Journal of Biology* 76(3): 583–591. <https://doi.org/10.1590/1519-6984.18614>
- JOHNSON R.J., JEDLICKA J.A., QUINN J.E., BRANDLE J.R. 2011. Global Perspectives on Birds in Agricultural Landscapes. In: Campbell W., Lopez Ortiz S. (Eds), *Integrating Agriculture, Conservation and Eco-tourism: Examples from the Field. Issues in Agroecology – Present Status and Future Prospectus*, vol 1. Springer, Dordrecht: 55–140. https://doi.org/10.1007/978-94-007-1309-3_3
- KANG W., MINOR E.S., PARK C.R., LEE D. 2015. Effects of habitat structure, human disturbance, and habitat connectivity on urban forest bird communities. *Urban Ecosystems* 18(3): 857–870. <https://doi.org/10.1007/s11252-014-0433-5>
- LAUBE I., BREITBACH N., BÖHNING-GAESE K. 2008. Avian diversity in a Kenyan agroecosystem: Effects of habitat structure and proximity to forest. *Journal of Ornithology* 149(2): 181–191. <https://doi.org/10.1007/s10336-007-0258-6>
- LAVEE D., SAFRIEL U.N., MEILIJSON I. 1991. For How Long Do Trans-Saharan Migrants Stop over at an Oasis? *Ornis Scandinavica* 22(1): 33–44. <https://doi.org/10.2307/3676619>
- LEDANT J.P., JACOB J.P., JACOBS P., MALHER F., OCHANDO B., ROCHÉ J.E. 1981. Update of the Algerian avifauna [Mise à jour de l'avifaune algérienne]. *Le Gerfaut* 71: 295–394.
- MÄKELÄINEN S., HARLIO A., HEIKKINEN R.K., HERZON I., KUUSSAARI M., LEPIKKÖ K., MAIER A., SEIMOLA T., TIAINEN J., ARPONEN A. 2019. Coincidence of High Nature Value farmlands with bird and butterfly diversity. *Agriculture, Ecosystems & Environment* 269: 224–233. <https://doi.org/10.1016/j.agee.2018.09.030>
- MARSDEN S.J., WHIFFIN M., GALETTI M. 2001. Bird diversity and abundance in forest fragments and Eucalyptus plantations around an Atlantic forest reserve, Brazil. *Biodiversity and Conservation* 10(5): 737–751. <https://doi.org/10.1023/A:1016669118956>
- MELLINK E. 1991. Bird communities associated with three traditional agroecosystems in the San Luis Potosi Plateau, Mexico. *Agriculture, Ecosystems & Environment* 36(1–2): 37–50. [https://doi.org/10.1016/0167-8809\(91\)90034-U](https://doi.org/10.1016/0167-8809(91)90034-U)
- MELLINK E., RIOJAS-LÓPEZ M.E., GIRAUDOUX P. 2016. A neglected opportunity for bird conservation: The value of a perennial, semiarid agroecosystem in the Llanos de Ojuelos, central Mexico. *Journal of Arid Environments* 124: 1–9. <https://doi.org/10.1016/j.jaridenv.2015.07.005>
- MAGURRAN A.E. 1988. Diversity indices and species abundance models. In: *Ecological Diversity and its Measurement*. Springer, Dordrecht: 7–45. https://doi.org/10.1007/978-94-015-7358-0_2
- MULWA R.K., BÖHNING-GAESE K., MATTHIAS S. 2012. High Bird Species Diversity in Structurally Heterogeneous Farmland in Western Kenya. *Biotropica* 44(6): 801–809. <https://doi.org/10.1111/j.1744-7429.2012.00877.x>
- MUÑOZ-SÁEZ A., PEREZ-QUEZADA J.F., ESTADES C.F. 2017. Agricultural landscapes as habitat for birds in central Chile. *Revista Chilena de Historia Natural* 90(1): 1–12. <https://doi.org/10.1186/s40693-017-0067-0>
- NAIDOO R. 2004. Species Richness and Community Composition of Songbirds in a Tropical Forest-Agricultural Landscape. *Animal Conservation* 7(1): 93–105. <https://doi.org/10.1016/j.jaridenv.2015.07.005>

- org/10.1017/S1367943003001185
- NEDJAR R., GUERGUEB E.-Y., HADDAD S., NOUIDJEM Y. 2024. First confirmed breeding record of the Eastern livaceous warblers (*Iduna pallida reiseri* Hilgert, 1908) in Ghardaïa region, Algerian Sahara. *Natural Resources and Sustainable Development* 14(1): 111–116. <https://doi.org/10.31924/nrsd.v14i1.153>
- PIRATELLI A.J., PIÑA-RODRIGUES F.C.M., RAEDIG C. 2019. Integrating Biodiversity Conservation into Agroecosystem Management: Using Birds to Bring Conservation and Agricultural Production Together. In: Nehren U., Schlüter S., Raedig C., Sattler D., Hissa H. (Eds), *Strategies and Tools for a Sustainable Rural Rio de Janeiro*. Springer Series on Environmental Management. Springer, Cham: 139–153. https://doi.org/10.1007/978-3-319-89644-1_10
- SIBLEY D. 2014. *The Sibley Guide to Birds*. Alfred A. Knopf, New York. Second edition. 624 p.
- SELLAMI M.H. 2008. A scientific guide for agricultural water management and biodiversity conservation. *Agricultural Water Management Research Trends*. 171 p.
- SELMİ S. 2007. Determinants of distribution, abundance and reproductive success of the Common Blackbird (*Turdus merula*) in southern Tunisian oases. *Ostrich* 78(2): 309–313. <https://doi.org/10.2989/OSTRICH.2007.78.2.31.111>
- SHACHAK M., PICKETT S.T.A., GOSZ J.R., PEREVOLOTSKI A. 2005. Biodiversity in Drylands: Toward a Unified Framework. Oxford University Press. 368 p. <https://doi.org/10.1093/oso/9780195139853.001.0001>
- SIMPSON E.H. 1949. Measurement of Diversity. *Nature* 163: 688. <https://doi.org/10.1038/163688a0>
- SPELLERBERG I.F., FEDOR P.J. 2003. A tribute to Claude Shannon (1916–2001) and a plea for more rigorous use of species richness, species diversity and the ‘Shannon–Wiener’ Index. *Global Ecology and Biogeography* 12(3): 177–179. https://www.researchgate.net/profile/Souad-Neffar/post/What_is_the_correct_name_for_the_Shannon_Diversity_Index/attachment/59d6484f79197b80779a3013/AS%3A466370589663232%401488202821265/download/shannon+weaver-wiener.pdf
- SVENSSON L., MULLARNEY K., ZETTERSTRÖM D. 2012. *Birds of Europe, North Africa and Middle East* [Les Oiseaux d'Europe, d'Afrique du Nord et du Moyen-Orient]. Delachaux et Niestlé, Paris. 446 p.
- SWEENEY O.F.M.D., WILSON M.W., IRWIN S., KELLY T.C., O'HALLORAN J. 2010. Are bird density, species richness and community structure similar between native woodlands and non-native plantations in an area with a generalist bird fauna? *Biodiversity and Conservation* 19(8): 2329–2342. <https://doi.org/10.1007/s10531-010-9844-7>
- TERRAUBE J., ARCHAUX F., DECONCHAT M., VAN HALDER I., JACTEL H., BARBARO L. 2016. Forest edges have high conservation value for bird communities in mosaic landscapes. *Ecology and Evolution* 6(15): 5178–5189. <https://doi.org/10.1002/ece3.2273>
- TSCHARNTKE T., CLOUGH Y., BHAGWAT S.A., BUCHORI D., FAUST H., HERTEL D., HO D., JUHRBANDT J., KESSLER M., PERFECTO I., SCHERBER C. 2011. Multifunctional shade-tree management in tropical agroforestry landscapes – a review. *Journal of Applied Ecology* 48(3): 619–629. <https://doi.org/10.1111/j.1365-2664.2010.01939.x>

An approach to the impact of weather variables on the growth of *Polylepis* species in the central Andes of Peru

Kevin Ortega Quispe^{1,2*}, Betty Cordova Torres¹, Meliza Molina Damas²,
Judith Oscanoa Ramos³, Lucia Enriquez Pinedo^{1,2}, Itala Flores Torres⁴,
and Dennis Ccopi Trucios^{1,2}

¹Department of Agrarian Technological Development, Santa Ana Agrarian Experimental Station, National Institute for Agrarian Innovation (INIA), Carretera Saños Grande Hualahoyo Km 8 Santa Ana, Huancayo, Junin 12006, Peru. E-mails: kevinorqu@gmail.com (K.O.Q)*, bcordova@inia.gob.pe (B.C.T), luciacep7@gmail.com (L.E.P), denniscopit@gmail.com (D.C.T)

²Research Group on Nature Conservation and Climate Change, Faculty of Forestry and Environmental Sciences, Universidad Nacional del Centro del Perú, Av. Mariscal Castilla 3909, 12006, Huancayo, Peru. E-mail: melizangely@gmail.com (M.M.D)

³Faculty of Forestry and Environmental Sciences, Universidad Nacional del Centro del Perú, Av. Mariscal Castilla 3909, 12006, Huancayo, Peru. E-mail: oscanoa.rje@gmail.com (J.O.R)

⁴Supervision and Monitoring Directorate at the Agricultural Experimental Stations, National Institute of Agrarian Innovation (INIA), Av. La Molina 1981, Lima 15024, Peru. E-mail: floresitala@gmail.com (I.F.T)

Received: 20 October 2024 / Accepted: 20 November 2024 / Available online: 10 January 2025



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

Abstract

The *Polylepis* genus, endemic to the South American Andes, faces significant threats due to environmental variations, which jeopardize its growth and survival. This situation underscores the urgent need to develop conservation strategies. The present research assesses the influence of meteorological variables, such as temperature and humidity, on the growth and adaptation of various *Polylepis* species in the central Peruvian Andes, aiming to optimize reforestation and sustainable management practices. The study was conducted in experimental plots at the Santa Ana Agricultural Station in Junín, Peru, where *Polylepis* saplings, obtained from different localities, were planted. Over two years, phenotypic variables (height and diameter) and meteorological variables (precipitation, humidity, temperature, and wind speed) were monitored to evaluate the relationship between environmental conditions and plant development. The results showed that high humidity negatively affected all species, however wind speed appears to promote plant growth by creating an ideal microclimate that reduces soil moisture. Precipitation and maximum temperature had limited impact, indicating relative resilience to these factors. It should be noted that the species from Huancavelica and Yauyos have been adapting better to local conditions compared to those from Cerro de Pasco, which are more sensitive to humidity. These findings highlight the importance of considering wind speed and humidity in reforestation planning to improve the adaptability of *Polylepis* species. We conclude that humidity is the most decisive meteorological factor for the growth of *Polylepis* under specific conditions, emphasizing its relevance in planning conservation and reforestation strategies in the Peruvian Andes.

Key words: forest conservation, phenotyping, relative humidity, wind velocity.

Introduction

Climate change represents significant risks to the sustainability of native tree plantations, affecting their survival, productivity, carbon balance, and water use (Cunningham et al. 2015). Consequently, the ecosystem services provided by these trees and their ability to recover from environmental changes are impacted (Ortega-Quispe et al. 2024, Rubilar et al. 2024). *Polylepis* Ruiz & Pav. is a genus unique to the South American Andes (Morales-Aranibar and Morales-Aranibar 2023); nevertheless, 44 of its 47 species are included in the IUCN Red List (IUCN 2024). The fragmentation of *Polylepis* forests in Peru, caused by human activities, threatens the loss of their vegetation cover, making conservation efforts imperative to prevent further degradation and protect this unique ecosystem (Franco-León et al. 2024). However, academics and field practitioners, in their attempt to preserve and restore these natural ecosystems, often work independently to conserve and understand them (Morales Moreno et al. 2018).

Understanding different species growth rates in a model plantation is fundamental to optimize the planting sites selection, taking into account the compatibility with the environment (Morales Moreno et al. 2018). In addition, efficient plantation management requires constant dynamics monitoring, both at the plantation level as a whole and of each individual tree (Flores Garnica and Reyes Cárdenas 2022). The *Polylepis* genus, one of the most representative endemic species of our continent, is gaining relevance due to its endemism and its crucial role in the ecological balance conservation. Among the *Polylepis* studied species are *Polylepis incana* Kunth, native to South Amer-

ica, which has low germination power and slow growth (Canales Gutiérrez et al. 2020). In contrast, *Polylepis racemosa* Ruiz Lopez & Pavon, native to Peru, shows faster growth compared to other species and spreads more easily (Segovia-Salcedo 2011). On the other hand, *Polylepis sacra* T. Boza & M. Kessler has a very distinct climatic niche (Boza Espinoza and Kessler 2022).

It is important to understand in detail these species in relation to the climatic variables that affect their growth and survival in order to know, understand and develop more effective strategies for reforestation and conservation of our natural forests (Acácio et al. 2024). From a technological perspective, this understanding facilitates the assessment of forest regeneration potential at multiple spatial scales, allowing the prediction of specific scenarios or species behaviour (Bedoya et al. 2024, Everingham et al. 2024). This information is key to assess the viability of species in different ecological contexts (Rank et al. 2022), which directly benefits the populations that depend on these ecosystems for their livelihoods and well-being. In addition, commercial forest plantations, using native species, provide multiple ecosystem services, such as timber production, carbon sequestration and biodiversity support (Ugarte-Guerra and Román-Dañobeytia 2020).

Recent forest projections have revealed changes in tree species density and composition as a result of temperature variations (De Fatima et al. 2023, Hsu et al. 2024). It is important to emphasize that our research, as well as other studies, has contributed to broaden the knowledge on the ecology and conservation of *Polylepis* (Renison et al. 1991), demonstrating that these trees present adaptive strategies for their survival (Ramos et al.

2013). In addition, significant differences have been identified between populations in the seedling growth range, influenced by climatic factors, such as light and temperature (Cai et al. 2016). It is important to note that climatic extremes can lead to considerable variations in the seedlings number continuity between species due to their varying sensitivity (Niu et al. 2014).

A key aspect in the high Andean ecosystems dynamics is how forest species respond to environmental conditions and historical land use (Schmitt et al. 2023). In this regard, research has shown that growth rates of various species are influenced both by their intrinsic characteristics and by external factors (Bellemare et al. 2002). A recent study on the growth of four native species in Peruvian Amazon plantations highlights that both species-specific traits and land use history critically influence development. This interaction is especially significant for *Polylepis* species, which thrive in extreme altitudes, where environmental factors like water availability, temperature, and land use impact their survival and growth (Ugarte-Guerra and Román-Dañobeytia 2020).

Therefore, this work aims to demonstrate the influence of climatic variables on phenotypic characteristics, in order to develop conservation and sustainable management strategies that will facilitate the adaptation of native forest species, such as *Polylepis*. The results of this research will provide concrete evidence that significantly contributes to the Sustainable Development Goals (SDGs), particularly SDG 13 and SDG 15, by evidencing improvements in ecosystem management in response to climate variations and promoting the conservation of mountain ecosystems in the Peruvian central.

Material and Methods

The study was conducted in three primary phases. In the initial phase, the planting of three *Polylepis* species was completed. The second phase focused on the collection of meteorological and phenotypic data. Finally, the third phase involved the analysis of the collected data (Fig. 1).

The plantation was established in demonstration plots managed by the Santa Ana Agrarian Experimental Station attached to the National Institute of Agrarian Innovation in the Paccha district, Jauja province, Junín region, Peru, as seen in Figure 2. The Jauja depression is a basin formed by Quaternary deposits, located at altitudes between 3100 and 3300 m a.s.l. (Coopi-Trucios et al. 2023, Cáceres et al. 2024). This basin is drained by the Mantaro River and two secondary tributaries, the Ricrán and Tulumayo rivers. The climate of this region is characterized by a dry and hot season from April to November, and a continuous rainy season from December to March. However, the duration of these seasons may vary due to various factors associated with the Andes and the Andean region.

As shown in Table 1, the study was carried out in three plots, where three species of *Polylepis* (*P. sacra*, *P. racemosa* and *P. incana*) were planted. The seedlings, 2-year-old and with average size of 30 cm total with a black polyethylene bag, were obtained from nurseries located in three different locations. The climatic characteristics of the source nurseries are presented based on the average values of variables recorded in 2022. This information comes from both the producers own records and data from the National Meteorology and Hydrology Service of

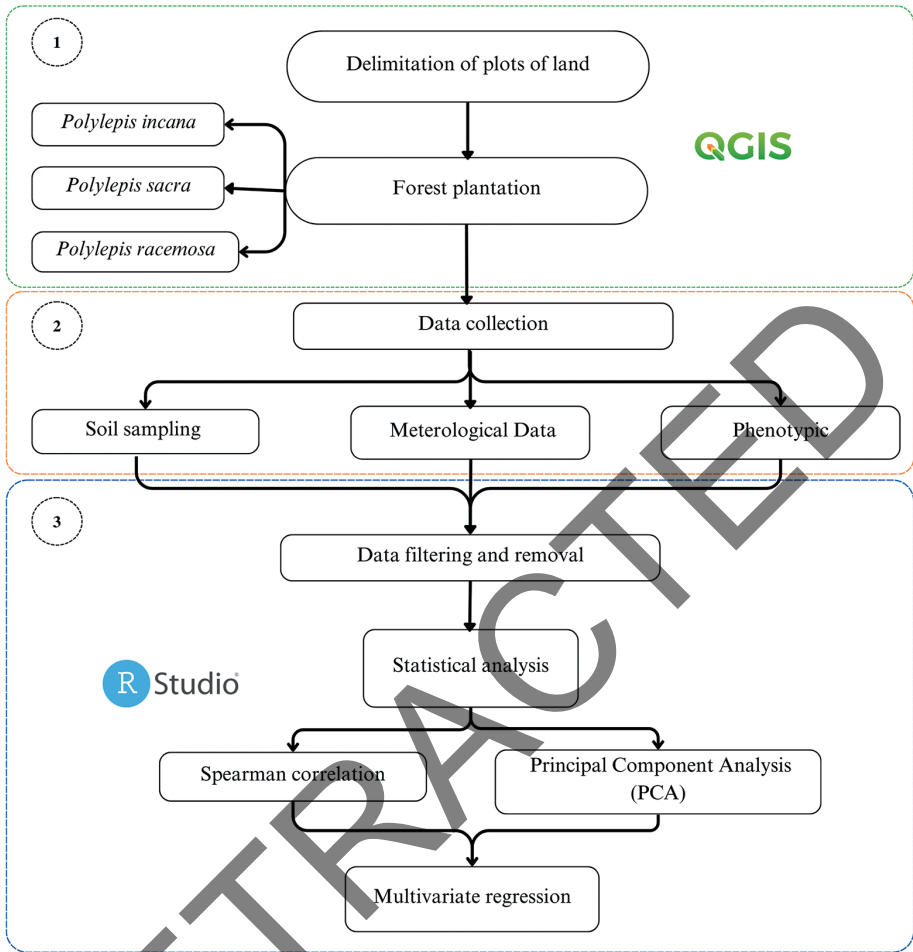


Fig. 1. Flow chart of the research process.

Peru, accessed through their official portal (SENAMHI 2024).

The soils where *Polylepis* was planted have a sandy loam texture, which limits water and nutrient retention, although the high sand content (54–58 %) allows for good drainage. Organic matter ranges between 1.4 and 1.8 %, which contributes to soil fertility, while variations in nitrogen (1.4 to 3.0%), phosphorus (0.07 to 0.15 mg·kg⁻¹) and potassium (13.6 to 72.5 mg·kg⁻¹) can limit growth. Soil analyses were carried out in the soil and foliar

laboratory (LABSAF) of the Santa Ana – Huancayo Experimental Station.

The seedlings were established on December 13, 2021 at the Los Andenes site of the Agrarian Experimental Station (EEA) and the Masajcancha community in Jauja.

Soil preparation was carried out through localized tillage during 2021, which involved digging 30 × 30 × 30 cm holes. In each hole, a substrate composed of a mixture of 20 % organic fertilizer and native soil was applied, providing essen-

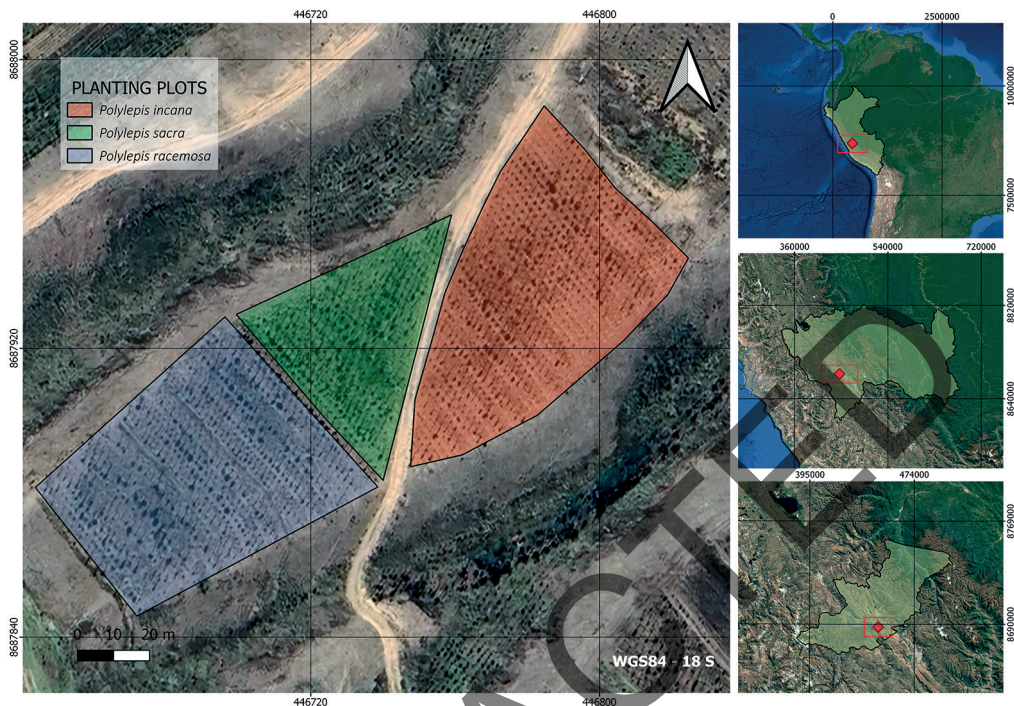


Fig. 2. Location of the experimental development site.

Table 1. Origin of the plantations.

Provenance	Species	Climatic characteristics					Number of seedlings
		Tmax, °C	Tmin, °C	Hum, %	Ws, m·s ⁻¹	P, mm·yr ⁻¹	
Yauyos	<i>Polylepis sacra</i>	25	10	62	2.3	2396.4	235
	<i>Polylepis racemosa</i>						201
Huancavelica	<i>Polylepis incana</i>	23	5	73	2.6	750.2	304
	<i>Polylepis racemosa</i>						246
Cerro de Pasco	<i>Polylepis racemosa</i>	20	3	57	3.2	1182.7	222
	<i>Polylepis incana</i>						

Note: Provenance in provinces of the central high Andean zone of Peru. The climatic characteristics correspond to the average of each parameter for the year 2022.

tial nutrients and improving the structure of the soil to promote plant growth. Seedlings, which measured approximately 15 to 18 cm in height with bare roots, were

obtained from certified nurseries in each collection region.

The design is represented by a distance of 3 m between horizontal rows,

each row contains the seedlings spaced 2 m apart, which allowed sufficient space for root development and efficient management. Irrigation was carried out by flooding during the first six months of the dry season, providing uniform and deep hydration of the soil during this critical establishment stage. During the rainy season, irrigation was not necessary and measures were taken, such as installing a fence with barbed wire to protect the plants from small animals, avoiding damage to leaves and tips.

Additionally, weeding was carried out every three months to control weed competition. Pest control was implemented using natural extracts, helping to reduce environmental impact compared to agrochemical use. In the second year, formative pruning was conducted to promote the plant's vertical growth, providing a strong structure suitable for future development.

Field activities involved measuring tapes, GPS devices, and cultivation tools, with safety measures implemented for the operators. The evaluations covered two years (2021–2022), continuing to date, and included measurements taken in March and December (rainy season) and June (dry season), focusing on height, diameter, shoots, and leaflets.

Meteorological data were obtained from the Santa Ana station (2019–2024) using a Davis Vantage Pro2 measuring device, informing evaluations and allowing for the calculation of averages. Data processing was done in RStudio Team (2020), applying initial data cleaning and the interquartile range (IQR) method to handle outliers and ensure quality.

To analyse the relationship between climatic variables and phenotypic development, Spearman's correlation was used, as it identifies monotonic relationships without assuming a normal distribu-

tion (Rovetta 2020). This method is valuable in forestry studies, as it addresses irregular or non-linear patterns in climatic variables that affect species growth (Mendivelso 2022, Bocianowski et al. 2024). By detecting non-linear relationships, this approach clarifies species' responses to climate changes (Allen et al. 2010).

A multivariate regression was conducted to assess the influence of climate on the growth of forest species, focusing on phenotypic variables, such as tree diameter and height. The aim was to evaluate how temperature, precipitation, and relative humidity simultaneously affect both diameter and height, providing insights into the phenotypic responses to climatic fluctuations (Pretzsch 2014, Dudenhöffer et al. 2018).

A Principal Component Analysis (PCA) was conducted to explore the relationships between climatic and phenotypic variables across different localities. Additionally, scatter plots were created to illustrate the relationships between climatic variables (precipitation, wind speed, humidity, and maximum temperature) and two phenotypic traits of *Polylepis* species: height and diameter.

Results and Discussion

Table 2 presents descriptive statistics for *Polylepis* from Cerro de Pasco, Yauyos, and Huancavelica. Cerro de Pasco has an average height (H) of 76.76 cm and a diameter (D) of 13.36 mm, with temperatures between 9.4 °C and 12.7 °C and average humidity of 73.0 %. Yauyos has a greater average height of 89.7 cm but a similar temperature range and humidity. Huancavelica features the highest average height at 114.6 cm and a diameter of 18.7 mm, suggesting more favourable

Table 2. Provenance of plantations.

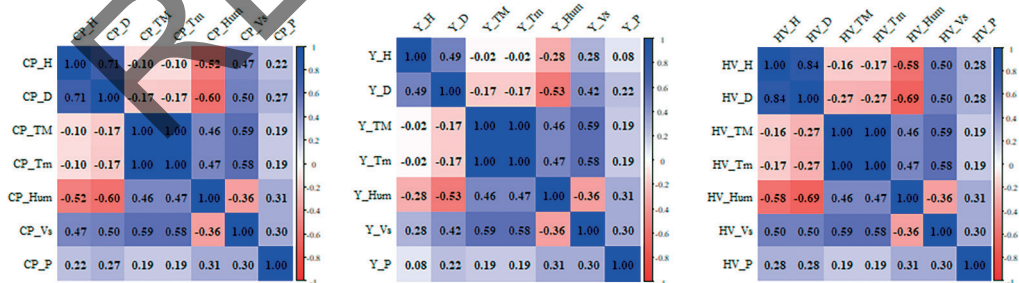
<i>n</i>	Indicator	<i>H</i> , cm	<i>D</i> , cm	<i>T</i> max, °C	<i>T</i> min, °C	<i>Hum</i> , %	<i>Ws</i> , m·s ⁻¹	<i>P</i> , mm·h ⁻¹
Cerro de Pasco								
468	mean	76.7	13.3	11.2	11.0	73.0	1.9	11.5
	max	127.0	33.2	12.7	12.6	81.7	2.2	28.2
	min	35.0	3.9	9.4	9.2	64.7	1.4	3.0
	StD	17.3	5.8	1.3	1.3	6.9	0.3	10.0
	Median	76.0	12.8	11.3	11.2	72.8	1.9	7.5
Yauyos								
436	mean	89.7	12.2	11.2	11.0	73.0	1.9	11.5
	max	135.0	28.2	12.7	12.6	81.7	2.2	28.2
	min	28.0	2.8	9.4	9.2	64.7	1.4	3.0
	StD	22.20	4.49	1.30	1.31	6.96	0.3	10.0
	Median	92.00	11.61	11.31	11.20	72.89	1.9	7.5
Huancavelica								
304	mean	114.6	18.7	11.2	11.0	73.0	1.9	11.5
	max	192.0	38.2	12.7	12.6	81.7	2.2	28.2
	min	54.0	4.4	9.4	9.2	64.7	1.4	3.0
	StD	27.7	8.2	1.3	1.3	7.3	0.3	10.0
	Median	115.0	18.6	11.3	11.2	72.8	1.9	7.5

Note: *n* is number of samples, *H* is height, *D* is diameter, *T*max is maximum temperature, *T*min is minimum temperature, *Hum* is humidity, *Ws* is wind speed, *P* is precipitation.

growing conditions. Humidity remained relatively constant across all locations, underscoring its significance for the phenotypic development of the species.

Figure 3 presents the correlation matrix for the three studied localities, where it is observed that humidity is negatively related to growth in height and diameter

of *Polylepis* plants, especially in Cerro de Pasco and Huancavelica. This suggests that high humidity levels may not be favourable for the development of this species in its new environment. Regarding the relationship between height and diameter, a positive correlation is found in all localities, being strongest in Huancaveli-

**Fig. 3. Correlation matrix.**

Note: The index (CP, Y, HV) that accompanies the variable represents: CP is Cerro de Pasco, Y is Yauyos, HV is Huancavelica.

ca (0.84), indicating that in this species, height growth is closely associated with diameter.

On the other hand, extreme temperatures (maximum and minimum) have minimal influence in Cerro de Pasco and Yauyos, while in Huancavelica, a slight negative correlation is observed. This suggests that the effect of temperature on the growth of *Polylepis* varies according to the species' adaptability. The results indicate that the growth of *Polylepis* is affected differently depending on the locality of origin and species, highlighting humidity as a relevant factor, particularly in higher-altitude localities, where this variable appears to limit plant development in terms of height and diameter.

Figure 4 shows the principal component analysis (PCA), illustrating how climatic variables influence the phenotypic characteristics (height and diameter) of *Polylepis* species from Cerro de Pasco, Yauyos, and Huancavelica. The points represent individual observations grouped by region, while the ellipses around each

group indicate the general trend of the species in each locality. The *Polylepis* species from Yauyos show a closer association with maximum temperature (T_{max}) and precipitation (P), suggesting that these climatic conditions positively impact height (H) growth and diameter (D) development in this region. This implies that in *Polylepis* species from Yauyos, height and diameter are particularly influenced by temperature and precipitation.

In contrast, the *Polylepis* species from Cerro de Pasco and Huancavelica appear more closely associated with relative humidity (Hum). In these species, humidity seems to play a more significant role in the development of height and diameter. This suggests that, in climates where humidity is the dominant factor, height and diameter growth patterns may differ from those observed in environments more influenced by temperature and precipitation. Overall, this analysis indicates that climatic variables have a differentiated impact on height and diameter development across regions, highlighting the im-

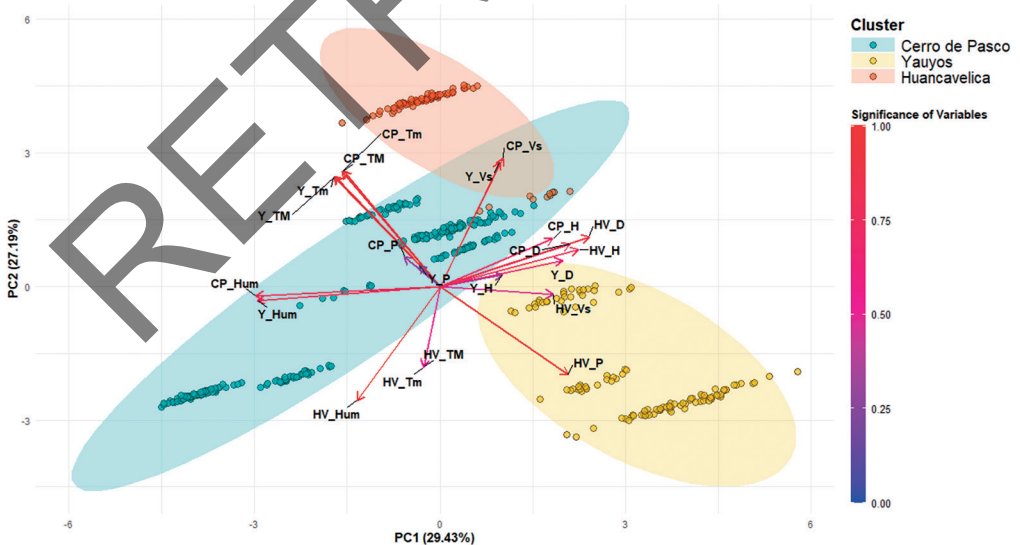


Fig. 4. Principal component analysis (PCA).

portance of considering specific environmental conditions in each locality to fully understand the phenotypic development of *Polylepis* species.

Multivariate regression analysis of climatic effects

Table 3 reveals the impact of climatic variables on *Polylepis* species native to Cerro de Pasco. The intercepts present significant *t*-values, with 15.149 for height and 17.028 for diameter. These results indicate that the evaluated climatic conditions have a significant influence on the growth of the species, evidencing a strong relationship between environmental factors and the phenotypic development of *Polylepis*.

Precipitation positively affects plant growth, which is shown in equation (1), with a 1-unit increase in precipitation producing increases of 0.58 units in height and 0.26 units in diameter, and an increase in 1 unit in wind speed resulting in increases of 8.93 units in height and 2.17 units in diameter. In contrast, a 1 unit increase in humidity results in decreases of 1.59 units in height and 0.67 units in diameter, suggesting that excessive humidity can inhibit growth. Maximum temperature was excluded from the model due to its

non-significant relationship.

The multivariate equation for the Cerro Pasco complex is expressed as follows:

$$\left(\frac{H}{D}\right) = \left(\frac{168.80}{55.30}\right) + \left(\frac{0.58}{0.26}\right)P + \left(\frac{8.93}{2.18}\right)Ws + \left(\frac{-1.57}{-0.67}\right)Hum \quad (1)$$

where: *H* is height, m; *D* is diameter, cm; *P* is precipitation, mm; *Ws* is wind speed, m·s⁻¹; *Hum* is humidity, %.

The effect of climatic variables on *Polylepis* species from Yauyos is demonstrated by significant *t*-values of 7.482 for height and 13.863 for diameter, as shown in Table 4. These results emphasize the strong impact of climatic conditions on species growth, highlighting the correlation between environmental factors and the phenotypic development of *Polylepis*.

Climatic variables influence plant height and diameter (equation 2). A 1-unit increase in precipitation leads to increases of approximately 0.27 units in height and 0.17 units in diameter, indicating that higher precipitation supports growth. Wind speed also positively impacts growth, with increases of 10.08 units in height and 1.23 units in diameter for each unit increase in speed. In contrast, a 1-unit increase in humidity results in decreases of 0.98 units in

Table 3. Multivariate regression with seedlings from Cerro de Pasco.

Indicators	Estimate	Std. Error	t-value	Pr (> t)
Height	Intercept	168.80989	11.14313	15.149
	<i>P</i>	0.58045	0.06989	8.305
	<i>Ws</i>	8.92997	2.32553	3.84
	<i>Hum</i>	-1.5861	0.1184	-13.397
Diameter	Intercept	55.30394	3.24786	17.028
	<i>P</i>	0.26286	0.02037	12.903
	<i>Ws</i>	2.16762	0.67781	3.198
	<i>Hum</i>	-0.67257	0.03451	-19.49

Note: Pr is *p*-value associated with a *t*-test; the variables mentioned: *P* is precipitation, *Ws* is wind speed, *Hum* is humidity.

Table 4. Multivariate regression with seedlings from Yauyos.

	Indicators	Estimate	Std. Error	t-value	Pr (> t)
Height	Intercept	138.7598	18.5468	7.482	4.14e-13
	<i>P</i>	0.2716	0.1163	2.335	2.00e-02
	<i>Ws</i>	10.0777	3.8706	2.604	0.00954
	<i>Hum</i>	-0.9788	0.1971	-4.967	9.80e-07
Diameter	Intercept	41.5395	2.99651	13.863	< 2e-16
	<i>P</i>	0.17287	0.0188	9.197	< 2e-16
	<i>Ws</i>	1.22651	0.62536	1.961	0.0505
	<i>Hum</i>	-0.46088	0.03184	-14.476	< 2e-16

Note: Pr is *p*-value associated with a t-test; the variables mentioned: *P* is precipitation, *Ws* is wind speed, *Hum* is humidity.

height and 0.46 units in diameter, suggesting that high humidity may hinder growth. Maximum temperature was excluded from the model, indicating it has no significant influence.

The multivariate equation for the Yauyos set is expressed as follows:

$$\left(\frac{H}{D}\right) = \left(\frac{138.76}{41.54}\right) + \left(\frac{0.27}{0.17}\right)P + \left(\frac{10.08}{1.23}\right)Ws + \left(\frac{-0.98}{-0.46}\right)Hum \quad (2)$$

The climatic variables influence on *Polylepis* species from Huancavelica (Table 5), indicating significant *t*-values of 16.07 for height and 21.256 for diameter. These results suggest that the analysed climatic variables substantially impact

species growth, reflecting a strong relationship between environmental conditions and the phenotypic development of *Polylepis*.

Plant height and diameter are influenced by climatic variables (equation 3). A 1-unit increase in precipitation results in increases of approximately 1.23 units in height and 0.43 units in diameter, indicating that higher precipitation enhances growth. Wind speed also positively impacts growth, with increases of 10.02 units in height and 0.95 units in diameter for each unit increase in speed. In contrast, a 1-unit increase in humidity leads to decreases of 3.06 units in height and 1.13 units in diameter, suggesting high humidity may negatively affect growth. Maxi-

Table 5. Multivariate regression with seedlings from Huancavelica.

	Indicators	Estimate	Std. Error	t-value	Pr (> t)
Height	Intercept	304.9475	18.9704	16.07	< 2e-16
	<i>P</i>	1.2312	0.119	10.35	< 2e-16
	<i>Ws</i>	10.0154	3.959	2.53	0.0119
	<i>Hum</i>	-3.0624	0.2016	-15.19	< 2e-16
Diameter	Intercept	94.85085	4.4624	21.256	< 2e-16
	<i>P</i>	0.43108	0.02799	15.401	< 2e-16
	<i>Ws</i>	0.94664	0.93128	1.016	0.31
	<i>Hum</i>	-1.13473	0.04741	-23.933	< 2e-16

Note: Pr is *p*-value associated with a t-test; where: *P* is precipitation, *Ws* is wind speed, *Hum* is humidity.

maximum temperature was excluded from the model, indicating it does not significantly impact this dataset. These results underscore the importance of understanding climatic influences on plant phenotype for optimizing agricultural practices and improving crop yields.

The multivariate equation or the Huancaavelica set is expressed as follows:

$$\left(\frac{H}{D}\right) = \left(\frac{304.95}{94.85}\right) + \left(\frac{1.23}{0.43}\right)P + \left(\frac{10.01}{0.94}\right)Ws + \left(\frac{-3.06}{-1.13}\right)Hum \quad (3)$$

Scatter plots in figures 5a, 5b and 5c illustrate the relationships between climatic variables – precipitation, wind speed, humidity, and maximum temperature – and two phenotypic characteristics of *Polylepis* species: height and diameter. Each plot includes a trend line showing the linear fit and a coefficient of determination, indicating the strength of the correlation between climatic and phenotypic variables.

The results show that humidity is the climatic variable most strongly correlated with the phenotypic growth of *Polylepis* species, particularly diameter, while precipitation and maximum temperature have a less significant impact. The figures indicate that humidity significantly influences the diameter and height. However, both precipitation and maximum temperature exhibit poor correlations with these traits, suggesting that other factors may contribute to their variability.

Discussion

The study found varied responses to climate changes in different locations, showing that these plants exhibit unique behaviours depending on their environment while growing. These results are consis-

tent with previous research analysing how *Polylepis* adapts to different conditions at high altitudes in the Andes.

For instance, the *Polylepis* species from Cerro de Pasco appear to benefit from the winds in their environment. We found that the vertical growth of these plants has a positive relationship with wind speed ($r = 0.47$), suggesting that the winds help them grow taller. This finding aligns with that of Marcora et al. (2021), who observed that in Andean ecosystems, wind can create microclimates that reduce humidity around plants, which is beneficial in poorly drained soils, such as the study site, which had a clayey, compact texture and high water saturation.

However, humidity is another important factor for these species, as their height and diameter growth significantly decrease in very humid environments (with negative correlations of $r = -0.52$ and $r = -0.60$, respectively). Cáceres et al. (2021) also observed this effect, indicating that high-altitude species like *Polylepis* can experience developmental issues in high-humidity conditions, as they may be at a greater risk of fungal diseases and water stress.

The *Polylepis* plants from Yauyos, on the other hand, displayed more neutral responses to temperature variations. The near-zero correlation between their height and maximum temperature ($r = -0.02$) suggests that these species are more tolerant of temperature fluctuations, likely due to thermal adaptation mechanisms similar to those described by Allen et al. (2010). They found that mountain plants develop cellular structures that allow them to withstand a wide range of temperatures. However, similar to the Cerro de Pasco species, the Yauyos species are also negatively affected by high humidity, with negative correlations in

Scatter Plots for CP Group

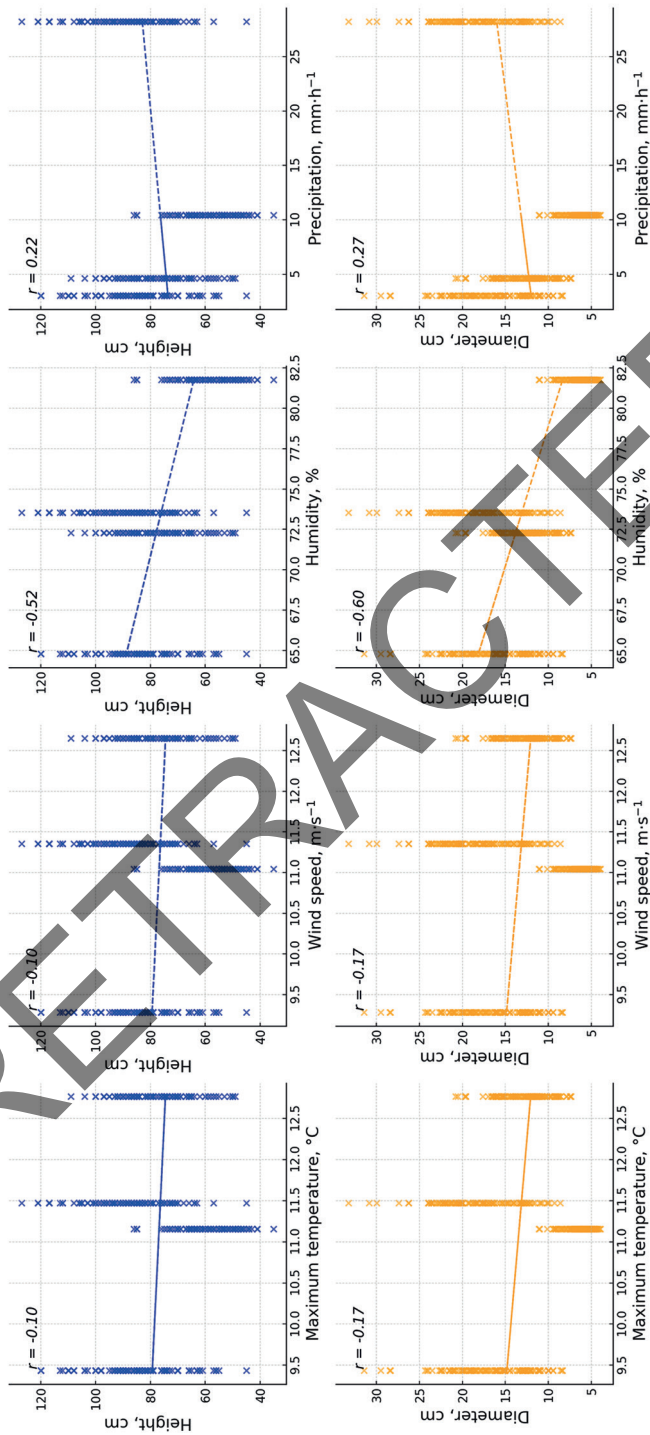


Fig. 5a. Variance plot representing the relationship between weather variables (precipitation, wind speed, humidity and maximum temperature) with height and diameter – location Cerro de Pasco

Scatter Plots for HV Group

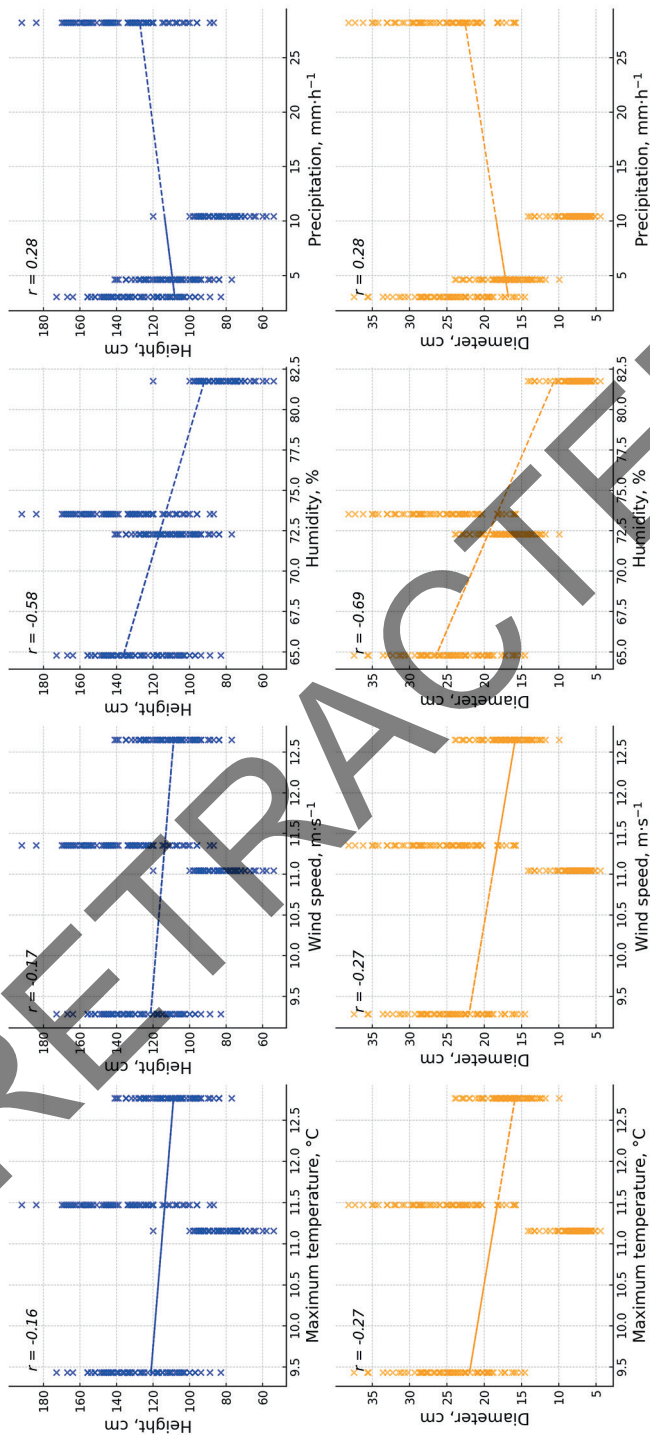


Fig. 5b. Variance plot representing the relationship between weather variables (precipitation, wind speed, humidity and maximum temperature) with height and diameter – location Yauyos.

Scatter Plots for HV Group

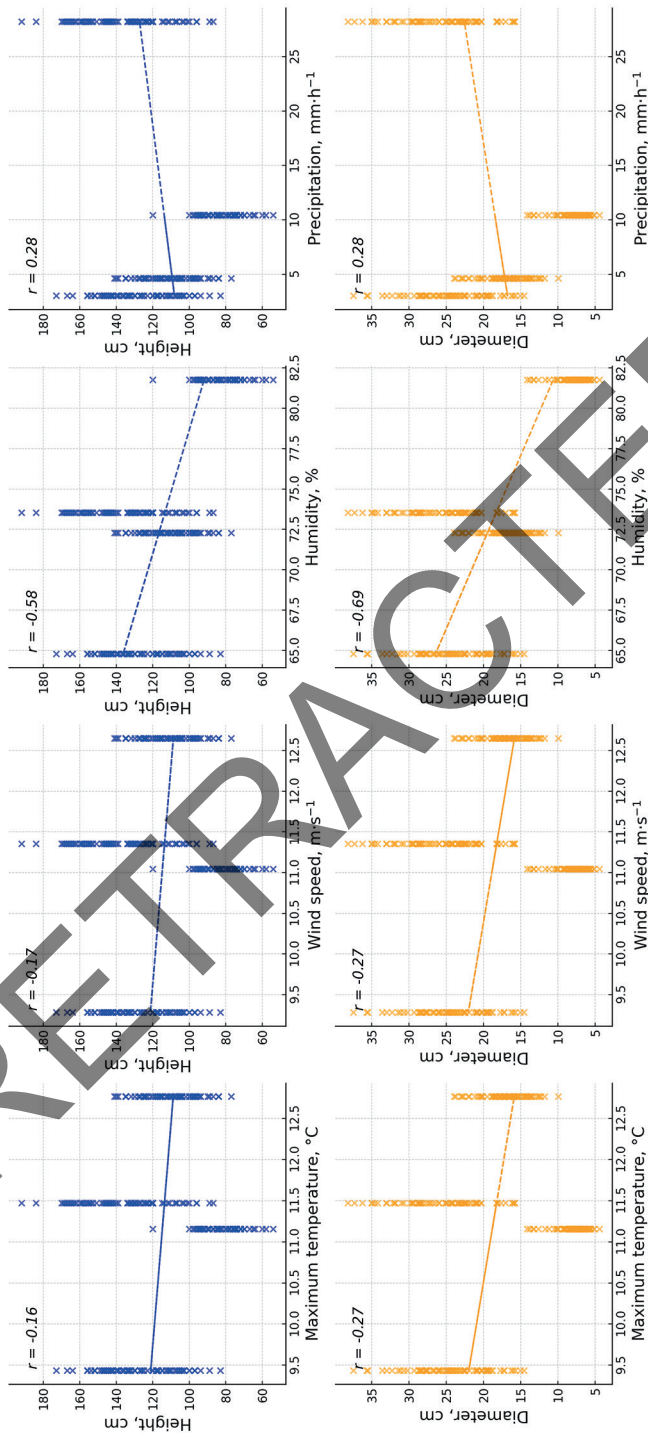


Fig. 5c. Variance plot representing the relationship between weather variables (precipitation, wind speed, humidity and maximum temperature) with height and diameter – location Huancavelica.

height ($r = -0.28$) and diameter ($r = -0.53$). This pattern is commonly seen in studies of high-altitude plants, where excessive humidity can hinder growth (Boza Espinoza et al. 2019).

The *Polylepis* plants from Huancavelica exhibited a behaviour similar to the Cerro de Pasco plants regarding wind (positive height correlation, $r = 0.50$). However, they are also highly sensitive to humidity, as indicated by strong negative correlations with height ($r = -0.58$) and diameter ($r = -0.69$). Previous studies, such as that by Rovetta (2020), found that many forest species in the region are highly susceptible to humidity, especially in areas with intense rainfall. Interestingly, these species showed a slight positive correlation with precipitation (r between 0.22 and 0.28 for height and diameter), suggesting that they benefit from a moderate amount of water without reaching excess levels. This aligns with findings by Carabazo-Hidalgo et al. (2023), who emphasized the importance of maintaining a balanced water regime to provide healthy growth without creating stress conditions for the plants.

A principal component analysis (PCA) further confirms these patterns, grouping species according to their climate responses: Cerro de Pasco is primarily associated with wind adaptability, Yauyos with a more balanced and tolerant response, and Huancavelica with a high dependence on precipitation and marked sensitivity to humidity. These findings suggest that moderate wind and precipitation levels favour the adaptation of these species in their new environments, while excessive humidity is a common barrier to growth across all evaluated species (Boza Espinoza et al. 2019). These insights are essential for understanding the ecological needs of each species, helping to inform

effective management and conservation strategies in Andean habitats.

Conclusion

The comparative analysis of *Polylepis* populations from Cerro de Pasco, Huancavelica, and Yauyos, planted in Huancayo, reveals that wind speed and relative humidity are the most influential climatic factors in the phenotypic development of these species. Wind speed appears to promote plant growth by creating an ideal microclimate that reduces soil moisture, while high humidity tends to inhibit this same process. Precipitation and maximum temperature, on the other hand, show minimal influence, indicating that, under high Andean conditions, these variables do not play a key role in modulating the *Polylepis* phenotype. These findings underscore the importance of considering the specific environmental conditions of the populations' origin when evaluating the phenotypic response of species in new environments.

References

- ACÁCIO V., DIAS F., FERREIRA M., RODRÍGUEZ P., MATIAS H., CALDEIRA M. 2024. Effects of shrub species dominance and diversity on oak seedling survival in Mediterranean woodlands: The interplay of abiotic conditions and plant traits. *Forest Ecology and Management* 555, 121713. 9 p. <https://doi.org/10.1016/j.foreco.2024.121713>
- ALLEN C.D., MACALADY A.K., CHENCHOUNI H., BACHELET D., McDOWELL N., VENNETIER M., KITZBERGER T., RIGLING A., BRESHEARS D.D., HOGG E.H. (TED), GONZALEZ P., FENSHAM R., ZHANG Z., CASTRO J., DEMIDOVA N., LIM J.H., ALLARD G., RUNNING S.W., SEMERCI A., COBB N. 2010. A global overview

- of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *Forest Ecology and Management* 259(4): 660–684. <https://doi.org/10.1016/j.foreco.2009.09.001>
- BEDOYA L., LÓPEZ F., CORTÉS A. 2024. Climate Change Responses of High-Elevation *Polylepis* Forests. *Forests* 15(5), 811. 20 p. <https://doi.org/10.3390/f15050811>
- BELLEMARE J., MOTZKIN G., FOSTER D.R. 2002. Legacies of the agricultural past in the forested present: an assessment of historical land-use effects on rich mesic forests. *Journal of Biogeography* 29(10–11): 1401–1420. <https://doi.org/10.1046/j.1365-2699.2002.00762.x>
- BOCIANOWSKI J., WROŃSKA-PILAREK D., KRYSZTOOAK-KANIEWSKA A., MATUSIAK K., WIATROWSKA B. 2024. Comparison of Pearson's and Spearman's correlation coefficients values for selected traits of *Pinus sylvestris* L. Research Square, Poznan University of Life Sciences. 20 p. <https://doi.org/10.21203/rs.3.rs-4380975/v1>
- BOZA ESPINOZA T.E., KESSLER M. 2022. A monograph of the genus *Polylepis* (Rosaceae). *PhytoKeys* 203: 1–274. <https://doi.org/10.3897/phytokeys.203.83529>
- BOZA ESPINOZA T.E., QUISPE R., KESSLER M. 2019. Taxonomic reevaluation of the *Polylepis sericea* complex (Rosaceae), with the description of a new species. *Systematic Botany* 44(2): 324–334. <https://doi.org/10.1600/036364419X15562052252225>
- CÁCERES Y., Lachmuth S., Schrieber K., Marcora P., Renison D., Hensen I. 2021. Germination responses of two key mountain tree species to single and combined fire-related stresses: does elevational origin matter? *Flora* 280, 151832. <https://doi.org/10.1016/j.flora.2021.151832>
- CÁCERES Y.Z., TORRES B.C., ARCHI G.C., MALLQUI R.Z., PINEDO L.E., TRUCIOS D.C., QUISPE K.O. 2024. Analysis of Soil Quality through Aerial Biomass Contribution of Three Forest Species in Relict High Andean Forests of Peru. *Malaysian Journal of Soil Science* 28: 38–52. <https://www.researchgate.net/publication/381433845>
- CAI N., XU Y., CHEN S., HE B., LI G., LI Y., DUAN A. 2016. Variation in seed and seedling traits and their relations to geo-climatic factors among populations in Yunnan Pine (*Pinus yunnanensis*). *Journal of Forestry Research* 27(5): 1009–1017. <https://doi.org/10.1007/s11676-016-0228-z>
- CANALES GUTIÉRREZ Á., RUTH Y., VILCA H. 2020. Germination power of *Polylepis incana* with application of different water treatments [Poder germinativo de *Polylepis incana* con aplicación de diferentes tratamientos de agua]. *Revista Cubana de Ciencias Forestales* 8(3): 495–506. http://scielo.sld.cu/scielo.php?script=sci_arttext&pid=S2310-34692020000300495
- CARABAJA-HIDALGO A., SABATÉ S., CRESPO P., ASBJORNSEN H. 2023. Brief windows with more favorable atmospheric conditions explain patterns of *Polylepis reticulata* tree water use in a high-altitude Andean forest. *Tree Physiology* 43(12): 2085–2097. <https://doi.org/10.1093/treephys/tpad109>
- CCOPI-TRUCIOS D., BARZOLA-ROJAS B., RUIZ-SOTO S., GABRIEL-CAMPOS E., ORTEGA-QUISPE K., CORDOVA-BUIZA F. 2023. River Flood Risk Assessment in Communities of the Peruvian Andes: A Semiquantitative Application for Disaster Prevention. *Sustainability (Switzerland)* 15(18), 13768. 15 p. <https://doi.org/10.3390/su151813768>
- CUNNINGHAM S.C., CAVAGNARO T.R., MAC NALLY R., PAUL K.I., BAKER P.J., BERINGER J., THOMSON J.R., THOMPSON R.M. 2015. Reforestation with native mixed-species plantings in a temperate continental climate effectively sequesters and stabilizes carbon within decades. *Global Change Biology* 21(4): 1552–1566. <https://doi.org/10.1111/gcb.12746>
- DE FATIMA V., DE ALMEIDA T., MARTINS S., FAUSTINO I., JACOVINE L., ALBUQUERQUE T., OLIVEIRA K., DA ROCHA S. 2023. Influence of meteorological variables on the initial growth of seedlings of native forest species in vegetation restoration plantings. *Scientia Forestalis* 51, e3952. 12 p. <https://doi.org/10.18671/scifor.v51.13>
- DUDENHÖFFER J.H., EBELING A., KLEIN A.M., WAGG C. 2018. Beyond biomass: Soil feedbacks are transient over plant life stages

- and alter fitness. *Journal of Ecology* 106(1): 230–241. <https://doi.org/10.1111/1365-2745.12870>
- EVERINGHAM S.E., OFFORD C.A., SABOT M.E.B., MOLES A.T. 2024. Leaf morphological traits show greater responses to changes in climate than leaf physiological traits and gas exchange variables. *Ecology and Evolution* 14(3), e10941. 16 p. <https://doi.org/10.1002/ece3.10941>
- FLORES GARNICA J.G., REYES CÁRDENAS Ó. 2022. Proceso de georreferenciación estándar de arbolado en una plantación forestal comercial. *Revista de Geografía Agrícola* 69: 81–94. <https://doi.org/10.5154/r.rga.2022.69.04>
- FRANCO-LEÓN P., NAVARRO GUZMAN M.A., OYAGUE PASSUNI E., IGNACIO APAZA J., JOVE CHIPANA C. 2024. Fragmentation, birds, and conservation of the '*Polylepis*' Forest in Southern Peru. *Cuadernos de Investigación Geográfica* 50(1): 179–199. <https://publicaciones.unirioja.es/ojs/index.php/cig/article/view/5823>
- HSU H.-W., STUKE M., BAKKER J.D., KIM S.-H. 2024. A time-to-event analysis for temperature dependence of seed germination in four conifers: Ecological niche and environmental gradients. *Forest Ecology and Management* 562, 121972. <https://doi.org/10.1016/j.foreco.2024.121972>
- IUCN 2024. IUCN Red List of Threatened Species. Version 2023. <https://www.iucnredlist.org/species/> (Downloaded on 11 November 2024).
- LARA W., BRAVO F., SIERRA C.A. 2015. measuRing: An R package to measure tree-ring widths from scanned images. *Dendrochronologia* 34: 43–50. <https://doi.org/10.1016/j.dendro.2015.04.002>
- MARCORA P.I., TECCO P.A., FERRERO M.C., FERRERAS A.E., ZEBALLOS S.R., FUNES G., HENSEN I. 2021. Are populations of *Polylepis australis* locally adapted along their elevation gradient? *Neotropical Biodiversity* 7(1): 246–256. <https://doi.org/10.1080/23766808.2021.1940049>
- MENDIVELSO F. 2022. Prueba no paramétrica de correlación de Spearman. *Revista Médica Sanitas* 24(1). <https://doi.org/10.26852/01234250.578>
- MORALES MORENO L.V., FUENTEALBA B., SEVILLANO C.S., GÓMEZ M.I., SEGOVIA-SALCEDO M.C., RENISON D., GREEN D., AUCACA C., HENSEN I. 2018. Opportunities to bridge gaps between science and practice in restoration of *Polylepis* ecosystems. *Ecologia Austral* 28(1): 291–300. <https://doi.org/10.25260/EA.18.28.1.1.529>
- MORALES-ARANIBAR L., MORALES-ARANIBAR C. 2023. Maps of the Distribution of *Polylepis* Forests in Southern Peru. In: Beskopylny A., Shamsyan M., Artiukh V. (Eds), XV International Scientific Conference 'INTERAGROMASH 2022'. Lecture Notes in Networks and Systems, vol 574. Springer, Cham: 3009–3018. https://doi.org/10.1007/978-3-031-21432-5_332
- NAZARNIA N., SCHWICK C., JAEGER J.A.G. 2016. Accelerated urban sprawl in Montreal, Quebec City, and Zurich: Investigating the differences using time series 1951–2011. *Ecological Indicators* 60: 1229–1251. <https://doi.org/10.1016/j.ecolind.2015.09.020>
- NIU S., LUO Y., LI D., CAO S., XIA J., LI J., SMITH M.D. 2014. Plant growth and mortality under climatic extremes: An overview. *Environmental and Experimental Botany* 98: 13–19. <https://doi.org/10.1016/j.envexpbot.2013.10.004>
- OGANA F.N., HOLMSTRÖM E., ALDEA J., LIZINIEWICZ M. 2024. Growth response of *Pinus sylvestris* L. and *Picea abies* [L.] H. Karst to climate conditions across a latitudinal gradient in Sweden. *Agricultural and Forest Meteorology* 353, 110062. 11 p. <https://doi.org/10.1016/j.agrformet.2024.110062>
- ORTEGA-QUISPE K., CCOPI-TRUCIOS D., LOZANO-POVIS A., LLANOS-DEL-PINO A., GABRIEL-CAMPOS E., CORDOVA-BUIZA F. 2024. Sustainable Management of Wastewater Sludge Through Composting with Effective Microorganisms: Enhancing the Growth of *Tecoma stans*. *Organic Farming* 10(2): 108–119. <https://doi.org/10.56578/of100202>
- PAREDES J. 1994. Geología del cuadrángulo de Jauja. *Ingemmet. Bol.* 48. Serie A. Lima. 150 p. <https://hdl.handle.org/10.26852/01234250.578>

- net/20.500.12544/168
- PELSTER D.E., KOLKA R.K., PREPAS E.E. 2009. Overstory vegetation influence nitrogen and dissolved organic carbon flux from the atmosphere to the forest floor: Boreal Plain, Canada. *Forest Ecology and Management* 259(2): 210–219. <https://doi.org/10.1016/j.foreco.2009.10.017>
- PRETZSCH H. 2014. Canopy space filling and tree crown morphology in mixed-species stands compared with monocultures. *Forest Ecology and Management* 327: 251–264. <https://doi.org/10.1016/j.foreco.2014.04.027>
- RANK R., MANETA M., HIGUERA P., HOLDEN Z., DOBROWSKI S. 2022. Conifer Seedling Survival in Response to High Surface Temperature Events of Varying Intensity and Duration. *Frontiers in Forests and Global Change* 4, 731267. 9 p. <https://doi.org/10.3389/ffgc.2021.731267>
- RENISON D., MORALES L., CUYCKENS G.A.E., SEVILLANO C.S., CABRERA AMAYA D.M. 1991. Ecología y conservación de los bosques y arbustales de *Polylepis*: ¿qué sabemos y que ignoramos? *Ecología austral* 28(1): 163–174. <https://doi.org/10.25260/EA.18.28.1.1.522>
- ROVETTA A. 2020. Raiders of the Lost Correlation: A Guide on Using Pearson and Spearman Coefficients to Detect Hidden Correlations in Medical Sciences. *Cureus* 12(11), e11794. 7 p. doi: 10.7759/cureus.11794
- RSTUDIO TEAM 2020. RStudio: integrated development for R. RStudio. Inc., Boston, MA. <http://www.rstudio.com/>
- RUBILAR R.A., VALVERDE J.C., BARRIENTOS G., CAMPOE O.C. 2024. Water and Temperature Ecophysiological Challenges of Forests Plantations under Climate Change. *Forests* 15(4), 654. 18 p. <https://doi.org/10.3390/f15040654>
- SCHMITT S., HÉRAULT B., DERROIRE G. 2023. High intraspecific growth variability despite strong evolutionary heritage in a neotropical forest. *bioRxiv* 2022.07.27.501745. 33 p. <https://doi.org/10.1101/2022.07.27.501745>
- SEGOVIA-SALCEDO M.C. 2011. Los riesgos de la reforestación de los páramos con especies exóticas: el caso de *Polylepis racemosa*. *Proyectos Andinas Páramo* 4(1). 4 p. <https://www.researchgate.net/publication/264383781>
- SENAMHI 2024. National Meteorology and Hydrology Service of Peru. <https://www.senamhi.gob.pe/site/descarga-datos/> (Downloaded on 12 November 2024).
- UGARTE-GUERRA J., ROMÁN-DAÑOBEYTIA F. 2020. Tasas de crecimiento de cuatro especies nativas en plantaciones forestales comerciales en cuatro regiones de la Amazonía peruana. *Revista Forestal del Perú* 35(3): 44–55. <https://doi.org/10.21704/rfp.v35i3.1600>

Acknowledgement to reviewers of the manuscripts submitted to *Forestry Ideas* in 2024:

- Burhanuddin **Adman** – Research and Development Institute for Natural Resources Conservation Technology, Balikpapan, Indonesia
- Marjan T. **Andreevski** – Ss. Cyril and Methodius University, Institute of Agriculture, Skopje, North Macedonia
- Olena **Andreieva** – Polissia National University, Zhytomyr, Ukraine
- Svetoslav **Anev** – University of Forestry, Sofia, Bulgaria
- Dwi Priyo **Ariyanto** – Universitas Sebelas Maret, Surakarta, Indonesia
- Nexhat **Balaj** – University for Business and Technology, Prishtina, Kosovo
- Milan **Barna** – Institute of Forest Ecology, Slovak Academy of Sciences, Zvolen, Slovakia
- Liliana **Baskorowati** – National Research and Innovation Agency, Bogor, Indonesia
- Oleksandr **Bayura** – Uman National University of Horticulture, Uman, Ukraine
- Ettayib **Bensaci** – University of M'Sila, M'Sila, Algeria
- Tatiana Erika **Boza Espinoza** – National Research Institute on Glaciers and Mountain Ecosystems (INAIGEM), Huaraz, Peru
- Victor **Busov** – Michigan Technological University, Houghton, MI, USA
- Matjaž **Čater** – Slovenian Forestry Institute, Ljubljana, Slovenia
- Violeta **Dimitrova** – University of Forestry, Sofia, Bulgaria
- Lachezar **Filchev** – Space Research and Technology Institute, the Bulgarian Academy of Sciences, Sofia, Bulgaria
- Fitriani **Fitriani** – Lampung State Polytechnic, Bandar Lampung, Indonesia
- Ángel Canales **Gutiérrez** – National University of the Altiplano of Puno, Peru
- Süleyman **Gülcü** – Isparta University of Applied Science, Isparta, Turkey
- Pouya **Hassandarvish** – University of Malaya, Kuala Lumpur, Malaysia
- Muhammad **Helmi** – Raden Rahmat Islamic University, Malang, Indonesia
- Yuliati **Indrayani** – Mulawarman University, Samarinda, Kalimantan Timur, Indonesia
- I Nengah Surati **Jaya** – Bogor Agricultural University, Bogor, Indonesia
- Zlatka **Kabatliyska** – University of Forestry, Sofia, Bulgaria
- Dmitrii **Kaplun** – Saint Petersburg Electrotechnical University 'LETI', St. Petersburg, Russia
- Galina **Koptsik** – Moscow Lomonosov State University, Moscow, Russia
- Heidi **Kratsch** – College of Agriculture, Biotechnology & Natural Resources, University of Nevada, Reno, USA
- Stefan **Kuzevic** – Technical University of Kosice, Kosice, Slovakia
- Ababsa **Labed** – Larbi Ben M'Hidi University, Oum El Bouaghi, Algeria
- Ganis **Lukmandaru** – Gadjah Mada University, Jakarta, Indonesia
- Mihajlo **Marković** – University of Banja Luka, Banja Luka, Bosnia and Herzegovina
- Diethart **Matthies** – University of Marburg, Marburg, Germany
- Mikhailo Vasylovych **Matusiak** – Vinnytsia National Agrarian University, Vinnytsia, Ukraine
- Boyan **Milchev** – University of Forestry, Sofia, Bulgaria
- Budi **Mulyana** – University of Sopron, Sopron, Hungary

- Budi H. **Narendra** – Ministry of Environment and Forestry, Bogor, Indonesia
 Diana **Natalia** – Tanjungpura University Jl. Prof. Dr. Hadari Nawawi, Pontianak, Indonesia
- Teodor **Nedelin** – University of Forestry, Sofia, Bulgaria
 Ned **Nikolov** – Colorado State University, Fort Collins, CO, USA
 Petia Simeonova **Nikolova** – Swiss Federal Research Institute WSL, Birmensdorf, Switzerland
- Nataliia **Nuzhyna** – Taras Shevchenko Kyiv National University, Kyiv, Ukraine
 Lucas Prado **Oscó** – University of Western Sao Paulo, Limoeiro, Brazil
 Oleksandr Stepanovych **Ostapchuk** – Uman National University of Horticulture, Uman, Ukraine
- Samuel Arung **Paembonan** – Hasanuddin University, Makassar, Indonesia
 Nora **Polláková** – Slovak University of Agriculture in Nitra, Nitra, Slovakia
 Dzhamal **Rakhmetov** – M. M. Grishko National Botanical Garden, National Academy of Sciences of Ukraine, Kyiv, Ukraine
- Jiří **Remeš** – Czech University of Life Sciences in Prague, Prague, Czech Republic
 Arfa Agustina **Rezekiah** – Lambung Mangkurat University, Banjarmasin, Indonesia
 Melya **Riniarti** – Lampung University, Lampung, Indonesia
 Mark Jun **Rojo** – Central Mindanao University, Maramag, Bukidnon, Philippines
 Desislava **Rozdina** – Sofia University ‘St. Kl. Ohridski’, Sofia, Bulgaria
 Katarzyna **Rubinowska** – University of Life Sciences in Lublin, Lublin, Poland
- Andi **Salamah** – University of Indonesia, Depok, Indonesia
 Fusun Balik **Şanlı** – Yıldız Technical University, İstanbul, Turkey
 Argyrios **Sapounidis** – Hellenic Fisheries Research Institute, University of Ioannina, Greece
- Netty Demak H. **Sitanggang** – Institut Pertanian Bogor, Bogor, West Java, Indonesia
 Dariusz **Sochacki** – Warsaw University of Life Sciences, Poland
 Svein **Solberg** – Norwegian Institute of Bioeconomy Research, Ås, Norway
 Anta **Sparinska** – Bulduri Agri-Food Technical School, Jūrmala, Latvia
 Dimitar **Stoykov** – Institute of Biodiversity and Ecosystem Research, BAS, Sofia, Bulgaria
- T. **Trimanto** – Purwodadi Botanic Garden, Indonesian Institute of Sciences, Pasuruan, Indonesia
- Evgeni **Tsavkov** – University of Forestry, Sofia, Bulgaria
 Zoya M. **Tsybalyuk** – M.G. Kholodny Institute of Botany, National Academy of Sciences of Ukraine, Kyiv, Ukraine
- Nikolina **Tzvetkova** – University of Forestry, Sofia, Bulgaria
 Tomàs Artés **Vivancos** – European Commission, Joint Research Centre, Ispra, Italy
 Edi **Wardiana** – Research Center for Horticultural and Estate Crops, National Research and Innovation Agency, Bogor, West Java, Indonesia
- Christine **Wulandari** – Lampung University, Bandar Lampung, Indonesia
 Ridwan **Yahya** – Kyoto University, Japan
 Pınar Arslan **Yüce** – Cankiri Karatekin University, Cankiri, Turkey
 Latiffah **Zakaria** – University Sains Malaysia, Pulau Pinang, Malaysia
 Muta Harah **Zakaria** – University Putra Malaysia, Selangor, Malaysia
 Vesna **Židovec** – University of Zagreb, Zagreb, Croatia