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Extraction of leaf essential oil from 'Khasia' landrace of *Piper betle* L.: An innovative business input to conventional agroforestry system

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Abstract

The 'Khasia' betel leaf-based agroforestry involving timber and non-timber crops is a natural non-destructive, chemical free traditional cultivation system adopted by the tribal communities of North Eastern India. The leaves are harvested five times a month and due to perishability the unsold leaves are discarded that sometime creates environmental pollution due to disease contamination in decomposed leaves. The excess leaves could be utilized for extraction of leaf essential oil having a shelf life of more than three years. The 'Khasia' betel leaves collected from Tripura state was used for extraction of essential oil with yield of 0.44% on fresh weight basis. The gas chromatography-mass spectroscopy (GC_MS) analysis detected 30 medicinally important components predominated by phenylpropenoid, sesquiterpenes and monoterpenes (90.3 %). The major components were chavibetol (50.4 %), chavicol (7.9 %), chavibetol acetate (6.1 %), chavibetol diacetate (2.3 %) and methyl chavicol (1.5 %). This phenylpropenoid class of aromatic compound are useful in pharmaceutical sector. The government aided training of the tribal communities in clean and green technology of essential oil extraction may open a new avenue of income generation, provide environmental sustainability, ecological equilibrium with articulate management of agroforestry waste.

Key words: community training, essential oil extraction, Khasia betel leaf, post-harvest management.

Introduction

Agroforestry system exhibits a sustainable model of land utilization integrating socially and ecologically acceptable agricultural crops with tree species for increasing overall productivity and providing soil restoration. In the North Eastern forest segment of India, a traditional agroforestry

system involving betel-vine (*Piper betle* L.) and other timber or non-timber crop is widely prevalent providing economic benefit to the tribal communities of that region (Das et al. 2016). Several important trees or shrubs with straight bole provide support and shade to the betel creeper, including *Mangifera indica* L., *Areca catechu* L., *Phyllanthus emblica* L., *Termina-*

lia arjuna (Roxb.) Wight & Arn., *Ananas comosus* (L.) Merr., *Musa sapientum* L., *Pongamia pinnata* (L.) Pierre, *Azadirachta indica* A. Juss, *Aegle marmelos* (L.) Corrêa, *Datura innoxia* Mill., *Piper longum* L., *Citrus reticulata* Blanco were found as support plant with vines of betel leaf (Uddin and Mukul 2012). The betel leaf plant is an aromatic medicinal plant and contains important chemical components with widespread application in medicine, pharmacology, food, and flavouring sectors (Guha and Nandi 2019). This agroforestry model is semi-organic in nature and this manure-based organic cultivation produces high-quality toxin free leaf safe for consumption as a masticator or mouth freshener. In betel-vine based agroforestry system in the initial stage of propagation, the upper canopy structure of the support plant is pruned for proper penetration of sunlight to the betel creeper (Nath et al. 2016). Within three to four months after the initiation of the cultivation, the system acquires the phenotype of natural forest system with sufficient canopy growth. The tribal villagers depend on both betel leaf as well as the support plant for their livelihood. The woods, fuel, fruits, betel leaves were harvested and sold for earning money.

For ages, the North Eastern hilly tribes depend on floral diversity for treatment of several ailments (Rahman et al. 2011). The 'Khasia' tribe of North Eastern India holds expertise in ethnomedicinal treatments and use agroforestry plant species for treating more than 40 ailments. The tribal people use green betel leaves for multiple cases including constipation, cough, ear infection, diarrhea, fever, stomach ailment and as aphrodisiac (Rahmatullah et al. 2010). In biodiversity enriched tropical countries the integration of medicinal plants in primary health care system could

serve as a cheap, viable and accessible treatment option compared to expensive drugs having side effects. In herbal treatment, the precise knowledge about the potential plant, confirmation of the potent plant part, formulation of the decoction and the accurate dose of the decoctions are priorities for adoption of the folk techniques (Islam and Sarwar 2020).

The 'Khasia' tribes adopts a special technique for the cultivation of betel leaf creepers and a skilled worker plucks nearly 3600 leaves per day from the creepers with local agro-tools and accessories. The leaves are kept in shaded condition in bamboo basket for 3–4 days with intermittent watering for keeping them fresh for sale in the local market. In the next step 350–360 leaves are made into a bundle called 'mora' and sold through middleman in the market (Haider et al. 2017). In North Eastern states the peak season for betel leaf business is considered from June to August. The monsoon month plays pivotal role in the production of highest amount of betel leaves. Contrary to northern and eastern India the betel leaf agroforestry in North East depends only on cow-dung manure and meager use of insecticide and fungicide leading to harvesting of pristine produce both for fresh consumption and post-harvest processing.

The betel leaf is a perishable cash crop with average shelf life of 4–5 days, withers and rot after 7–10 days in ambient conditions decreasing the market value. As the tribes use betel leaf for herbal treatment, the training of the tribes on extraction of leaf essential oil (LEO) could provide them the opportunity to use the LEO for treatment purposes (Uddin and Mukul 2012). It has been proved that in most of the cases minute amount of essential oil (0.1–6.3 %) out competes the aqueous extracts in anti-bacterial activities (Man et

al. 2019). The community training of the tribal people about the use of clean and green technologies for extraction of essential oil could enable them to use the forest waste for daily healthcare and also for additional income generation through the utilization of an innovative agro-technology. In this paper 'Khasia' betel leaves collected from Tripura state was utilized for extraction of leaf essential oil and subsequent analysis of chemotypic profiling of the LEO was done to investigate the chemical profile and importance of the LEO and in determining its usage in medicinal and aromatic industries.

Material and Methods

Plant material and extraction of essential oil

Specimen betel leaves were collected from Kanchanpur village of Dasda block of North Tripura district of India and brought to the laboratory for further study and analysis. The betel creepers were marked and herbarium of the leaf specimen was preserved in the Genetics & Plant Breeding departmental laboratory. In North Tripura region only 'Khasia' cultivar is grown throughout the forest and leaves were collected randomly from 10 creepers and utilized for extraction of essential oil in a Clevenger-type apparatus using the modified method of hydro-distillation (Mondal 2022). The data was analyzed using MS Excel with three replications for each plant.

Analysis and characterization of the essential oil constituents

The LEO extracted from 'Khasia' betel leaves were utilized for chemical analysis.

The composition of essential oil was detected using gas chromatography-mass spectroscopy (GC-MS) techniques. The identification of individual compounds was carried out using retention index (RI) determined using a homologous series of n-alkanes (C_7 to C_{30} , Supelco Bellefonte, PA, USA) and comparing mass spectra with those of authentic sample, as well as mass spectra library search in NIST and WILEY Mass Spectral Library and by comparing with a mass spectral literature data (Adams et al. 1995).

Result and Discussion

The hydro-distillation technique was able to recover good amount of LEO from the fresh, as well as unsold waste leaves. The LEO yield was found to be 0.44 % on fresh weight basis (Table 1). The colour of the oil is light green with spicy phenolic fragrance. The thrown-away diseased leaf samples where decomposition has just initiated were also included in the trial. The obtained result is analogous to previous study that revealed the betel leaf essential oil recovery from diverse cultivars ranges from 0.09–0.51 % in fresh weight basis (Sankaret al. 1996).

The GC-MS analysis detected the presence of 30 components in the LEO (Table 2). Although 90.3 % of the LEO was characterized, the essential oil is mainly predominated by phenylpropanoid followed by sesquiterpenes and monoterpenes. The 'Khasia' leaves contain highest amount of chavibetol (50.4 %) followed by chavicol (7.9 %), chavibetol acetate (6.1 %), chavibetol diacetate (2.3 %) and methyl chavicol (1.5 %), respectively. The LEO contain a noticeable amount of sesquiterpenes compound β -caryophyllene (4.8 %), γ -muurolene (2.9 %)

and germacrene D (2.9 %) that modulates the anti-microbial and insecticidal property of the plants. The phenylpropanoid families of secondary metabolites are profusely found in the plant kingdom providing defense against UV radiation, high intensity light rays, phytoalexins (Deng and Lu 2017). All the components identi-

fied in leaf essential oil of 'Khasia' cultivar of *Piper betle* possess valuable medicinal properties taking from malarial treatment, hepato-protective (Depiet al. 2020), anti-cancerous activities (Preethy et al. 2017), as well as profound action against drug-resistant tuberculosis (Endriyatno 2022).

Table 1. Morpho-biochemical parameters of betel leaf.

Length of leaves, cm	Breadth of leaves, cm	Petiole length, cm	Weight, g	Oil content, %	pH	Taste	Texture	Colour
14.1 ±1.83	9.8 ±1.11	3.11 ±0.69	3.31 ±0.68	0.44 ±0.05	4.07 ±0.23	Spicy	Rough, pubescent	Green with brown patches

Note: Oil content was calculated relative to fresh weight.

Table 2. Essential oil composition of betel leaf accession.

Type of constituent	RI ^a	RI ^b	Area, %	Molecular weight, g·mol ⁻¹	Type	Uses
Leaf alcohol	851	851	0.1	-	Alcohol	Sweet aroma, fights diseases
α-pinene	933	932	0.1	136.23	Monoterpene	Treatment of urinary stone, bladder
Camphene	949	946	0.1	136.24	Monoterpene	Anti-inflammatory, anti-oxidant
Sabinene	973	969	t	136.23	Bicyclic monoterpene	Anti-fungal, anti-inflammatory
β-myrcene	990	988	0.1	136.23	Monoterpene	Flavouring agent
p-cymene	1024	1020	t	134.21	Monoterpene	Anti-inflammatory, anti-oxidant
Limonene	1029	1024	0.1	136.24	Cyclic monoterpene	Anti-obesity, anti-cancer, anti-oxidant, anti-fungal
1.8-Cineole	1031	1026	0.8	154.25	Monoterpene	Respiratory, cardiovascular diseases
(Z)-β-ocimene	1035	1032	0.1	136.23	Acyclic monoterpene	Anti-fungal, scent
(E)-β-ocimene	1046	1044	0.5	136.23	Monoterpene	Cosmetics, anti-perspirant

Type of constituent	RI ^a	RI ^b	Area, %	Molecular weight, g·mol ⁻¹	Type	Uses
γ-terpinene	1057	1054	t	136.23	Monoterpene	Anti-oxidant
Terpinolene	1088	1086	t	136.23	Monoterpene	Anti-proliferative
Linalool	1099	1095	0.6	154.25	Monoterpene	Insecticide, fragrant
Camphor	1141	1144	nd	152.23	Monoterpene ketone	Antiseptic, antipruritic
Terpinen-4-ol	1177	1174	t	154.25	Terpineol	Antimicrobial, anti-inflammatory
α-terpineol	1191	1186	0.1	154.25	Tertiary monoterpene	Anti-convulsant, anti-nociceptive
Methyl chavicol	1200	1195	1.5	148.2	Phenyl propane	Stomach cramp, muscle tension
Decanal	1204	1201	0.1	156.2	Aldehyde	Anti-fungal
Chavicol	1256	1247	7.9	134.18	Phenyl propane	Headache, toothache
Safrole	1291	1285	t	162.19	Phenyl propanoid	Antibiotic, antiangiogenic
α-cubebene	1347	1345	1.9	204.35	Tricyclic sesquiterpene	Flavour and fragrance
Eugenol	1358	1356	0.3	164.2	Phenyl propanoid	Toothache, gastrointestinal
Chavibetol	1376	1370	50.4	164.2	Phenyl propanoid	Antioxidant, fungicide
α-copaene	1377	1374	0.7	204.36	Sesquiterpene	Anti-malarial, anti-cancer
β-bourbonene	1385	1387	0.3	204.35	Sesquiterpenoid	Anti-microbial
β-cubebene	1391	1387	0.5	204.35	Tricyclic sesquiterpene	Citrus like scent, flavor
Methyl eugenol	1405	1403	0.3	178.23	Phenylpropanoid	Flavour, anaesthetic
β-caryophyllene	1421	1417	4.8	204.36	Sesquiterpene	Anti-inflammatory, anti-microbial
β-copaene	1433	1430	0.2	204.35	Tricyclic sesquiterpene	Pesticide, flavouring
α-humulene	1453	1452	1.0	204.35	Monocyclic sesquiterpene	Appetite suppression, weight loss
γ-murolene	1477	1478	2.9	204.35	Sesquiterpene	Anti-bacterial
Germacrene D	1481	1484	2.9	204.35	Sesquiterpene	Perfume, anti-microbial
Bicyclogermacrene	1495	1500	0.8	204.35	Germacrene	Malaria and tumor
δ-cadinene	1523	1522	1.6	204.35	Sesquiterpene	Malaria, headache, toothache, burn
Chavibetol acetate	1527	1524	6.1	176.21	Benzoate ester	Influenza, fatigue, diuretic

Type of constituent	RI ^a	RI ^b	Area, %	Molecular weight, g·mol ⁻¹	Type	Uses
Unknown	1557	-	0.2	-	-	
Chavibetol diacetate	1644	-	2.3	164.20	benzoate ester	Influenza, fatigue, diuretic
α-cadinol	1654	1652	1.0	222.37	Sesquiterpenoid alcohol	Hepatoprotective, drug resistant tuberculosis
Unknown	1744	-	t	-	-	-
Total component			90.3			

Note: RI^a – calculated Retention Index in Elite-5 capillary columns using a homologous series of *n*-alkanes (C₇-C₃₀ hydrocarbons), RI^b – Retention Index in published library (Adams et al. 1995), t – trace ≤0.1 %, IM – identification method based on the GC-FID results (RI) and mass-spectrometry detection (MS), nd – not detected. Suvaas (*Ocimum basilicum* L.) data was taken from Srivastava et al. (2022).

The 'Khasia' leaf essential oil (EO) is a promising product with multiple utilities and shows a substantially higher shelf life than aqueous extract and could be stored in small vial in any safe place at tribal home occupying small area. The price of an essential oil distillation unit is approximately \$ 2450 and price of 50 ml oil is nearly \$ 16. The machine works well with nominal electricity cost for 12–15 years. In each day nearly three cycles of extraction could be done with a recovery of more than 300 ml of EO per day. A continuous flow of water is required for the hydro-distillation for three hours but that water is re-cyclable. The unsold leaves could be utilized for oil extraction and has the potential to make a prominence in the medicinal industry. The community training of the tribal villagers on essential oil extraction could support them in livelihood enrichment. Male and female members of 'Khasia' tribe contributes equally to betel leaf-based agroforestry. The cultivation, pruning, mulching, cutting was done by male counterparts, whereas the processing and marketing operations were done

by female members. The betel leaf is harvested five times a month and in such a condition the training of betel leaf oil extraction could aid the tribal villagers to utilize excess betel leaves for essential oil extraction. As 'Khasia' betel leaf is grown in a wide area in North Eastern Indian states, the storage and extraction protocol will remain the same and could be adopted by several tribes of that region for large scale Khasia betel-leaf essential oil production.

Conclusions

The betel leaf-based agroforestry is typical to tropical countries mainly covering the South East Asian countries of the world. The betel leaf creeper is a predominant non-timber cash crop of North Eastern (NH) India. The perishable nature of the crop produces huge amount of agro-waste. The waste and unsold leaves of the agro-forestry system could be utilized for essential oil (EO) extraction. The extracted EO is golden in colour with spicy,

strong fragrance, chavibetol rich, costly product with a shelf life of more than three years. The Khasia tribe of NH region utilizes betel leaf for daily health care and it is regarded as an important ethno-medicinal plants. The training of the forest people on Khasia betel leaf essential oil extraction technique could support them in the incorporation of simple, clean and green agro-techniques in advancement of traditional agroforestry with waste management. This system could act as an innovative cottage industry and may be adopted by the South East Asian countries for meaningful utilization of the perishable betel leaves and diverse parts of the creepers for essential oil extraction. The framework involving betel leaf germplasm could unwind novel avenues for sustainable utilization of the non-timber agroforestry models with futuristic profitable business strategies along with judicious agro-waste management.

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Deciphering the anthropogenic challenges of peat swamp forest degradation to improve awareness and emphasis on restoration in South Sumatra

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Abstract

Peat Swamp Forest (PSF) belongs to a unique ecosystem and will be very difficult to be recovered if already degraded, thus we need to be fully realised about this ecosystem. The research aimed to analyse the anthropogenic challenges of PSF degradation, to improve awareness and to make urgent emphasis in providing their restoration. This research was conducted within 2020–2023 in South Sumatra Indonesia. The research method applied field survey and laboratory work. Current PSF was threatened its existence, its various practical functions were neglected and favoured the economic benefits of oil palm (*Elaeis guineensis* Jacq.). The peat thickness is for determining its agriculture suitability, peat depth is allowed for agriculture if its thickness is < 100 cm (classified as marginally suitable, S2), peat thickness > 300 cm must be conserved (classified as not suitable, N). Patterns of PSF degradation are creating impermeability layers of water; changing plant type and density; and modifying plant types of land cover. The pattern of changing plant type and density (executed by land speculators) determined two-third the PSF degradation. Hence, the government has to make policy decisions based on PSF vulnerability and the negative impact of its degradation at global, state, provincial, district, sub-district and local levels and followed by agricultural programs on how to improve income of local people.

Key words: impermeable layers, land cover, patterns, plant density, plant type.

Introduction

Common functions of peat swamp forest (PSF) include biomass production (agriculture, fishery, forestry etc.); providing biodiversity (species, variety and gene); storing, filtering, buffering and transforming; physical media (roads, infrastructure etc.); sources of raw materials (water,

peat, fuel, energy etc.); and cultural heritages (Armanto and Wildayana 2022; Armanto et al. 2022, 2023; Le Goff et al. 2022). All functions have to be maintained, so that PSF can actually function as a life supporting system for humans. Some PSF benefits in our daily life are various ranging from fertilisers, power sources, fuel producers and other benefits (Holidi

et al. 2019, Guth et al. 2022, Vilas-Boas et al. 2022).

PSF belongs to a unique ecosystem and will be very difficult to be recovered if they are already degraded, thus we need to be fully aware of this ecosystem (Negassa et al. 2019, Suab and Avtar 2020, McGuire et al. 2022). About 77 % of South Sumatra PSF have been cleared for plantation and agricultural purposes in a broad sense. This way of clearing largely did not follow conservation methods, i.e., by cutting, burning, and continued conversion to oil palm (*Elaeis guineensis* Jacq.) (Armanto 2019a, 2019b). In the last twenty years, there has been considerable release of carbon into the atmosphere from land and affecting the global carbon cycle. It was estimated at least 5 % of the total anthropogenic carbon emissions was contributed from fires (Wildayana and Armanto 2018a, 2018b; Armanto and Wildayana 2023).

The negative impacts of biological environments arise and PSF loss is not fully realised by the local assessors because of the lack of overall data on it, particularly on biodiversity, physical and chemical characteristics. The research aimed to analyse the anthropogenic challenges of degradation, to improve awareness and to make urgent emphasis in providing PSF restoration.

Materials and Methods

This research was conducted within 2020–2023 in Ogan Komering Ilir (OKI) District, South Sumatra Indonesia (Fig. 1). Geographically the research location is located to the North with coordinates 104°57'13.23" E and 3°19'55.95" S; East 105°3'21.72" E and 3°24'0.99" S; South 104°57'13.20" E and 3°30'7.64" S; and West of 104°53'16.70" E and 3°25'38.62"

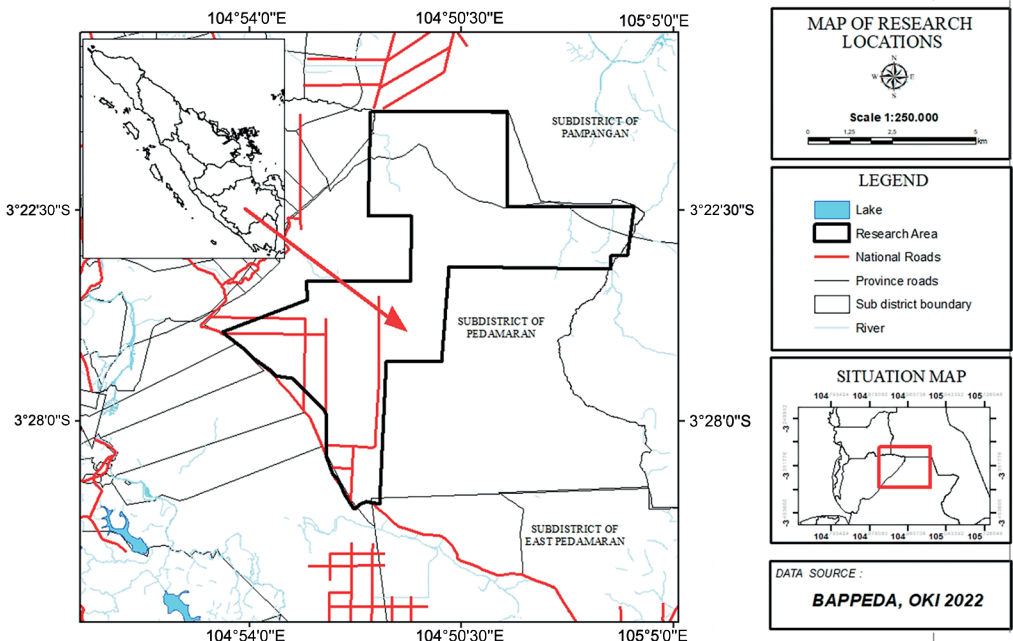


Fig. 1. The location of research area in OKI District, South Sumatra.

S with a research area of 10,000 ha. The research method applied was a field survey method. Sampling method was carried out by three types of PSF land uses (i.e., oil palm; secondary forest; bush and natural grass). Data collection was conducted through three techniques, namely direct field observation, in-depth interviews with respondents and field documentation. Interviews with respondents were carried out using questionnaires. From each land use, 20 respondents were determined by random sampling. The total number of respondents interviewed from the three land

uses was 60 households (15 % of the total population of 400 households). In-depth interviews were done with key informants, most of whom came from community leaders consisting of sub-district heads, village leaders and NGOs. The collected data were analysed, presented and performed in forms of tables and charts.

The general description of the respondents is presented in Table 1. The PSF thickness was measured using a peat drill at randomly selected viewing points and mapped to determine the area by planimetry. Land suitability was carried

Table 1. General characteristics of selected 60 PSF respondents.

Variables	Parameters	Description and unit	Average $\pm$ StDev
Physical PSF	Land suitability	Suitable (S2, peat depth < 100 cm), %	6.46 $\pm$ 2.88
		Marginally suitable (S3, peat depth of 100–300 cm), %	85.15 $\pm$ 14.65
		Not suitable (N, peat depth > 300 cm), %	8.39 $\pm$ 4.70
	Area	PSF size, ha	5.02 $\pm$ 4.92
Socio- economics	Age	Age at conversion, years	40.51 $\pm$ 7.34
	Education	Education length, years	12.55 $\pm$ 1.87
	Trading	Involvement in trading at the time of PSF acquisition, years	26.06 $\pm$ 4.21
	Public service	Involvement in public service at the time of PSF acquisition, years	15.53 $\pm$ 3.37
	Subsistence	Involvement in subsistence farming at the time of PSF acquisition, years	20.66 $\pm$ 6.72
	Commercial plants	Involvement in commercial plants at the time of PSF acquisition, years	27.75 $\pm$ 5.91
	Local	Identification with local tribe group, %	27.09 $\pm$ 8.97
Respondents	Non-local immigrants	First generation immigrants from non-local tribes, %	32.73 $\pm$ 6.63
	Not local farmers & not immigrants	Second or more generation immigrants from non-local tribes, %	40.18 $\pm$ 5.88
	No PSF experience	Experience through plantation, %	5.70 $\pm$ 4.92
Previous experience	Upland agriculture experience	Experience through other plantations, %	44.02 $\pm$ 7.73
	Plantation labourers	Experience through oil palm plantation, %	50.28 $\pm$ 6.11
	Conversion start age	Years since planting the PSF	10.42 $\pm$ 3.99

out according to Regulation of the Agriculture Ministry of Concerning Guidelines for Land Suitability in Agriculture Commodities Nr 79/Permentan/OT.140/8/2013.

Results and Discussion

General characteristics of selected respondents

In general, more than 74 % of farmers have an average PSF size of < 5 ha, only a small proportion of farmers have > 5 ha. It means that most of the owners only fulfil their own family needs (Table 1). The respondents' age at the time of conversion was approximately 41 years with an average length of education of 12 years. They have been involved in trading (average 26 years); or domiciled as a civil servant (15 years); or subsistence farming (20 years); or cash crops (27 years).

The respondents' socio-economic status was adequate, in general they were not beginners in business. However, this data appeared to be gender biased because almost all of the respondents were male (99 %). These respondents generally had permanent jobs, had sufficient capital and this PSF conversion was only an extension of their work to increase income. In general, respondents converted PSF using their own capital, without banking assistance.

PSF respondents in general were dominated by non-immigrants non-local farmers (40 %); followed by non-local immigrants (33 %); and local farmers (27 %). The few respondents who came from local farmers were caused by a lack of motivation and a lack of understanding of PSF developments. The results of the field and laboratory data analysis are presented in Table 1.

About 45 % of respondents were Javanese, Banjar and Bugis because PSF are generally located in immigrant villages occupied by Javanese, Banjar and Bugis. These tribes are ethnic groups who moved to South Sumatra to develop PSF. Javanese who migrated could come directly from Java or who migrated from other provinces in Sumatra. Banjar, Bugis and local groups moved to the PSF location due to difficulties in obtaining agricultural lands. Previous experience described the activities of farmers prior to PSF conversion, including working as plantation labourers or through ownership of other PSF farming. The main respondents played an important role in driving PSF expansion.

PSF extent and land suitability

The research site has an area of about 10,000 ha having four PSF thicknesses, i.e., less than 100 cm (6.46 %), 100–200 cm (24.90 %), 200–300 cm (60.25 %), and above 300 cm (8.39 %). Commonly, PSF was used for oil palm and pineapple (*Ananas comosus* (L.) Merr.), rice fields and uncultivated fields. Generally, the PSF thickness of < 100 m was commonly utilised for gardening, fishery, housing, offices and industry. PSF thickness of 100–200 cm was used for food plants, 200–300 cm for plantation plants, oil palm and above 300 cm for groundwater infiltration, conservation and protected area (Fig. 2).

PSF suitability for agriculture is mainly determined by the thickness and maturity of peat, peat depth is still allowed to be cultivated for agriculture if the thickness is < 100 cm, and even then it is included in the marginal appropriate class (S2). If the thickness is > 300 cm, then the peatland must be conserved (classified as not suitable, N).

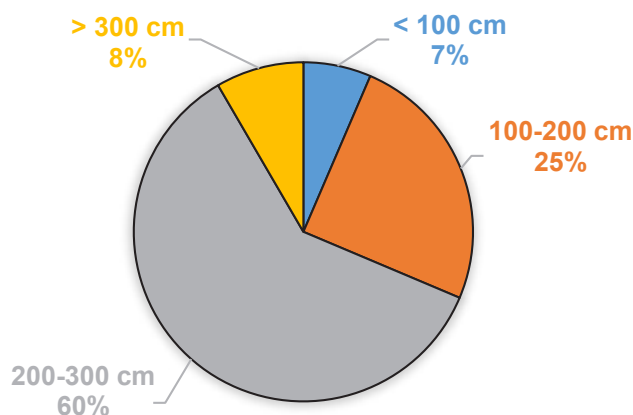


Fig. 2. PSF extent and distribution based on their peat depths.

From year to year PSF undergoes land conversion for oil palm, settlements, and agriculture in general. Similarly to the condition of the people, farmers are more likely to sell land to the industry sectors for the development and opening of new oil palm. The number of food plants' farmers from year to year decreased compared to large industry plantations. This change occurs because farmers choose other work skills to meet their current life interests, so they prefer to work as tenants of other land farmers. The status of conservation areas (peat depths > 300 cm) was now becoming increasingly unclear and have not been categorised as a protected area by the government. Some protected areas were licensed by the government as a concession area for oil palm. Therefore, the main management objectives for the conservation area (PSF thickness > 300 cm) are becoming increasingly unknown. Even though the area declaration has been established by the government as a National Park, it was still unable to provide long-term conservation guarantees due to illegal logging, forest and fire, as well as land conversion. Consequently

the naming of the area as a conservation area was confused, but peat degradation action occurs in a planned and structurally planned manner.

According to Ministry of Agriculture Nr. 38/2020 (Ministry of Agriculture 2022) concerning Implementation of Indonesian Sustainable Oil Palm Certification, oil palm plantations are required to provide 30 % conservation areas of the total concession area. The reality showed that oil palm plantations are only able to provide less than 30 %, resulting in

negative impacts on the environment, such as floods, droughts and decreased biodiversity.

Anthropogenic challenges of PSF degradation

Based on our observation results, PSF areas that have been logged and burned repeatedly have resulted in lower density and diversity of stems compared to areas that have only been burned once and with no history of logging. PSFs that have been burned before have the potential to burn again because of the availability of dead, unburnt biomass and existing vegetation that can become a reserve of bio-fuels for subsequent fires. Analysis of fires in the field shows that repeated fires are mostly found in areas with non-forest secondary vegetation. The high intensity and frequency of fires has fuelled vegetation that is dominated by pioneer vegetation, low-growing herbaceous plants, with few trees. Forest and land fires have reduced the surface elevation, resulting in burning areas with vegetation and PSF, which have had a serious impact on flooding and

hindered plant regeneration.

Types of anthropogenic challenges of PSF degradation in the research area are summarised in Figure 3, and are generally divided into two types, namely instinctive ones and permanent challenges. Perma-

nent ones are very difficult or impossible to fix, rather than instinctive that are often technical or economic in nature and easier to overcome. In this research, permanent challenges are dominantly concerned due to field reality.

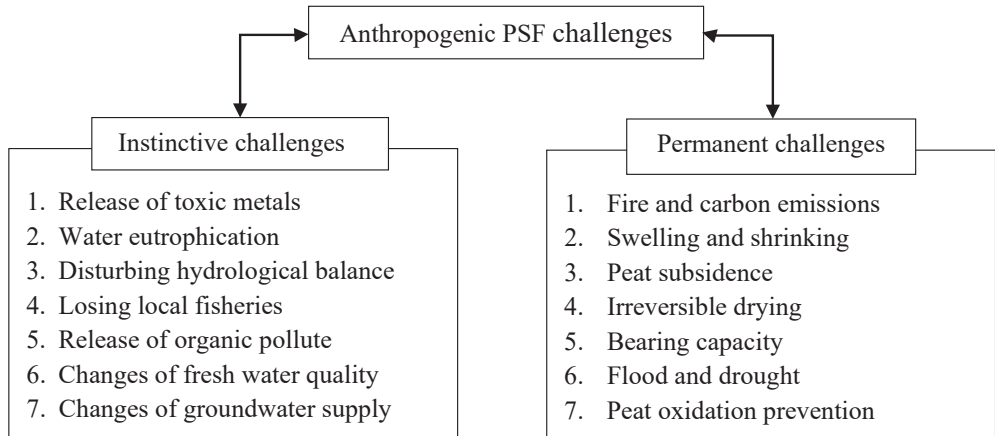


Fig. 3. Types of anthropogenic challenges of PSF degradation.

Patterns and executors of PSF degradation

There are three patterns and executors and each had different characteristics in terms of the executors. They are presented in Table 2.

Creating impermeable layers of water

The impermeable layers of water are made through PSF hardening and compaction processes for roads, industries and residential (Zuhdi et al. 2019). Impermeability means that water cannot penetrate the PSF vertically due to the presence of impermeable layers on the surface. This pattern is generally carried out by powerful investors, government, state officials with a total area of 2123 ha (21.23 %). It is difficult for the government

to regulate as policy makers, because they have strong access to policy makers at any level (sub-district, district, provincial and national).

Changing plant type and density

Changing plant type and density is generally carried out by land speculators (businessmen who want to monitor their land ownership) by conducting land clearing, illegal logging and cultivating oil palm plantations. As a result, several PSF areas were neglected and dominated by oil palm, shrubs and natural grasses. This pattern makes a dominant contribution of 5978 ha (59.77 %) and has the most global impact on the hydrological cycle, water production and in the long term can trigger acute and prolonged water shortages and flooding.

Table 2. Patterns and executors of PSF degradation.

No	Patterns	Respondents		
		Speculators (businessmen)	Governments	Local farmers
A. Creating Impermeable layers of water				
1	Making road	√	√	-
2	Making industries	√	√	-
3	Making residentials	√	√	-
B. Changing plant type and density				
1	Land clearing	√	-	-
2	Illegal logging	√	-	-
3	Oil palm plantation	√	-	-
C. Modifying plant types of land cover				
1	Subsistence farming	-	-	√
2	Sonor system	-	-	√
3	Local fisheries	-	-	√

Note: Sonor system means the way how to produce food farming based on the local treatments.

Modifying plant types of land cover

This pattern was generally carried out by local people living in the surrounding PSF areas to meet their needs of firewood and sustaining their life. PSF degradation through this pattern was relatively minimal (1899 ha or 18.99 %). Firstly, PSF areas were cleared by using fire and cultivated for food plants agriculture (sonor system). Although the land clearing was relatively small, the fire use for land clearing was widely used because harvesting of agricultural products (e.g., rice and corn) was carried out by farmers each three months. The harvesting residues were all destroyed by burning, the farmers did not put the harvesting residues into the soils because it was so expensive and required a lot of manpower. Consequently, impacts on PSF degradation also needed to be

considered. This could be seen from the number of hotspots in the region of the sonor system, which was the maximum. The government needed to make some solutions on how to manage PSF areas in order to control all of them properly. If all patterns could be controlled, then they could be automatically controlled.

The executors of PSF degradation are given in Figure 4, showing that businessmen played important roles compared to others, who were 60 %, 21 %, and 19 % respectively. The role of local people in causing PSF degradation occurred because they were unable to carry out large-scale land clearing, while businessmen were able to conduct macro-scale land clearing efforts which were only mostly aimed at economic development. This was exacerbated by the government's relatively small role (only 21 %), so that

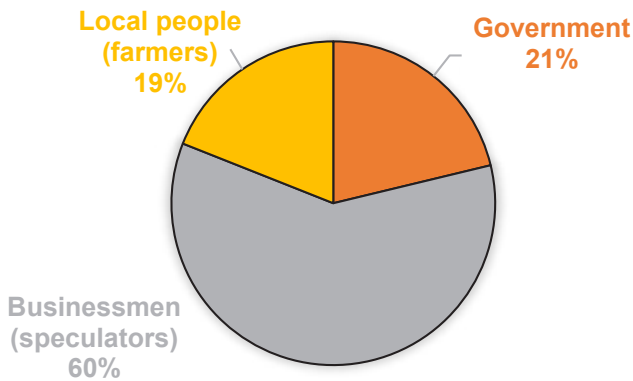


Fig. 4. Executors of PSF degradation.

most of the businessmen's efforts to develop economic activity in PSF were very difficult to be controlled both by the government and local people.

Conclusions

The current peat swamp forest status was threatened its existence, the various functions of practical PSF were neglected and favoured the economic benefits of oil palm. The peat suitability for agriculture is mainly determined by its thickness and maturity, peat depth is still allowed to be cultivated for agriculture if the peat thickness is < 100 cm, and even then it is included in the marginal appropriate class (S2). If the peat thickness is > 300 cm, then the PSF must be conserved (classified as not suitable, N). Patterns of PSF degradation are creating impermeability layers of water; changing plant type and density; and modifying plant types of land cover. Thus, it is imperative to restore and conserve the PSF areas. The pattern of changing plant type and density (executed by land speculators) determined two-third the PSF degradation. Hence, the government has to make policy decisions

based on PSF vulnerability and the negative impact of PSF degradation at global, state, provincial, district, sub-district and local levels and followed by agricultural programs on how to improve income of local people.

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Assessment of physico-chemical status of waters in selected sampling sites of Chepelarska River, Bulgaria

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Abstract

Water is not just a commercial product, but a common good and a limited resource that should be protected and used in a sustainable manner, in both terms – of quality and quantity. However, water is under pressure due to variety of uses from different sectors, such as industry, agriculture, tourism, transport, energy, etc. which leads to deterioration in the quality of water resources. The aim of the study is to assess the chemical status of Chepelarska River, right tributary of the main river in Southern Bulgaria – Maritsa, based on more than 10 physico-chemical parameters for the period 2015–2021. Data were provided by the Executive Environmental Agency (ExEA) to the Ministry of Environment and Water (MOEW). The evaluation of the studied river is based on Ordinance No N-4/14.09.2012 (concerning the characterisation of surface waters) and Ordinance on environmental quality standards for priority substances and some other pollutants (Resolution of the Council ... 2010), in accordance with the requirements of Directive 2000/60/EU. To achieve the set goal, the Canadian Complex Water Quality Index (CCME-WQI) was applied, through which a complex and differentiated assessment of the status of water in terms of its quality was carried out. The obtained results show constant excesses of the norms for the indicators nitrite-nitrogen (N-NO_2), total nitrogen (TN), total phosphorus (TP) and orthophosphates (P-PO_4). According to them, organic pollution of river waters is mainly of agricultural and municipal-domestic origin. The industrial activities in the area carried out for decades to this day could be considered as a source of a possible pollutant that led to an increased content of heavy metals – copper (Cu), cadmium (Cd), manganese (Mn) and especially zinc (Zn). The obtained new data is a key emphasis in making management decisions to mitigate and prevent current and future pollution of river systems, as a result of various anthropogenic impacts.

Key words: chemical status, complex index, water quality.

Introduction

The protection and use of water in a manner that adequately meets the needs of modern society requires precise monitoring of water quality. This becomes possible through the application of a scientifically based system for assessing of water quality status, aligned with European and national regulatory requirements. At EU level, a key element of water legislation is The Water Framework Directive 2000/60, establishing the framework for action in the field of water policy (European Parliament ... 2000). The Water Framework Directive outlines the legal framework for protection and restoration of clean water in the EU and for ensuring its long-term and sustainable use. In this sense, by implementing a complex of programs, plans and measures in accordance with the current regulatory requirements, the member states must strive to achieve at least a 'good' status of water resources.

The status of river waters in physico-chemical aspect is very often determined by one or several parameters. This represents a differentiated assessment of water quality. In general the water quality is influenced by a complex of natural (hydrological, atmospheric, climatic, topographical and lithological) and anthropogenic factors. The suspension of the normal functioning of aquatic ecosystems is a result of the pollution of river waters mainly due to anthropogenic activity. The sources of water pollution (according to the way of entry into the water body) can be grouped into two types: point and diffuse. Regardless of how pollutants enter river waters, they degrade river ecosystems. Agricultural activities, for example, are usually concentrated near rivers, but since river floodplains are fertile enough, pollution can be registered if the cultivat-

ed areas are improperly disposed of and overdosed with phosphorus and nitrogen fertilizers. Livestock breeding also has an adverse effect on the quality of river waters. Wastewater from animal breeding complexes is heavily polluted mainly with organic and inorganic suspended substances. Industrial processes are sometimes a source of pollution and discharge into rivers of chemical waste products (e.g. heavy metals such as Fe, Mn, Cd, Cu, Zn). In this sense, water quality assessment is fundamental to the study and use of water. In our days, modern practices of determining the qualitative status of river waters and its change in time and space, the so-called complex assessments, are constantly being developed and applied. The use of new methods for complex determination of water quality is a public challenge of particular importance (Uddin et al. 2021). In this sense, carrying out a complex analysis and evaluation is a good basis for the preparation of environmental policies and the implementation of more effective control in areas marked by significant anthropogenic impact on river systems. Water management is one of the most important aspects of government in any developed country. The modern Bulgarian legislation, which refers to the water sector and is part of the legislation of the EU, is based on the Act on waters – published in the State Gazette No 67 of 27.07.1999, and is in force since 28.01.2000 (Anonymous 2000).

The aim of the study is to assess the chemical status of Chepelarska River, right tributary of the main river in Southern Bulgaria – Maritsa, based on more than 10 physico-chemical parameters for the period 2015–2021.

A distinctive innovation in this study is the achievement of a comprehensive assessment of water quality of Chepelar-

ska River. The waters are mainly used for electricity production, irrigation, industrial water supply and to satisfy the domestic needs of the population. In addition, historically, the waters of the river have been heavily polluted by the lead and zinc industries, located near the town of Laky (European Parliament ... 2010, Hristova 2012, Basin Directorate ... 2018, Radeva 2022). The problem studied in the present article is also partially examined by Dospatliev et al. (2015), who studied the content of Pb and Cd for the period 2010–2013. Gartsyanova 2022 evaluated the water quality of Maritsa River basin and respectively partially referred the research for Chepelarska River. New analysis was performed by Gecheva et al. in 2023 when the authors studied the accumulated heavy metals and trace elements in aquatic plants, and on this basis they obtained a macrophyte-based assessment of ecological status. The various studies by far conducted on Chepelarska River are too limited. Taking into account this fact, it is necessary to conduct a regional study of its physico-chemical status. In this sense, the assessment of river water quality is based on Ordinance No N-4 of 14.09.2012 concerning the characterisation of surface waters (according requirements for good condition) and Ordinance on environmental quality standards for priority substances and some other pollutants (Resolution of the Council ... 2010, MOEW 2012).

Materials and Methods

Study area

Chepelarska River (known also as Asenitsa or Chaya) is a right tributary of Maritsa River with a length of 85.9 km and

a catchment area of 1010 km² (Hristova 2012). The river originates in the area of Rozhen saddle, in the Western Rhodopes. Near the town of Chepelare and the village of Hvoyna, it flows in a narrow valley with valley extensions (small hollows). It changes its direction several times from northeast to northwest. In the Upper Thracian lowland, it divides into arms and flows as a right tributary into Maritsa River in the area of Katunitsa village. Its river network is characterised by a high density in its upper course, draining the eastern slopes of Chernatitsa and Dobrostan hills. The average multi-year runoff is determined by the changing weather conditions throughout the year and due to the trends in climate change. Chepelarska River has a rain-snow recharge with a maximum in the period April–May and minimum – September and August. It flows into Maritsa River at 148 m a.s.l., 2.5 km south of the village of Rogosh (Basin Directorate ... 2018).

Nowadays the qualitative status of the surface waters in Chepelarska River basin is a direct reflection of the diverse and dynamic combinations of natural and anthropogenic factors. Its analysis and assessment are based on data for the period from 2015 to 2021 and provided by the Executive Environmental Agency to MOEW. Due to the specificity of the sampling and completeness of the source data, three sampling sites presented in Table 1 and Figure 1 were selected to achieve the purpose of the present study. In addition, the sampling sites of the studied watersheds were chosen so as to be representative both for the areas with developed agricultural activity and animal husbandry, tourism, and for those with industrial production. Chepelarska River after the town of Chepelare (Ch1) and near village of Bachkovo (Ch2) belongs to

Table 1. Sampling sites of the study.

Sampling sites	Code of the sampling sites	Coordinates, °	Code on the map
Chepelarska River after the town of Chepelare	BG3MA05295MS0630	N 41.73509 E 24.68886	Ch1
Chepelarska River near village of Bachkovo	BG3MA00523MS0600	N 41.94440 E 24.85281	Ch2
Chepelarska River before mouth	BG3MA05213MS0570	N 42.14570 E 24.87722	Ch3

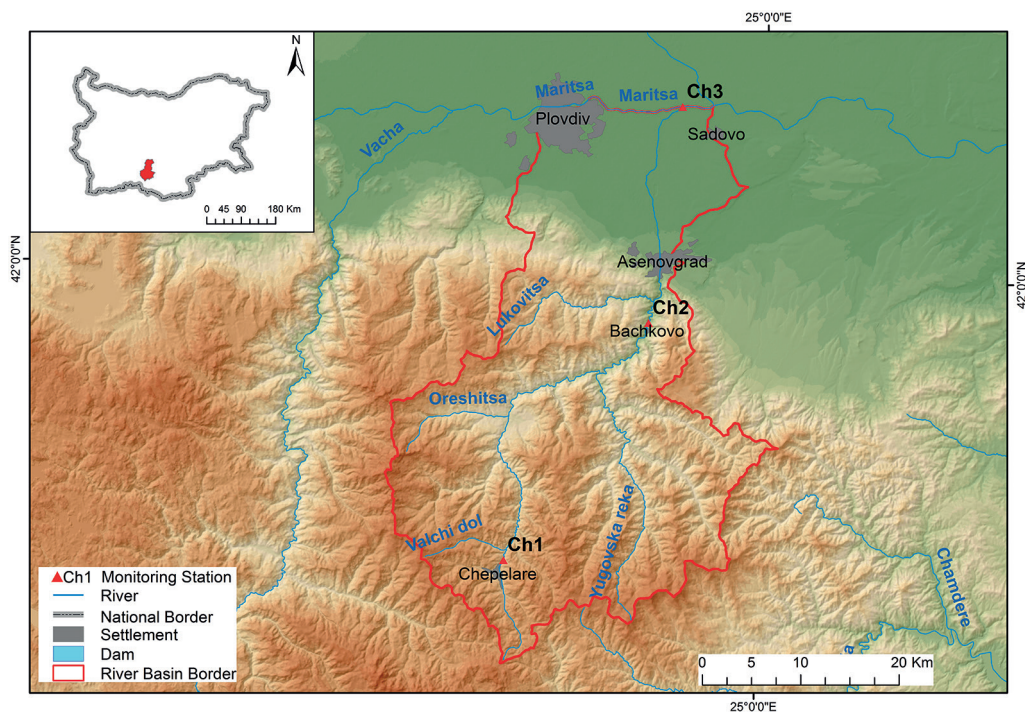


Fig. 1. Study area.

R3 (mountain) water type, and Chepelarska River before mouth (Ch3) is defined as water type R5 (semimountain) (Basin Directorate ... 2018).

Methods

Water quality assessment and monitoring of rivers have been globally used all over the world to determine the sources

of pollutants and their effects in temporal and spatial aspect. Evaluation of surface water quality usually is a complicated process due to undertaking multiple parameters which impact the overall water quality (Jafarabadi et al. 2016).

The quality status of the sampling sites in this study was assessed by following physico-chemical parameters: pH, electrical conductivity, dissolved oxygen, ammonium nitrogen (N-NH_4), nitrates

(N-NO₃) and nitrites (N-NO₂), orthophosphates (P-ortho-PO₄), content of total nitrogen and phosphorus (TN and TP), biochemical oxygen demand (BOD₅) and the concentration of eight chemical elements – iron (Fe), manganese (Mn), cadmium (Cd), lead (Pb), arsenic (As), copper (Cu), nickel (Ni), zinc (Zn). The physico-chemical parameters were collected at least 4 times a year (MOEW 2012).

In order to provide a standardised method for comparing the status and changes in water quality based on selected parameters and summarizing the obtained data in an easily expressed and easily understood format, a number of quality index assessments have been developed and are being developed. According to studies by some authors, more than 20 water quality indices are applied worldwide today (Uddin et al. 2021). Complex index assessments have a number of advantages compared to the differentiated ones used in hydroecological practice. They provide an opportunity not just a complex assessment to be received, but also a differentiated assessment of water quality. Complex indices provide a generalised assessment of the status of water quality, by obtaining a simple or rank value that can be easily understood by the public, water distributors, planners, managers and policy makers (Lumb 2006). Questions related to the quality of river waters in our country have become more relevant since the end of 1990s. Varbanov and Gartsyanova (2015, 2017) have significant contribution to the application of the complex methods for assessment and analysis of the status of surface water bodies in Bulgaria.

In order to achieve the set goal, the Canadian Water Quality Index was applied in the present study (CCME 2001). The anthropogenic impact affecting the status of

water bodies by physico-chemical parameters or quality elements using this index is determined by using three components. The first one is the range of impact (F_1), which reflects the range of quality indicators that do not meet the normatively defined threshold values. The second component is frequency (F_2), showing the ratio of the values at which the content of potential pollutants with a concentration above the permissible norms was found and the total number of values according to the studied indicators. The third indicator – amplitude (F_3), expresses the degree of deviation of the values that do not meet the legal norms, compared to the corresponding reference values. The water quality index is calculated according to the formula (1):

$$WQI = 100 - \left(\frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732} \right). \quad (1)$$

The divisor 1.732 normalises the obtained value in the interval from 0 to 100, where 0 means ‘worst quality’, 100 – ‘best quality’ of water. CCME-WQI applied model also offers the following differentiation of the water quality status: excellent ($WQI = 95-100$), good ($WQI = 80-94$), fair ($WQI = 65-79$), marginal ($WQI = 45-64$), poor ($WQI = 0-44$) (CCME 2001).

Results and Discussion

The waters of Chepelarska River at the sampling site Ch1, both at the beginning and in the end of the study period are defined as ‘highly polluted’. For 2017 and 2018, CCME-WQI values classifies the river in ‘good’ condition category. From 2019 to 2021, the values of WQI again place the river in this section in the category of ‘poor’ condition, with the lowest value WQI being recorded in 2020 (figs 2 and 3).

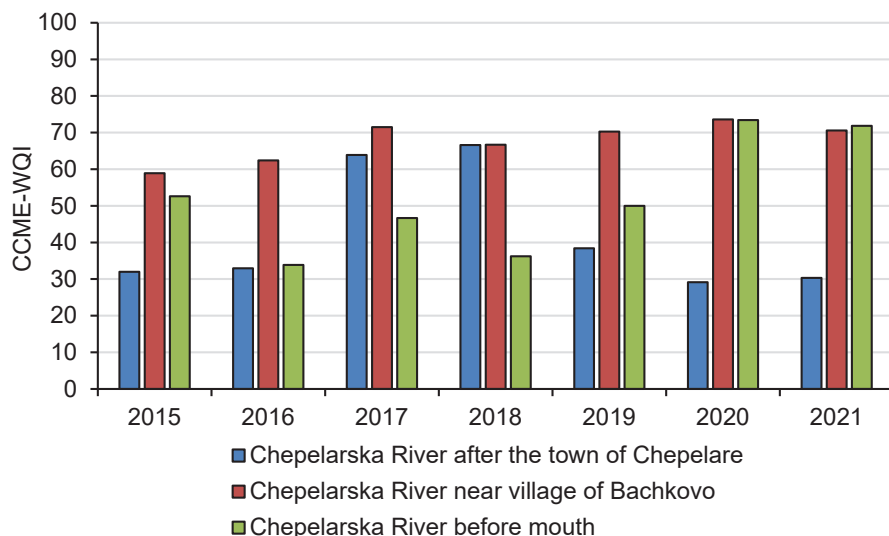


Fig. 2. Change in *WQI* values calculated for Chepelarska River in the period 2015–2021.

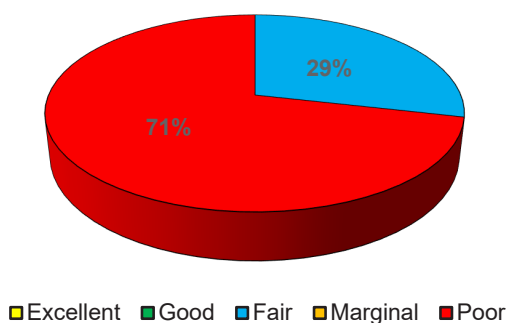


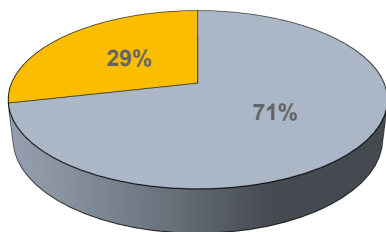
Fig. 3. Distribution of water quality status of Chepelarska River at the point Ch1 by categories for the period 2015–2021.

From the analysis of the available data and the results obtained for the physico-chemical pollution of surface waters by each component, it is clear that their deteriorated condition is mainly due to the 'bad' values of the following indicators: dissolved oxygen, N-NO_2 , in rarer cases of N-NO_3 , TN and TP, P-PO_4 and BOD_5 . The excesses of the registered values are most often up to 10 times. An exception is the measured values for the indica-

tor N-NO_2 , for which values in 2015 and 2016 exceedance by more than 25 times from the permissible thresholds were reported (for example on 08.08.2016 – $0.77 \text{ mg}\cdot\text{L}^{-1}$). In 2016, single excesses between 10 and 25 times over the permissible values for the TP, P-PO_4 indicators were also recorded. From 2019 to the end of the research period, the average excess of the normative thresholds for the values of the indicator TP, is between 10 and 25 times, and the cases of deviation exceeding 25 times are not rare (e.g. 08.05.2020 – $2.48 \text{ mg}\cdot\text{L}^{-1}$, 05.02.2021 – $0.90 \text{ mg}\cdot\text{L}^{-1}$). The results obtained on the basis of the available data show that during the research period only Mn was in concentrations not exceeding the standards by more than 10 times. The maximum content was established on 10.11.2020 – $72.1 \text{ }\mu\text{g}\cdot\text{L}^{-1}$.

As a result of the applied complex *WQI*, it was concluded that Chepelarska River at the sampling site Ch2 in 2015 and 2016 was in a 'critical' quality status. River waters are defined as 'polluted'. From

2017 to the end of the period, according to the calculated values of CCME-WQI, the river in this section changes its category and meets the regulatory requirements for 'good' surface water quality. The applied index has the highest value in 2020 – 73.6 (figs 2 and 4).



■ Excellent ■ Good ■ Fair ■ Marginal ■ Poor

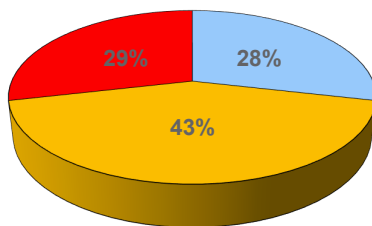
Fig. 4. Distribution of water quality status of Chepelarska River near Ch2 by categories for the period 2015–2021.

The obtained results designate that of the analysed indicators, N-NO_2 , P-PO_4 , TN and TP showed an excess of norms up to 10 times. An exception is the pH indicator, for which individual cases of discrepancies up to 10 times the reference values are detected. On 11.13.2021, a maximum content of TP of $0.36 \text{ mg} \cdot \text{L}^{-1}$ in this section of the river course was detected, exceeding the legal requirements between 10 and 25 times. Heavy metal values generally met the quality standards except for Cu and Zn. The content of these metals was usually 10 times higher than the permissible level. A single deviation from the reference content for Cd was registered in 2016. In February 2017 and 2018 (respectively on 08.02 and 26.02) the concentration of Cu exceeded the permitted thresholds between 10 and 25 times (the detected values are $12.7 \text{ } \mu\text{g} \cdot \text{L}^{-1}$ and $11.6 \text{ } \mu\text{g} \cdot \text{L}^{-1}$). From 2019 to 2021, the content according to this indicator registered

deviations from the norms up to 10 times.

According to the values of the quality index, from the beginning of the period to 2019, in the lower courses the surface waters of Chepelarska River, before flowing into Maritsa River, are defined as 'polluted' and 'highly polluted'. Therefore, the river in this section does not meet the requirements for 'good' physico-chemical condition. The lowest CCME-WQI score was registered in 2016 and was just 33.9. In 2020 and 2021, the quality status of the river waters slightly improves and the river reaches the criteria for good quality status, the index values are 73.4 and 71.9, respectively (figs 2 and 5).

The main indicators reflecting the anthropogenic impact in the estuarine area are electrical conductivity, N-NO_2 , N-NH_4 and TN. Their values usually exceed the norms up to 10 times. In 2016 (11.08.2016 and 08.11.2016, $4.00 \text{ } \mu\text{g} \cdot \text{L}^{-1}$ and $3.00 \text{ } \mu\text{g} \cdot \text{L}^{-1}$, respectively) a N-NO_2 content exceeding 25 times the permissible limit was detected. From 2019 to 2021, dissolved oxygen, N-NO_3 and P-PO_4 were added to the quality indicators listed above that do not meet the legally defined criteria for good water quality. Thus, in practice at this control point, almost all analysed indicators,



■ Excellent ■ Good ■ Fair ■ Marginal ■ Poor

Fig. 5. Distribution of water quality status of Chepelarska River in Ch3 by categories for the period 2015–2021.

which determine the physico-chemical status of the river waters, register excesses over the reference values. Regarding heavy metal pollution in this section of the studied watershed, the deteriorated water quality is due to the high content, in addition to Zn and Cu, also to the excessive concentration of Mn and Cd. Values exceeding the standards up to 10 times for the metals listed above are relatively constant over time. An exception to the values exceeding, often 25 times the regulated standards, is indicated only by Cu. For example, on 11.08.2016, an extreme value of $1160.00 \mu\text{g}\cdot\text{L}^{-1}$ was reported for Zn, and on 10.10.2018, Cd had a content of $265.00 \mu\text{g}\cdot\text{L}^{-1}$.

Based on the results obtained from the applied CCME-WQI, the following summary can be made:

- Spatially, the cleanest are the waters of Chepelarska River at the sampling site on the bridge for the village of Bachkovo, and the most polluted is the river before it flows into Maritsa River.

- The quality status of the surface water varies, both in the individual years of the research period, and also in the different points, and no direction of deterioration or improvement of its quality is established.

- Leading and constant are the excesses of the norms for the nitrite nitrogen (N-NO_2), especially for Chepelarska River after the town of Chepelare (over 25 times), total nitrogen (TN) and total phosphorus (TP) and orthophosphates (P-PO_4) (up to 10 times the requirements for 'good' condition). The deviations from the regulated values for the other physico-chemical indicators are not determined to be so frequent.

- The increased content (very often up to 10 times, not rarely between 10 and 25 times and in some cases over 25 times exceeding the standards) of copper (Cu),

cadmium (Cd), manganese (Mn) and especially zinc (Zn) (the most often more than 25 times of excess) at the sampling site of Chepelarska River before it flows into Maritsa River, determines the extremely poor quality of the river waters in terms of heavy metal content.

- Due to the nature of the identified polluting substances, a negative impact on the quality status of the surface waters of Chepelarska River in the studied sampling sites is caused by the discharge of untreated or insufficiently treated communal-household (incl. and faecal) waters. Additional peril to the quality of surface waters is the presence of numerous micro-dumps, as well as landfills that do not meet the regulated requirements. A significant problem are the settlements with a partially constructed or unconstructed sewage system and, last but not least, agricultural activities – crop farming on one hand, through excessive fertilization and use of plant protection products, and livestock farming on the other, by improper storage of significant amounts of manure.

- CCME-WQI can be used for assessment of water quality for specific purposes. For example – drinking, aquatic life, recreation, irrigation and livestock. Due to the aim of this study it is possible the calculation of the index for these needs to be performed by the authors in the future.

Conclusions

The present study provides important new knowledge for water quality status of Chepelarska River. The quality assessment is obtained by applying of CCME-WQI. The results reveal the advantages of the used complex index, allowing to obtain complex and differentiated assessments for different temporal and spatial generalisations,

both for the whole river and for separate sections of it. It can be assumed that the lack of a wastewater treatment plant in the town of Chepelare and the proximity of Pamporovo resort complex are the main possible reasons for the deteriorated water quality in the relevant section of the studied basin. It is recommended treatment facilities to be built after larger settlements (especially resort complexes) and to reduce pollution from agriculture in the lower reaches of the river, by application of good agricultural practices. One of the limitations in this study was the lack of official information regarding the main diffuse and point pollutants. In this sense providing an up-to-date picture of the physico-chemical status of Chepelarska River is a basis for future planned activities in the catchment area of the river for identifying the specific anthropogenic sources of pollution. This research would be a key emphasis in making management decisions for development and implementation of a complex of programs, projects and measures, specialised in limiting and preventing current and future pollution. At the end, the results obtained of Chepelarska River study contribute to the regional research in the field of water quality and could be used in the future for preparation of a regional qualitative categorization of surface waters in the country.

Acknowledgments

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Assessing the age structure, growth rate and condition of *Squalius cephalus* (Cyprinidae) in the middle and upper streams of the Ogosta River

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Abstract

The aim of this research is to analyse the growth and condition factor of Chub (*Squalius cephalus* L.) from the Ogosta River in north-western Bulgaria. The river belongs to the Danube basin. The study focuses on the Chub population in the middle zone of the Ogosta River, situated above the Ogosta Reservoir. The data was collected in November 2021, with a total of 76 specimens captured using electrofishing techniques. The sample consisted predominantly of three-year-old fish, with the most common size group falling within the size range 11–13 cm. The standard length of the fish ranged from 5.6 cm to 42.6 cm, while the gutted weight varied from 2.2 to 1270.2 g. The estimated length-size (L - S) relationship was determined as $L = 0.1913 \cdot S + 2.701$ ($r^2 = 0.97$), and the weight-length (W - L) relationship was derived as $W = 0.0105 \cdot L^{3.15}$ ($r^2 = 0.99$). The results were evaluated in comparison to 14 local populations of Chub in rivers across Bulgaria. The data indicate a relatively slow growth rate of the species in the Ogosta River. This study is the first of its kind to focus on the Chub population in the middle zone of the Ogosta River following the construction of the Ogosta Dam. It provides valuable insights into the impact of hydropower construction on the Chub population in the area.

Key words: age and size composition, Chub, linear growth, weight growth.

Introduction

The Chub (*Squalius cephalus* Linnaeus, 1758) is widespread in Europe, the Black Sea, the Azov Sea, the Caspian Sea and most of the inland waters in Anatolia (Kottelat and Freyhof 2007, Çiçek et al. 2015, Becer and Sari 2017, Özpiçak et al. 2018). In the West the distribution of the Chub extends to rivers in England (War-

ren et al. 2022) and France, north of the Pyrenees Mountains (Kottelat and Freyhof 2007). In Northern Europe, it is found in the rivers of southern Sweden, Ireland (Caffrey et al. 2008) and Finland (Kottelat and Freyhof 2007), as well as in the Northern Dvina River (Boznak 2020). To the East, the Chub's range reaches the Ural River. On the Balkan Peninsula, the species inhabits the rivers of the Black Sea

and Danube basins (Zhukov 1989, Karapetkova and Zuivkov 1995, Kottelat and Freyhof 2007, Becer et al. 2017, Tanović et al. 2022) and some rivers of the Adriatic basin (Pavlovski et al. 2020). In Asia Minor, the species reaches the Euphrates River basin (Aydin et al. 2015). The Chub is primarily found in the middle and lower zones of fast-flowing rivers, but it can also inhabit colder lakes and reservoirs. As an omnivorous species, the fish's diet consists of a variety of plants and animal organisms, which can vary depending on the age and season (Zhukov 1989). The breeding period for this species in Bulgaria typically lasts from April to July. During the summer, it tends to linger in rapids and pools, while in colder periods it retreats to deeper parts of the river bed (Michaylova 1970).

The Chub is a highly abundant fish species in water courses throughout Bulgaria (Dikov et al. 1994) and is popular among anglers in the country (Raikova-Petrova et al. 2017). Numerous studies conducted in various locations in Bulgaria have examined the age, growth and length-weight ratio of *Sq. cephalus* (Dikov 1988, Mari-

nov 1989, Dikov et al. 1994, Dikov and Zhivkov 2004, Hamui et al. 2007, Raykova-Petrova et al. 2017). Additionally, foreign authors have also studied the species in different parts of its range (Aydin et al. 2015, Becer and Sari 2017, Benzer and Gül 2017, Özpiçak et al. 2018, Özcan and Serdar 2019, Tanović et al. 2022, Warren et al. 2022). This study aims to investigate the growth biology of *Sq. cephalus* in the upper and middle courses of the Ogosta River, which are important habitats for this species. The study specifically focuses on analysing the age and length composition, as well as the length-weight relationship of the Chub population.

Study Area

The Ogosta River, depicted in Figure 1, is the largest watercourse in the Northwestern region of Bulgaria, as shown in Figure 2. With a length of 144.1km, it ranks 7th among the Bulgarian 'largest' rivers (Hristova 2012). Originating below the Vrazha Glava peak (1935 m a.s.l.) in the Balkan Range, the Ogosta River collects

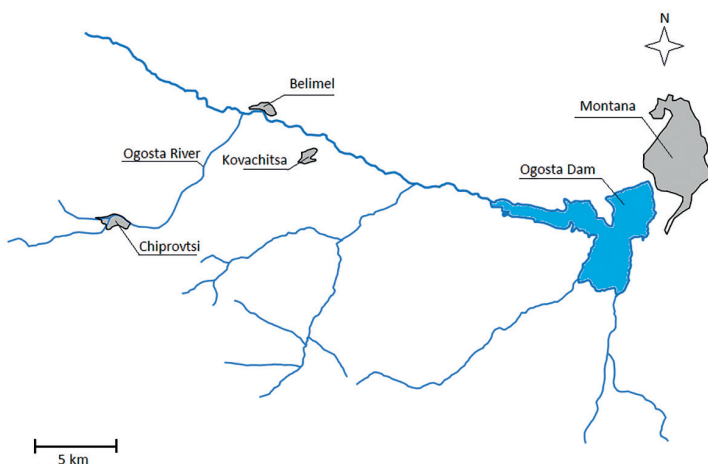


Fig. 1. Schematic map of Ogosta River's middle zone.



Fig. 2. Location of the studied region of Bulgaria.

waters from numerous tributaries before merging with the Danube River near the town of Oryahovo. The construction of the Ogosta Dam in 1986, near the town of Montana, divided the river into two parts. For the purpose of this study, the middle zone of the river, situated above the dam, was selected (see Table 1).

The ecological characteristics of the studied river section were determined as follows: the river meandered through a hilly area, resulting in noticeable fluctuations in the depth of its flow, which were carefully observed and documented. The riverbed consisted of a mix of larger and smaller stones, along with gravel. The terrain was sloping, facilitating a swift water current. The banks were densely covered with black alder and white willow, their branches extending over the riverbed. The tree roots provided hiding spots for fish seeking refuge from the strong current, with hidden holes between the roots serving as shelters. The studied segment of the riverbed was situated at an elevation ranging from 190 to 380 m a.s.l. The research was conducted in the autumn season, during which the measured daily water temperature ranged from 8 to 12 °C, while the recorded levels of dissolved oxygen varied between 4.8 and 7.6 mg·m⁻³.

Materials and Methods

The study utilized a sample of 76 Chub individuals. Sampling was conducted at five designated areas within the middle zone of the Ogosta River (refer to Table 1). The collection of sampling material occurred during the autumn of 2021, employing the technique of electrofishing. For this purpose, a SAMUS 725G converter was employed, capable of delivering up to 640 V direct current (DC), with a frequency of 50 Hz and an output power of up to 200 W. The capture procedure adhered to the guidelines outlined in the EN 14011:2004 instruction for sampling fish using electricity to ensure water quality. The majority of the data was collected in the vicinity of Gorna Kovachitsa and Belimel villages. The largest female specimens were captured in the lower part of the studied section, near the confluence of the Ogosta River with the dam of the same name.

Measurements were taken of the standard length (*SL*) and total length (*TL*) with an accuracy of 1 mm, as well as the gutted weight (*W*) with an accuracy of 1 g. Fish age was determined through the examination of fish scales, utilizing an Olympus CX 31 microscope set at a magnification of 40×.

Table 1. Sampling sites at the Ogosta River: distribution and location.

No	Location	Geographic coordinates		Altitude, m a.s.l.	Date of sampling
		N	E		
1	Near the confluence of the Ogosta River and the Ogosta Dam	43°23'49"	23°03'58"	195	17.11.2021
2	Near the strawberry farm	43°24'20"	23°03'16"	221	17.11.2021
3	Near the village of Gorna Kovachitsa	43°25'20"	23°00'40"	250	17.11.2020
4	Near the village of Belimel	43°25'33"	22°57'30"	305	18.11.2020
5	Near the town of Chiprovtsi	43°23'42"	22°55'26"	380	18.11.2020

The linear growth of a fish was determined by performing a back-calculation of its length (L) based on the diagonal oral radius of a scale (S), as described by Ricker (1979). This relation can be expressed by the following linear equation (1):

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

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

Absolute annual linear incensement was accepted as a characteristic of the growth (Zhivkov 1972), calculated by formula (2):

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

where: t – absolute annual linear incensement, mm; L_n ; L_{n-1} – the average standard length of fish for two consecutive years, cm.

The estimation of weight (W) values, excluding entrails, was conducted using the W - L relation. The formula (3), proposed by Ricker (1979), has been extensively employed by various authors (Zhivkov 1981, 1999; Prodanov 1982; Raikova-Petrova and Zhivkov 1993; Kukushkin 1997; Belomacheva et al. 2005).

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

where: W – gutted body weight, g; L – standard length of fish, cm; a and b – equation coefficients.

To compare the length growth of different Chub populations, a method employed by Zhivkov (1972) involves ranking them based on their average length at the same age.

Condition of a population is studied in three ways:

1) By calculating a classical coefficient (K_f) of the Fulton equation (4).

$$K_f = (W \cdot L^{-3}) \cdot 10^2, \quad (4)$$

where: L – weighted average standard

body length, cm; W – weighted average gutted body weight, g.

2) By calculating a coefficient K_b , using the Fulton equation, but instead of exponent 3, exponent b from the population weight-length relationship from equation (3) is used.

3) By comparison of weight growth (W) of fish from different populations, a method proposed by many authors (Goldspink 1979; Zhivkov 1981, 1999; Basami and Grove 1985; De Silva 1985; Raikova-Petrova 1992). A relation is expressed by the equation (5).

$$W_L = a \cdot L^b, \text{ g}, \quad (5)$$

where: L – standard length of fish, cm; W – gutted weight of fish, g; a and b – equation coefficients.

In order to obtain comparable values of W in equation (3), pre-selected rounded values of L (10, 20, 30 and 40 cm) are substituted in place of L ($L = 10$, $L = 20$, $L = 30$, $L = 40$). Using equation (5) with the listed values of L (cm), allows obtaining the corresponding values of mass W : $W_{L=10}$, $W_{L=20}$, $W_{L=30}$, $W_{L=40}$. The so-obtained mass values for each of the studied populations are then compared (Zhivkov 1981, 1999; Raikova-Petrova and Zhivkov 1993). The association degree between L and S , as well as between W and L variables, was determined by a correlation coefficient (r^2). All data were calculated by using MS-Excel 2010.

Results and Discussion

Age and size composition

In the Ogosta River, the Chub population encompasses individuals ranging from one to five years of age, as depicted in Figure 3. As zero and one-year-old fish are less susceptible to electrofishing, they

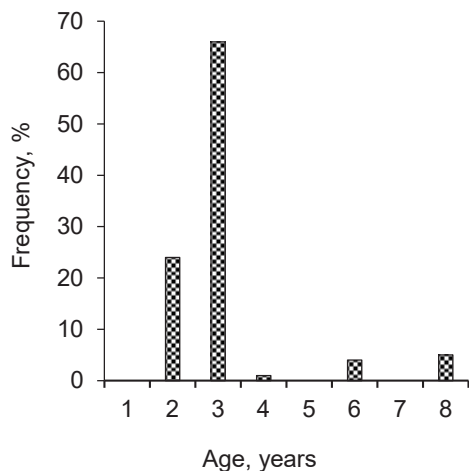


Fig. 3. Age structure of Chub from the Ogosta River.

were not included in the sample. The most abundant individuals among those captured were the three-year-old Chubs, accounting for over half of the catch at 63 %. The second most numerous age group comprised two-year-old fish (24 %). Notably, no five and seven-year-old fish were recorded during the sampling. Six and eight-year-old fish were captured in the winter quarters near the confluence of the Ogosta River and the reservoir bearing the same name. During the warm period of the year, it is likely that older fish take advantage of the abundant food resources in the dam. However, in spring and autumn, when they are searching for more suitable breeding and wintering locations, these fish migrate into the river.

Among the Chub specimens collected from the Ogosta River, the largest individual was an eight-year-old fish measuring 42.6 cm in standard length (*TL* 49.6 cm) and weighing 1270.2 g (with a total weight of 1433.4 g). The mean length of the sample was 13.6 ± 7.9 cm, and the mean weight was 104.9 ± 263.1 g. The size group ranging from 11.1 to 13.0 cm

was the most abundant. Notably, there were relatively few specimens longer than 18 cm (refer to Fig. 4). Since the specimens were collected in late autumn, electrofishing was conducted at the wintering sites. The largest specimens were females that wintered in the pits near the river's confluence with Ogosta Reservoir. Males, as well as young fish, winter in the deeper places further upstream.

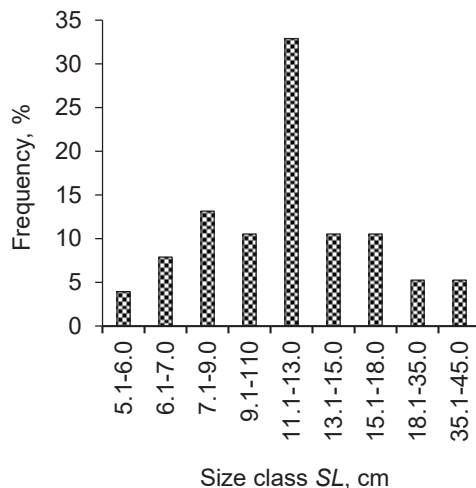


Fig. 4. Size classes of Chub of the Ogosta River.

The stable conditions in the Ogosta Reservoir, along with the abundant food resources and protection from predators like otters and cormorants, create favourable conditions for the Chub to attain older ages and larger sizes. Notably, the age and size of the *Sq. cephalus* specimens from the Ogosta River surpass all previously reported data in the country (Table 2).

Growth rate

The relation between the fish length and the scale radius is represented with the equation (6).

$$SL = 0.19137 \cdot S + 2.701, r^2 = 0.97, \\ n = 76, \quad (6)$$

The growth rate in length is comparatively sluggish during the early stages of development and picks up pace in four, five, and six-year-old Chubs (see Table 3). As the fish age, the yearly growth gradually diminishes and reaches its lowest point in eight-year-old individuals.

By comparing the length (*SL*) of Chub fish of the same age from various rivers that are experiencing a decline (see Table 4), it is evident that the Iskar River, originating from the Danube watershed, and the Veleka River, originating from the Black Sea watershed, exhibit the fastest growth rates. Conversely, the linear growth of Chub in the Ogosta River is among the

slowest in Bulgaria. This can be attributed to the highly disturbed outflow of the Ogosta River, primarily caused by the Ogosta Dam near the city of Montana. The dam divides the river into two distinct sections with contrasting beds and water flow. Upstream of the dam, the river is characterized by shallow depths, swift currents, and a bottom covered with stones, gravel, and sand. Downstream of the dam, the river has a higher water volume, a more even and calm current, and greater depth. The bottom is sandy and adorned with aquatic vegetation. Unfortunately, the dam lacks a fish passage, rendering bottom-up fish migration impossible.

As a result, fish move upstream from the dam to spawn, while younger age

Table 2. Age and maximum size of the Chub from the rivers of Bulgaria.

River	Author	Age, years	Length (<i>L</i>), cm	Weight (<i>W</i>), g
Sredetska	Dikov et al. 1994	3	16.2	77
Fakiyska	Dikov et al. 1994	4	18.0	111
Palakaria	Dikov et al. 1994	6	18.6	114
Vit	Dikov et al. 1994	6	20.4	153
Vit	Dikov 1988	7	29.0	425
Lesnovska	Raikova-Petrova et al. 2017	5	29.5	476
Veleka	Zhivkov et al. 2003	5+	39.0	800
Iskar	Hamui et al. 2007	7+	38.8	1150
Ogosta	Our data 2021	8	42.6	1272

Table 3. Back-calculated standard body length (*SL*) of Chub from the Ogosta River.

Age group	<i>n</i>	Mean calculated <i>SL</i> , cm at age							
		<i>L</i> ₁	<i>L</i> ₂	<i>L</i> ₃	<i>L</i> ₄	<i>L</i> ₅	<i>L</i> ₆	<i>L</i> ₇	<i>L</i> ₈
II	19	4.6	7.5						
III	49	4.6	7.5	11.9					
IV	1	4.0	6.0	10.6	18.0				
VI	3	4.0	5.2	9.0	15.9	24.9	31.8		
VIII	4	4.2	6.2	11.7	18.8	25.5	32.2	35.6	37.5
Mean calculated <i>SL</i> , cm	76	4.3	6.4	10.8	17.6	25.2	32.0	35.6	37.5
Mean observed <i>SL</i> , cm		nd	7.1	12.7	20.1	nd	31.0	nd	39.6
Annual increment <i>t</i> _{<i>L</i>} , cm		4.3	2.1	4.6	7.1	7.8	6.8	3.4	1.9

Note: nd – missing data.

Table 4. Comparison of mean observed length (SL) of Chub at the same age.

River	Source	Total body length (SL), cm							
		L_1	L_2	L_3	L_4	L_5	L_6	L_7	L_8
Kamchia [#]	Marinov 1989	4.2	7.5	10.4	14.0	-	-	-	-
Dunav [#]	Marinov 1989	3.7	8.1	10.6	-	-	-	-	-
Ogosta [*]	Our data 2021	4.3	6.4	10.8	17.6	25.2	32.0	35.6	37.5
Palakaria [*]	Jocev and Dikov 1991	4.2	8.4	12.7	14.5	17.4	18.6	-	-
Vit [*]	Dikov 1988	4.4	8.9	12.7	15.0	17.9	20.4	-	-
Veleka [*]	Dikov et al. 1994	5.0	11.0	15.5	19.5	22.3	-	-	-
Lesnovska [*]	Raikova-Petrova et al. 2017	7.0	11.2	16.0	20.0	23.5	-	-	-
Dryanovska [#]	Marinov 1989	4.7	8.5	12.9	20.5	28.5	-	-	-
Rositsa [#]	Marinov 1989	3.8	8.9	15.7	-	25.7	-	-	-
Lom [#]	Marinov 1989	5.8	9.0	-	-	-	-	-	-
Fakiyska [*]	Dikov et al. 1994	5.1	10.4	15.4	18.0	-	-	-	-
Skutt [#]	Marinov 1989	6.0	10.5	14.2	18.3	-	-	-	-
Veleka [*]	Dikov and Zhivkov 2004	5.8	11.4	15.7	2.3	30.1	-	-	-
Osam [#]	Marinov 1989	6.2	12.8	-	-	-	-	-	-
Sredetska [*]	Dikov et al. 1994	6.4	13.0	16.2	-	-	-	-	-
Iskar [*]	Hamui et al. 2007	6.8	13.6	19.9	25.8	29.6	33.9	35.8	-

Note: * – calculated length; # – observed length.

groups remain and develop in this area. Additionally, the hydroelectric plant near the town of Chiprovtsi (refer to Fig. 1) significantly influences the water levels in the river stretch between Chiprovtsi and Montana. The absence of migration routes, fluctuating water flow, colder temperatures, and faster water in this region further impact the growth of Chub.

Mass was calculated using the well-de-

finied and nearly functional relation (7) between body length and weight (W - L), which is characteristic of the Chub.

$$W = 0.0105 \cdot SL^{3.15}, r^2 = 0.99, n = 76. \quad (7)$$

Chub's weight gain exhibits a distinct pattern, characterized by a significant increase until the sixth year. Although the annual increment decreases in seven- and eight-year-old fish, it remains relatively high, as shown in Table 5. However,

Table 5. Back-calculated gutted body weight (W) of Chub from the Ogosta River.

Age group	n	Mean calculated W , g at age							
		$W1$	$W2$	$W3$	$W4$	$W5$	$W6$	$W7$	$W8$
II	19	1.3	6.0						
III	49	1.3	6.0	25.8					
IV	1	0.8	3.0	17.9	95.0				
VI	3	0.9	1.9	10.7	64.3	264.2	571.1		
VIII	4	1.0	3.3	24.4	108.9	284.8	594.0	815.1	960.2
Mean calculated W , g	76	1.1	4.0	19.7	89.4	274.5	582.6	815.1	960.2
Mean observed W , g		nd	5.0	34.0	177.0	nd	533.0	nd	1113.0
Annual increment, g		1.0	3.0	17.2	71.7	187.9	308.1	221.1	145.1

Note: nd – missing data.

it is important to note that one-year-old fish have a significantly lower calculated mass. This indicates that the conditions for their development in the middle zone of the Ogosta River are not particularly favourable. Additionally, due to their small size, young fish are more susceptible to heavy losses during winter.

Condition factor

The condition of the fish was assessed by calculating the condition factor (K_b) (Table 6) from the rivers Ogosta, Lesnovska and Iskar, as well as comparing fish of the same length (10, 20, 30 and 40 cm) from different water bodies (refer to Table 7).

The condition factor (K_b) indicate that growth conditions for Chub are significantly better in the Iskar River.

Although the mass of older fish from the Ogosta River approaches that of the Iskar River, the condition factor (K_b), which represents the entire population, is nearly four times higher in the Iskar River. This suggests that adult Chub in the Ogosta River benefit from the more abundant food resources in the Ogosta Reservoir. However, juvenile Chub in the middle zone of the river develop under less favourable conditions.

Despite using TL and TW measurements, the data reveals that Chub in water bodies located in Eastern and Black

Table 6. Condition coefficients.

River	Source	Condition coefficients	
		K_f	K_b
Ogosta	Our data 2021	1.67	1.14
Lesnovska	Raikova-Petrova et al. 2017	2.98	2.71
Iskar	Hamui et al. 2007	3.39	4.08

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

Table 7. Weight calculated using Length-Weight relationship at the same length.

Water body	Source	Equation of the total population	Average weights (W_L , g) calculated at the same rounded lengths (L , cm)			
			W_{10}	W_{20}	W_{30}	W_{40}
Terme River	Özpiçak et al. 2018	$TW = 0.005 \cdot TL^{3.29}$	9.9	97.7	372.0	960.6
Karasu River	Özcan and Serdar 2019	$TW = 0.006 \cdot TL^{3.27}$	11.2	107.8	405.8	1039.7
Yedikir Dam	Özpiçak et al. 2018	$TW = 0.007 \cdot TL^{3.21}$	11.4	105.1	386.1	972.1
Akçai River	Özpiçak et al. 2018	$TW = 0.006 \cdot TL^{3.28}$	11.6	112.7	427.1	1098.8
Adbal River	Özpiçak et al. 2018	$TW = 0.007 \cdot TL^{3.22}$	11.7	109.6	404.9	1023.6
Ogosta River	Our data 2021	$GW = 0.0105 \cdot SL^{3.15}$	15.0	133.4	478.9	1185.8
Lesnovska River	Raikova-Petrova et al. 2017	$GW = 0.015SL^{3.03}$	16.3	133.7	457.7	1096.3
Keban Dam	Aydin et al. 2015	$TW = 0.0084 \cdot TL^{3.14}$	16.7	164.1	624.9	1613.9
Iskar River	Hamui et al. 2007	$GW = 0.024 \cdot SL^{2.94}$	20.9	160.4	528.4	1231.0

Note: W_L – weight of the fish, rounded values of length (10 to 40 cm), TW – weight with entrails, GW – gutted body weight, TL – total length, SL – standard length.

Sea Anatolia exhibit lower mass (Table 7). These observed differences can be attributed to the significant variations in climatic conditions between the compared areas. Interestingly, the data for *Sq. cephalus* from Keban Reservoir, situated on the Euphrates River in Southeastern Anatolia, align closely with our results, and in some cases, even exceed them. This finding suggests that, in addition to the warm climate and extended growing season, the dam provides a plentiful food supply. The growth in mass is particularly faster in larger Chubs, as they consume smaller fish within the dam.

Conclusions

Chub in the Ogosta River exhibits slower growth in length compared to those in the Danube River and its Bulgarian tributaries. Furthermore, the overall condition of the species in the Ogosta River is relatively poor. The development of hydro technical infrastructure in the area is likely to have a detrimental effect on the Chub population in the Ogosta River. However, it is worth noting that the Ogosta Dam offers favourable conditions for the feeding and survival of the older age groups of this species.

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Author's statement

The present study was conducted in compliance with national legislation. Electrofishing was performed under a permit issued by the Minister of the Ministry of Agriculture and Food of Bulgaria.

Conflict of interest

The author declares no conflict of interest.

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Timing of migration and breeding phenology of European Turtle dove (*Streptopelia turtur*) in Bulgaria

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Abstract

Between 2014–2022 we monitored the arrival and departure date of European Turtle doves (*Streptopelia turtur*) in Bulgaria. We collected data on first arrival date through observations in different part of the country between April 1 and May 1. In September, we collected data about the end of the species autumn migration. Data on breeding behaviour were collected between 2017–2022 from 41 nests. The correlation between the height of the position of nests and the height of the trees on which they were located was examined by Spearman rank moment test. Two peaks of fledging were established, i.e. at the end of June and the end of July. The mean height of the nests was 4.6 m. There is a significant positive correlation between tree height and nest height ($r = 0.82$, $p < 0.0001$). The mean clutch size was 1.84 and the mean brood size was 1.6 young/successful pair. Breeding success for all period was 82.76 %.

Key words: breeding success, brood size, clutch size, migration timing.

Introduction

European Turtle dove (*Streptopelia turtur* L., 1758) is a game bird of great importance for many hunters in Europe. Its breeding population is declining, and it falls in the category of vulnerable species (Birdlife International 2019). Mediterranean countries hold one of the largest breeding populations in Europe (Fisher et al. 2018). Bulgaria falls in the eastern migration route of

the species (Marx et al. 2016) and at present, it is one of the primary game species. Hunting season spreads from the second Saturday of August until 30 November. But to guarantee the sustainable management of the species, since 2021 the number of hunting days and hunting bags have been reduced.

The purpose of this study is to present data on the arrival and departure dates of the European Turtle dove, as well as data

on the reproduction of the species in the last decade.

Materials and Methods

Between 2014–2022 we collected data on first arrival date of Turtle doves in Bulgaria through observations in different parts of the country between April 1 and May 1. In September, we collected data about the end of the species autumn migration. In the period 2014–2018, observations were conducted mainly in Southern Bulgaria, and between 2019–2022 in the rest of the country (Fig. 1).



Fig. 1. Study area of European Turtle dove in Bulgaria.

Note: triangles indicate the areas where data were collected.

Data were collected through observations carried at different times of the day. Dawn and dusk observations were conducted on the same days. Thus, the morning and evening observations were distributed relatively evenly in time. The dates of the first and last Turtle doves seen were recorded, as well as the dates of the first and last breeding song heard. In addition, the periods in which fledglings were observed were also recorded. Turtle

dove breeding data were collected from 41 nests monitored throughout the period 2017–2022. For each nest we determined its height, the height of tree, tree species, number of eggs, also clutch and brood sizes when possible. The correlation between the nests' height and the trees' height on which they were located was examined by Spearman rank moment test. We used this test to check whether the birds choose a specific part of the tree crown or whether the nests are randomly located in different cases. Breeding success was calculated by the proportion of successful nests/nesting attempts. Under nesting attempt we accept the cases in which a pair was found with a built nest, also for successful nesting we accept the cases with fledglings. The brood size was defined as the number of fledged juveniles per successful breeding pair.

Results

The first arriving birds were observed between April 15 and 26. The first singing Turtle doves were recorded in the period April 22 – May 1. The last recorded songs were between August 09 to August 21 for the entire period for which we have information (Fig. 2, Table 1). Autumn migration was between September 15 and September 23 (Table 1). After that, only single individuals were observed in Sakar Mountain Southern Bulgaria.

The first fledglings were observed at the end of June (2017–2020), but in 2021–2022 were recorded in the first half of June. The second peak of fledging was observed in the second half of July (Table 2).

During the study period, information was collected from 41 Turtle dove nests,

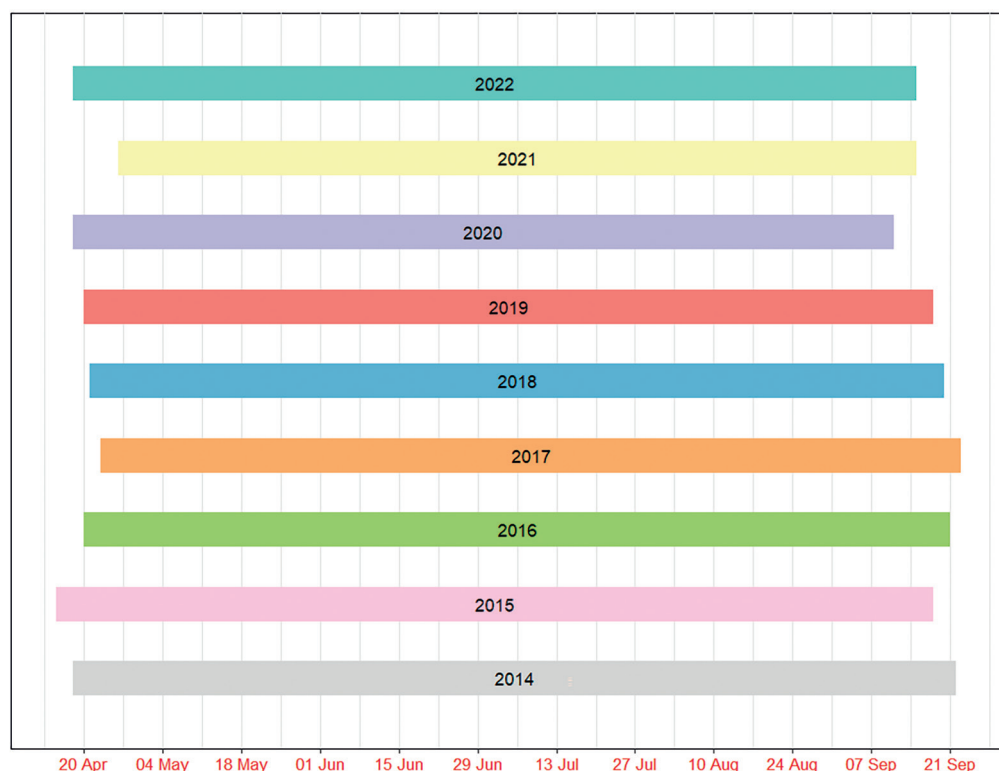


Fig. 2. Dates of arrivals and departures of European Turtle doves in the period 2014–2022.

Table 1. Migration time of European Turtle dove between 2014–2022.

Year	Date of arrival	First song	Last song	Departure
2014	18 – 23.04	28.04	21.08	15 – 25.09
2015	15 – 21.04	26.04	17.08	18 – 30.09
2016	20 – 24.04	23.04	20.08	21 – 30.09
2017	23 – 27.04	01.05	13.08	23 – 30.09
2018	21 – 26.04	01.05	01.08	20 – 30.09
2019	20 – 26.04	01.05	10.08	18 – 30.09
2020	18 – 24.04	22.04	09.08	11 – 20.09
2021	26 – 30.04	30.04	21.08	15 – 25.09
2022	18 – 23.04	23.04	21.08	15 – 25.09

mostly from Southern Bulgaria. The nests were located on 11 tree species from 10 genera (Table 3). The average height at which the nests were located was 4.6 ± 1.4 (2.5–8 m), (mean $\pm$ SD (min-max)),

and the average height of the trees on which they were located was 6.6 ± 1.9 (3.5–11.5 m). There is a significant positive correlation between nest height and tree height $r = 0.82$, $p < 0.0001$. As the

Table 2. Periods of observations of fledglings.

Year	Dates	
	June	July
2017	27 – 29	n/a
2018	22 – 23	n/a
2019	20 – 22	18 – 21
2020	21 – 23	19 – 21
2021	09 – 13	10 – 12
2022	11 – 13	20 – 24

height of trees increases, so does that of the nests. The average clutch size of successful breeding pairs was 1.84 (1–2) eggs and the average brood size was 1.6 (1–2) (mean (min-max)) juveniles. Out of 41 observed nests, five (12.2 %, $n = 41$) were unsuccessful, in 24 cases we observed successful breeding ($n = 41$) and we didn't have information about 12 nests ($n = 41$). Breeding success for all periods was 82.76 % ($n = 29$).

Table 3. Data for breeding of European Turtle dove between 2017–2022, nest height distribution, height of used trees and clutch, brood sizes and nesting success.

No	Species tree/shrub	Nest height, m	Plant species height, m	Data	Clutch size	Brood size	Nesting success
1	<i>Quercus pubescens</i> Willd.	3.4	4.1	06.05.2017	n/a	n/a	n/a
2	<i>Robinia pseudoacacia</i> L.	4	5.5	27.06.2017	1	n/a	0
3	<i>Pinus nigra</i> Arn.	6.5	9	28.06.2017	0	n/a	n/a
4	<i>Quercus pubescens</i> Willd.	3	5	28.06.2017	n/a	n/a	n/a
5	<i>Pinus nigra</i> Arn.	8	9.3	28.06.2017	2	n/a	1
6	<i>Robinia pseudoacacia</i> L.	4.3	5.5	17.05.2018	2	2	1
7	<i>Fraxinus ornus</i> L.	4.8	6	02.06.2018	n/a	n/a	n/a
8	<i>Pinus nigra</i> Arn.	5	7.5	22.06.2018	n/a	1	1
9	<i>Populus</i> sp.	6	11.5	22.06.2018	n/a	2	1
10	<i>Robinia pseudoacacia</i> L.	5.1	7.1	22.06.2018	n/a	1	1
11	<i>Quercus pubescens</i> Willd.	3.8	6.4	23.06.2018	n/a	2	1
12	<i>Pinus nigra</i> Arn.	4.6	8.5	23.06.2018	n/a	2	1
13	<i>Pinus nigra</i> Arn.	5.1	8.6	04.05.2019	0	n/a	n/a
14	<i>Robinia pseudoacacia</i> L.	3.5	6	23.05.2019	n/a	n/a	n/a
15	<i>Quercus pubescens</i> Willd.	5.5	6.4	24.05.2019	2	n/a	1
16	<i>Pinus nigra</i> Arn.	6.5	8.6	24.05.2019	2	n/a	1
17	<i>Acer negundo</i> L.	6.5	8	24.05.2019	2	n/a	1
18	<i>Pinus nigra</i> Arn.	8	9	24.05.2019	n/a	n/a	n/a
19	<i>Quercus cerris</i> L.	4.5	6.5	24.05.2019	2	n/a	0
20	<i>Ulmus minor</i> Mill.	3.1	4.3	24.05.2019	n/a	1	1
21	<i>Prunus cerasifera</i> Ehrh.	3.5	5.2	25.05.2019	n/a	2	1
22	<i>Carpinus orientalis</i> Mill.	2.5	3.5	25.05.2019	2	n/a	1
23	<i>Quercus pubescens</i> Willd.	3.5	5	25.05.2019	2	n/a	1
24	<i>Pyrus</i> sp.	3	4.2	08.06.2019	0	n/a	n/a
25	<i>Quercus pubescens</i> Willd.	4.5	6	19.07.2019	2	1	1
26	<i>Quercus pubescens</i> Willd.	4	6	19.07.2019	2	n/a	1
27	<i>Ulmus minor</i> Mill.	3.2	4.3	19.07.2019	2	2	1

No	Species tree/shrub	Nest height, m	Plant species height, m	Data	Clutch size	Brood size	Nesting success
28	<i>Quercus cerris</i> L.	4.1	6	20.07.2019	2	n/a	0
29	<i>Pinus nigra</i> Arn.	4	8.8	30.05.2020	n/a	n/a	n/a
30	<i>Quercus cerris</i> L.	6.1	8.2	20.07.2020	1	n/a	0
31	<i>Pinus nigra</i> Arn.	4	8.4	22.05.2021	2	n/a	1
32	<i>Quercus pubescens</i> Willd.	3.5	5.3	25.05.2021	2	n/a	1
33	<i>Pinus nigra</i> Arn.	6.5	8	10.06.2021	2	2	1
34	<i>Populus</i> sp.	6.3	8	13.05.2022	2	n/a	0
35	<i>Quercus pubescens</i> Willd.	3.2	4.5	15.05.2022	1	n/a	n/a
36	<i>Pinus nigra</i> Arn.	6.2	9	10.06.2022	0	n/a	n/a
37	<i>Ulmus</i> sp.	4.3	5	11.06.2022	0	n/a	n/a
38	<i>Robinia pseudoacacia</i> L.	3.5	4.5	20.07.2022	n/a	2	1
39	<i>Quercus pubescens</i> Willd.	3	5	20.07.2022	n/a	1	1
40	<i>Quercus pubescens</i> Willd.	4	5	21.07.2022	n/a	1	1
41	<i>Quercus cerris</i> L.	6	8.5	21.07.2022	n/a	2	1

Discussion

The results of our study on arrival times confirm those of the most recent studies in Bulgaria and other parts of Europe (Baptista et al. 2015, Gruychev 2017, Gruychev and Mihaylov 2019). However, we do not have registered early arrivals – at the beginning of April as reported in studies at the end of the last century (Simeonov et al. 1990). The period of data collection shows that in the spring Turtle doves arrive in large numbers in the second half of April (Table 1). The autumn migration of the species is occurring in the second half of September. During the monitored period we have no individual recorded in October. Our study shows a shortening of the stay time of Turtle doves in Bulgaria, compared to the data from the end of the last century (Simeonov et al. 1990).

Here we reported two peaks of fledglings – end of June and second half of July, which indicates likely 2 clutches of the species. Although there are sightings of late-breeding single Turtle doves in August, we still have no evidence of a

definite third nesting in Bulgaria. Our results are in agreement with the already known data from earlier research (Simeonov et al. 1990, Nankinov 1994, Browne and Aebischer 2004, Baptista et al. 2015, Gruychev 2017, Gruychev and Mihaylov 2019).

The average height at which the nests were located was 4.6 m, about 1 m lower than those found in Sakar (Gruychev 2017). The average height of the trees is also lower – 6.6 m. However, the values of these heights fall within those reported in other studies for Europe (Patev 1950, Nankinov 1994, Browne and Aebischer 2004, Browne et al. 2005, Gruychev 2017, Squalli et al. 2022). The height of the nests is positively related to the height of the trees on which they are located. This strategy is related to protecting the nests from terrestrial predators (Guan et al. 2018, Carboneras et al. 2022, Squalli et al. 2022), and in some parts of the range also from reptiles (Mansouri et al. 2020b, Mansouri et al. 2021). A similar correlation between nest and tree height has been reported in other parts of the species range

(Aitouakli and Bensaci 2021).

Breeding success in our study was 82.76 %. Breeding success of Turtle doves in different parts of Morocco was reported to be between 73.8 % and 86.1 % (Hanane and Baamal 2011, Mansouri et al. 2020a). In Algeria mean breeding success was 74.68 % (Aitouakli and Bansaci 2021), in Extremadura, Spain it was 53 %, in Madrid – between 36–58 % (Rocha and Hidalgo 2002). According to recent research in Spain, it was reported as 57 % (Arroyo et al. 2019). The breeding success of Turtle dove in Bulgaria was high, compared to other parts of the species' range for which information is available. Mean clutch size reported in our study was 1.84 eggs/successful breeding pair. This result is higher than the one found for Sakar Mountain between 2014–2016 years (Gruychev 2017). It falls within those reported for the species, being close to that of Morocco (Hanane and Baamal 2011) and higher than for some parts of Algeria, Spain and UK (Browne et al. 2005, Arroyo et al. 2019, Aitouakli and Bensaci 2021). The average brood size for the entire period of the present study was 1.6, with 60 percent of cases having two fledglings and the rest one ($n = 15$, Table 3). This result is in agreement with reports from the UK (Browne et al. 2005).

The higher breeding success in Bulgarian Turtle dove population compared to other populations in Europe shows its importance for the conservation of the species in Europe.

Conclusion

This study reports a shift in the arrival dates of Turtle doves compared to those at the end of the last century. We experience a delay of up to two weeks in some

years in arrival times. The reasons are probably due to factors in the species' wintering grounds. Similar to the known data from previous research, the majority of birds make two broods. According to the collected data, breeding success and clutch size are relatively high. This determines the relatively high reproductive potential of the breeding population of the species in Bulgaria. Likely the limiting factors on the population should be sought in the breeding habitats or along the migration route of the species.

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Authors' statement

The present study was conducted in accordance with the national legislation. Data were collected with a permit issued by the Minister of the Ministry of Agriculture, Food and Forestry of Bulgaria.

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Altitudinal and latitudinal variation in leaf phenology of European beech (*Fagus sylvatica* L.) in Western Bulgaria

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Abstract

Forest phenology has gained increasing attention due to its role in understanding and monitoring the effects of climate change on ecosystems. This article compares the main phenological events of European beech (*Fagus sylvatica* L.) over six years in three mountains in Western Bulgaria – Western Stara Planina, Osogovo, and Belasitsa. The correlations between the start of the season (SOS) date, max of the season (MOS) date, end of the season (EOS) date, and length of the season (LOS), on one hand, and the altitude and latitude, on the other, was assessed. Results showed that all studied phenological events of European beech correlate significantly with the elevation – SOS and LOS positively, while MOS and EOS – negatively. The relations were more substantial in the north-sloped mountains and poorer in the Osogovo Mt., where stands cover northern, but also eastern and southern facing slopes. The latitude was a significant factor for MOS and EOS, which occur the later the further south the mountain is. The latest SOS in Osogovo, which leads to an alignment of LOS with that of Petrohan, decreases altitude's influence on these phenological events. Analysing spatial patterns of vegetation changes can help identify variations in phenological events across different areas.

Key words: end of season, forest phenology, length of season, max of season, remote sensing, start of season.

Introduction

Forest phenology studies the timing and seasonal patterns of various biological events within a forest ecosystem (Stearns and Lieth 1974). These events are often related to the life cycles and behaviours of plants, animals, and other organisms that inhabit the forest. Plant phenology focuses on timing critical events such as budburst,

flowering, fruiting, leaf colour change, senescence, and leaf drop. In recent years, forest phenology has gained increasing attention due to its role in understanding and monitoring the effects of climate change on ecosystems (Richardson et al. 2013, Piao et al. 2019, Gray and Ewers 2021). Changes in phenology can indicate shifts in climate patterns and provide insights into how ecosystems respond to

these changes (Jeong et al. 2011, Zhao et al. 2016). Studying forest phenology can help scientists and researchers better predict and manage potential impacts on forest ecosystems and their services, such as carbon sequestration, biodiversity support, and water regulation. Changes in phenology can have significant ecological implications, as they can impact the interactions between different species within the ecosystem. For example, if the timing of leaf unfolding and drop shifts due to changing climate conditions, it can affect the duration of photosynthetic activity and, as a result, carbon sequestration (Grossiord et al. 2022).

Phenology can change with increasing altitude and latitude due to variations in temperature, light, and other environmental factors. According to Hopkins' law (Hopkins 1918), in temperate latitudes, as the elevation or distance from the equator increase, temperatures tend to decrease, close to linear. Such variations can lead to a delay in the timing of phenological events. Spring phenological events like budburst, flowering, and leaf emergence may occur later at higher altitudes/latitudes than at lower altitudes/latitudes (Čufar et al. 2012, Dittmar and Elling 2005, Schieber et al. 2013). Conversely, autumn events occur earlier at higher altitudes/latitudes. As a result, the growing season at higher altitudes/latitudes is often shorter due to colder temperatures, affecting the duration and timing of various phenological events (Vitasse et al. 2009). In addition, Tzvetkova and Anev (2014) found that the spring phenophases in young beech individuals depend strongly on the autumn temperatures of the previous year. The shorter growing season may compress the time available for plants to complete their life cycles, potentially impacting their growth and reproduction.

Higher altitudes/latitudes are more likely to experience more extended periods of snow cover during the winter (Yue et al. 2022). Snow can act as an insulator, delaying the warming of the ground in spring. It can further delay the onset of spring phenological events. Changes in altitude/latitude can also influence the amount and quality of sunlight that reaches a location. Higher altitudes may receive more intense sunlight due to reduced atmospheric filtering. As a result, the timing of events like flowering and leaf development, which often depend on photoperiod (the duration of light exposure), can significantly impact. On the other hand, Ahrens and Henson (2015) show that on the same day and time, as the latitude increases, the zenith angle increases, which leads to more intensive refraction of light, primarily in the short-wave spectrum; direct solar radiation decreases, which reflects on the temperature regime and, therefore, on the phenology.

Altitudinal gradients can create diverse microclimates within relatively short distances than latitudinal gradients (Leuschner and Ellenberg 2017). These microclimates can lead to variations in phenological timing even within the same altitude range, as local factors such as slope, aspect, and topography can play a significant role. However, the correlation between altitude/latitude and phenology can be complex and vary depending on the specific geographic location, climate, and species present in the ecosystem. Researchers study these patterns to understand better how ecosystems respond to changing environmental conditions (Jeong et al. 2011), including shifts in temperature associated with increasing altitude. Schuster et al. (2014) conclude that cold-air pools considerably impact the vegetation period of deciduous trees.

Therefore, trees in the mid-hillside slopes gain advantages compared to lower elevations.

Observations of phenology using remote sensing devices, such as satellite imagery and Unmanned Aerial Vehicles (UAVs), along with machine learning, are promising techniques (Ciocîrlan et al. 2022). Remote sensing can detect abrupt changes in vegetation cover, indicating the occurrence of phenological events (Morain 1974). For instance, a sudden increase in greenness may indicate the onset of leaf emergence, while a decrease in greenness could signify leaf senescence. Remote sensing can provide information at various spatial scales, from individual pixels to extensive landscapes (Asner and Martin 2008, Pettorelli 2013). Analysing spatial patterns of vegetation changes can help identify variations in phenological timing across different areas. Remote sensing methods can be used to determine phenological events by monitoring changes in vegetation characteristics from a distance, often using satellites or airborne sensors (Kimball et al. 2004). These methods are based on the fact that different phenological stages can result in distinct changes in the reflectance of light from vegetation, which can be detected and analysed using remote sensing spectral indices (Treitz and Howarth 1999). Remote sensing sensors capture data over time, allowing for the creation of time series datasets. Researchers can identify shifts in phenological events by analysing the changes in spectral indices or other vegetation-related parameters over time (Garonna et al. 2014). Algorithms and statistical techniques can be applied to detect the timing of specific events based on these changes. Remote sensing data can be used to develop models that relate phenological events to environmental

variables (Waggoner and Parlange 1974). For example, temperature, precipitation, and photoperiod can influence a phenological event's timing.

Spectral indices are mathematical combinations of different bands of light reflected from the Earth's surface. Examples include the most used index – Normalized Difference Vegetation Index (NDVI) (Pettorelli 2013) and the Enhanced Vegetation Index (EVI) (Jiang et al. 2008, Zhang et al. 2014). These indices are sensitive to changes in greenness and water content in vegetation. They can be used to track the onset of the growing season (budburst), the peak of photosynthetic activity (full canopy), and the senescence of vegetation (leaf colour change). The Plant Phenology Index (PPI) is a relatively new physically based spectral index that quantifies the timing of various phenological events in plants, such as leaf emergence and leaf senescence, and which improved monitoring of plant phenology because strongly related to the leaf area index (Jin and Eklundh 2014). Seasonal trajectories of the PPI (ST-PPI), constructed according to Jönsson et al. (2018), in which the model regression is a sum over double logistic functions (Fischer 1994), adapted by Beck et al. (2006) for NDVI. ST-PPI is used for the calculation of phenological events such as start of season (SOS) date, max of season (MOS) date, end of season (EOS) date, and length of season (LOS) in days. The biophysical parameters available in the Copernicus land monitoring platform at ten-day intervals monitor the vegetation phenology and the productivity of ecosystem habitats. Ciocîrlan et al. (2022) point out that the biophysical parameters based on Sentinel satellites, available on the Copernicus land monitoring platform, showed satisfactory accuracy in predicting an average site value of

the percentage of leaf cover.

The study aimed to assess the correlation between the main phenological events of European beech and altitude and latitude. SOS, MOS, EOS, and LOS of beech stands in three mountains in Western Bulgaria – Stara Planina, Osogovo, and Belasitsa, were compared.

Materials and Methods

Objects

Three typical for European beech (*Fagus sylvatica* L.) mountains in Western Bulgaria (Western Stara Planina, Osogovo, and Belasitsa) were chosen to assess the relation of phenology with altitude and latitude because of the wide variation in elevation

and the position in the north-south direction of these mountains. The experimental-and-training forest range ‘Petrohan’ in Western Stara Planina Mountain, the hunting enterprise ‘Osogovo’ in Osogovo Mountain, and the forest enterprise ‘Petrich’ in Belasitsa Mountain were chosen because of compact European beech stands and their similar longitude. Petrohan and Petrich enterprises are situated on the north slope of the Western Stara Planina and Belasitsa Mountains, while Osogovo enterprise covers northern but also eastern and southern facing slopes (Fig. 1).

Three forest enterprises’ management plans (IAG 2023) were used to describe the experimental objects. Only stands of natural origin, within the studied mountains and with the domination of European beech in the canopy, are evaluated (Table 1).

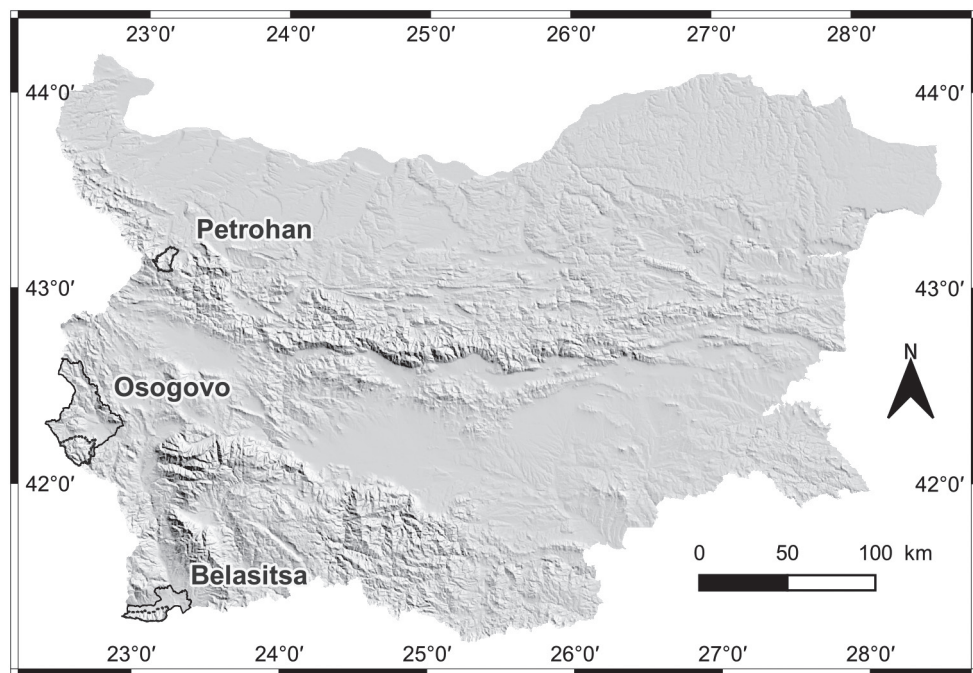


Fig. 1. Experimental objects on a Bulgaria relief map.

Note: Solid lines present the territory of experimental enterprises, while the dot-lines are enclosed their cross-section with studied mountains.

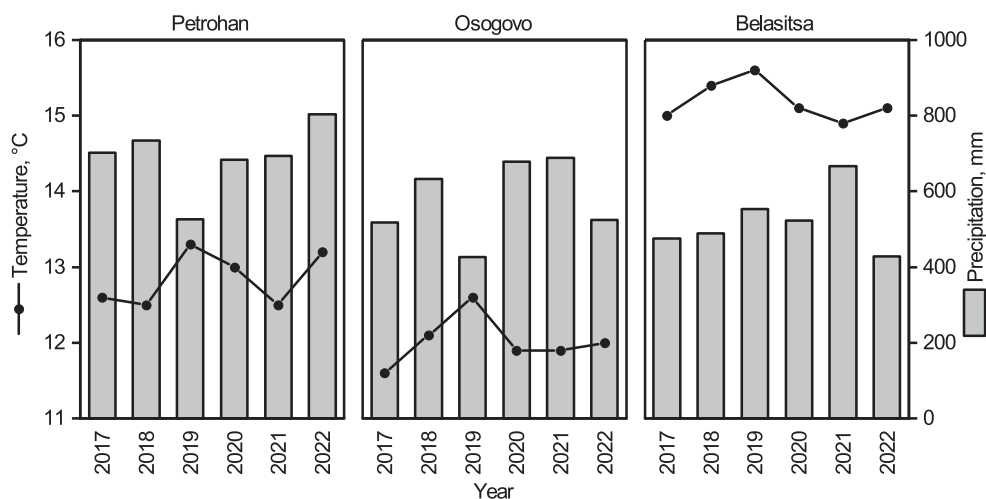
Table 1. Geographic coverage of European beech stands in the experimental objects.

Object	Petrohan	Osogovo	Belasitsa
Latitude range	43°06'28"– 43°12'47"	42°06'01"– 42°21'07"	41°18'54"– 41°22'56"
Longitude range	23°04'20"– 23°13'46"	22°22'04"– 22°45'13"	22°56'16"– 23°13'47"
Altitude range* of stands, m a.s.l.	1241 [394–1635]	1061 [680–1741]	1430 [378–1808]
Main soil type	Cambisols	Cambisols	Cambisols
Average age of stands, years ±SE	115.6 ±1.7	99.5 ±0.9	109.8 ±1.2
Number of stands	922	2400	1124
Average height of stands, m ±SE	21.87 ±0.22	18.52 ±0.13	20.66 ±0.20
Average DBH, cm ±SE	31.15 ±0.43	29.17 ±0.38	30.48 ±0.42

Note: * Altitude range is present as Δ altitude [Min–Max].

The wide range of altitudinal variation of three objects allows for examining the influence of elevation on phenology. At the same time, the significant difference in latitude entitles the effect of geographical position to be outlined. Petrohan enterprise is open on the northeast to the vast Moesia Plain and protected on the southwest from the main Stara Planina Mountain ridge. The Struma River valley and

the local influence of the western transfer of air masses along the Strumeshnica River valley influence the Belasitsa climate. Osogovo is surrounded by the high fields of Western Bulgaria, characterized by a harsher climate – cold winters and hot and dry summers. Altitude and latitude variations provoke significant differences in climatic conditions, especially in air temperature and precipitation (Fig. 2).

**Fig. 2. Annual average air temperature and total precipitation trends for the study period.**

Note: The annual temperature and precipitation are presented at the foot of the mountains – town of Berkovitsa (405 m a.s.l.) for Petrohan, town of Kyustendil (518 m a.s.l.) for Osogovo, and town of Petrich (227 m a.s.l.) for Belasitsa.

Methods

SOS, MOS, EOS, and LOS of each stand were determined based on satellite images by the ‘Copernicus Land Monitoring Service’ by ‘High-Resolution Vegetation Phenology and Productivity’ product. Satellite images for western Bulgaria were downloaded from the servers of Copernicus WEkEO (Copernicus 2023) for the related phenological indicators. The values of assessed events were calculated from the seasonal trajectory (Zhang et al. 2014) of the plant phenological index (*PPI*) (eq. 1) (Jin and Eklundh 2014):

$$PPI = K \cdot \ln \left(\frac{DVI_{\max} DVI}{DVI_{\max} DVI_{\text{soil}}} \right), \quad (1)$$

where: *DVI* is the difference of near-infrared and red reflectance; $DVI_{\max}$ is the temporal maximum of *DVI*; DVI_{soil} is the soil *DVI*; *K* is a gain factor given by the canopy light extinction efficiency, which depends on leaf inclination angle ≈ 0.5 , according Jin and Eklundh (2014), solar angle and the diffuse fraction of solar radiation. The seasonal trajectory ($STPPI_{\text{DOY}}$) was constructed with a non-linear double logistic function (Fischer 1994), adapted by Beck et al. (2006) for NDVI, and described for *PPI* by Smets et al. (2022) (eq. 2):

$$STPPI_{\text{DOY}} = MINV + (MAXV - MINV) \cdot \left(\frac{1}{1 + e^{-L_{\text{SLOPE}}(DOY - SOS)}} + \frac{1}{1 + e^{-R_{\text{SLOPE}}(DOY - EOS)}} - 1 \right), \quad (2)$$

where: *MINV* is average $DVI_{\min}$ before SOS and after EOS; *MAXV* is a maximum *DVI* in growing period; L_{SLOPE} and R_{SLOPE} are slope of greening up and senescent period, respectively; *DOY* is a day of the year. $STPPI_{\text{DOY}}$ is used to derive the assessed phenological events, calculated

after the end of each growing season.

The altitude of each stand is calculated based on Copernicus’ digital elevation map of Europe – EU-DEM, v.1.1 (Copernicus 2016). All satellite images were processed with an object-oriented Python framework for the popular open-source geographic information system QGIS, v.3.28.10 – Firenze. Python code (Gandhi 2021) automates image processing with built-in raster extraction and zonal statistics tools. The resulting attribute tables were exported as CSV comma-delimited files for processing in the open-source statistical software RStudio (v.2023.06.2+561) and MS Excel (Office 365).

Pearson correlation coefficients were calculated between phenological events and the latitude of each stand in three objects, year by year, for the 2017–2022 period. One-way ANOVA tests and Tukey post hoc analysis were performed to determine the difference between the average dates of occurrence of SOS, MOS and EOS, and LOS in days of the whole period for Petrohan, Osogovo and Belasitsa.

Results and Discussion

SOS correlates strongly positively with the elevation of stands in all three mountains, although significant variations can be observed in separate years (Fig. 3).

The highest correlation coefficients (above 0.75) in all years, except 2018, were observed in Petrohan. Such a strong correlation can be explained by the highest latitude among the studied objects, suggesting the latest warming in the spring. The correlation is significantly poorer in Osogovo, where, due to the hollow nature of the foot of the mountain, late spring colds are more frequent. A part

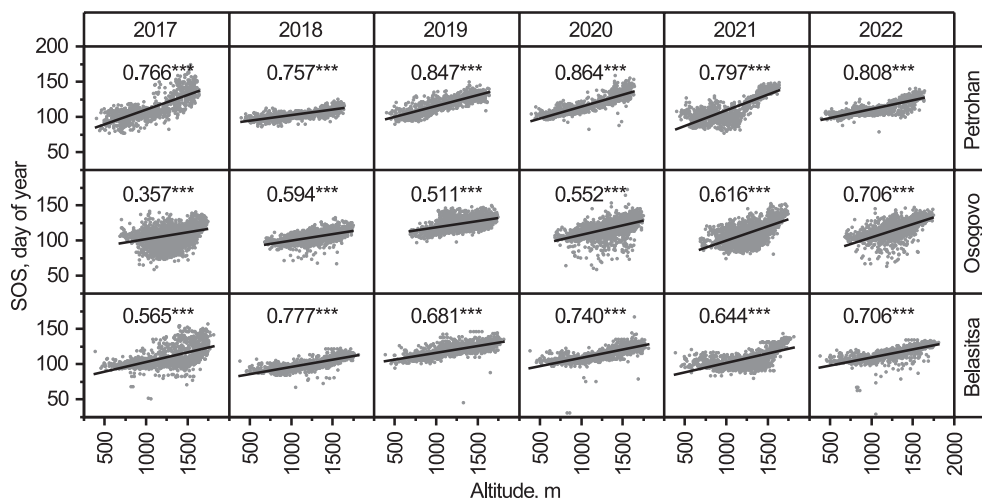


Fig. 3. Start of season (SOS) date in relation to altitude during studied period (2017–2022).

Note: Dots present SOS of each stand. The black lines show a correlation between altitude and SOS. Values above the line are Pearson correlation coefficients (***) – p -value < 0.001).

of the stands in Osogovo grows on the mountain's southern slope, which may be an additional factor that weakens the correlation between SOS and altitude. Average slopes ($\pm$ SE) of linear regressions show that SOS delay on every 100 meters elevation gain is 2.33 ± 0.04 days in Belasitsa, 2.67 ± 0.04 days in Osogovo, and 3.16 ± 0.04 days in Petrohan. Our results are comparable to those of other authors investigating the correlation between unfolding in European beech and altitude. Dittmar and Elling (2005) established around two days every 100-meter delay at the start of vegetation in Southern Germany. Similar results were reported by Čufar et al. (2012) for Slovenia, where the leaf unfolding shift is 2.6 days for every 100 meters. Schieber et al. (2013) showed a 2.83–3.00 days shift in the onset of spring phenophases per 100 m of an increase in altitude in the Inner Western Carpathians, Slovakia.

The tendency is similar for the relation between altitude and MOS. Except for

2018, in which April was extremely dry, Petrohan's MOS depends strongly positively on altitude. In more southern Belasitsa and especially in Osogovo, where there are stands at a south slope, this correlation weakens significantly, especially in 2017 and 2019, which can be explained by a potentially better adaptation of European beech populations in these mountains to the small amount of precipitation (Fig. 4).

The linear regressions' mean slopes ($\pm$ SE) show that the MOS delay per 100 meters of altitude is 2.74 ± 0.04 days in Belasica, 2.45 ± 0.04 in Osogovo, and 2.89 ± 0.05 in Petrohan.

The correlations between altitude and EOS are negative, significantly weak than with SOS and MOS, and are even lost in individual years (Fig. 5).

The poor correlations are possible because the transition between summer and winter is shorter with climate changes. This is consistent with other authors' findings that phenological phases at the

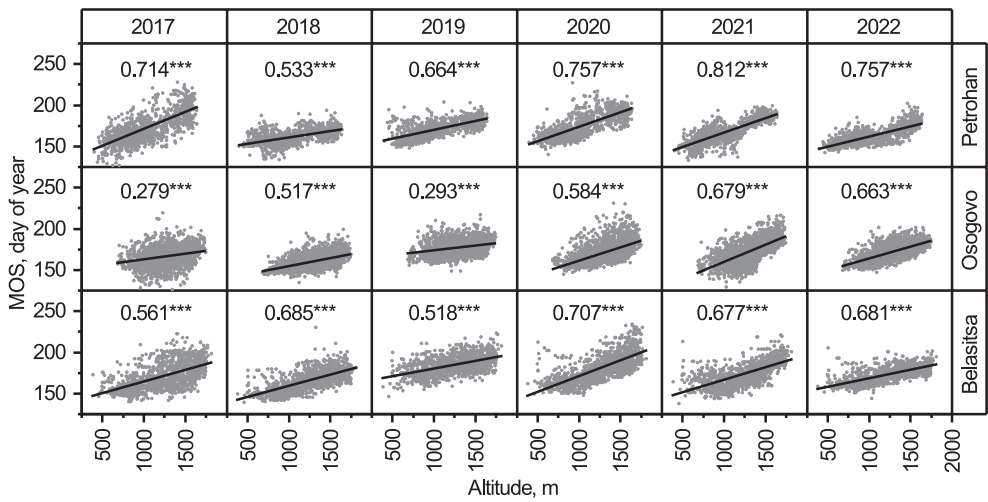


Fig. 4. Max of season (MOS) date in relation to altitude during studied period (2017–2022).
Note: Dots present MOS of each stand. The black lines show a correlation between altitude and MOS. Values above the line are Pearson correlation coefficients (** – p -value < 0.001).

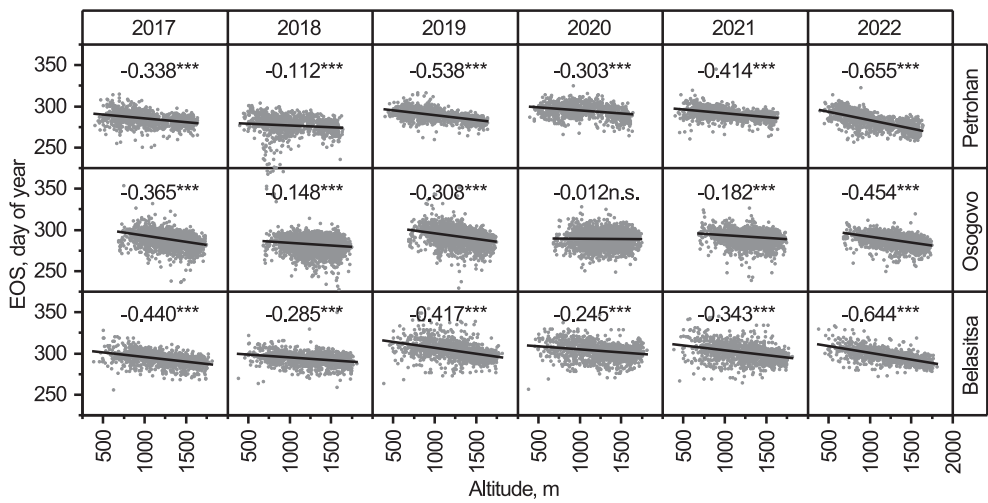


Fig. 5. End of season (EOS) date in relation to altitude during studied period (2017–2022).
Note: Dots present EOS of each stand. The black lines show a correlation between altitude and EOS. Values above the line are Pearson correlation coefficients (** – p -value < 0.001; n.s. – non-significant).

end of the growing season are poorly related to altitude (Chmielewski and Rötzer 2001). Still, they may also be due to the greater sensitivity of European beech to late spring frosts than to autumn chills

(Stefanov and Ganchev 1953), which recent studies (Wang et al. 2022) suggest may be on the wane. There is no clear tendency to strengthen or weaken the correlation among years or sites of the study.

Given that the correlation is lost in individual years, a more substantial factor than altitude can be assumed to determine autumn leaf colouration in European beech. For every 100-meter increase in altitude, EOS occurs earlier by 1.14 ± 0.04 days in Belasica, 0.94 ± 0.03 days in Osogovo, and 1.05 ± 0.04 days in Petrohan. While, for Slovenia, Čufar et al. (2012) established a slightly higher value of regression slope (1.89 ± 0.02) between altitude and leaf colouring, but in Southern Germany, leaf discolouration showed no altitudinal dependence due to cold-air tailback (Dittmar and Elling 2005).

The length of the season, as a function of SOS and EOS, lengthened substantially after the 1980s (Garonna et al. 2014), mostly due to the later onset of EOS (Jeong et al. 2011, Zhao et al. 2016). However, the negative correlation with altitude remains strong, especially on northern slopes (Fig. 6).

Vegetation season is getting shorter with an increase of altitude by 100-metre, with 3.34 ± 0.05 days in Belasica, 3.53

± 0.05 days in Osogovo, and even 4.21 ± 0.05 days in Petrohan. The correlations were poorer in Petrohan and Osogovo in 2018, when spring was arid and intensified at all three sites in the warmer 2019 and 2022. The poorer correlations in Osogovo are probably due to the variety of exposures. Still, they may also be because of the later SOS (Fig. 7) due to the valley character of the climate. Such local influences in southern Germany have a more substantial impact on the end than on the beginning of the growing season (Dittmar and Elling 2005). Schieber et al. (2013) establish that the duration of the growing season shortened by about 4.4 days per each altitudinal 100 m in the vertical gradient in Inner Western Carpathians, Slovak Republic.

The studied period was too short to establish significant SOS, MOS, EOS, and LOS change trends in individual years. For this reason, the average dates of occurrence of the main phenological events (SOS, MOS, and EOS) and the average length of the growing season (LOS) were

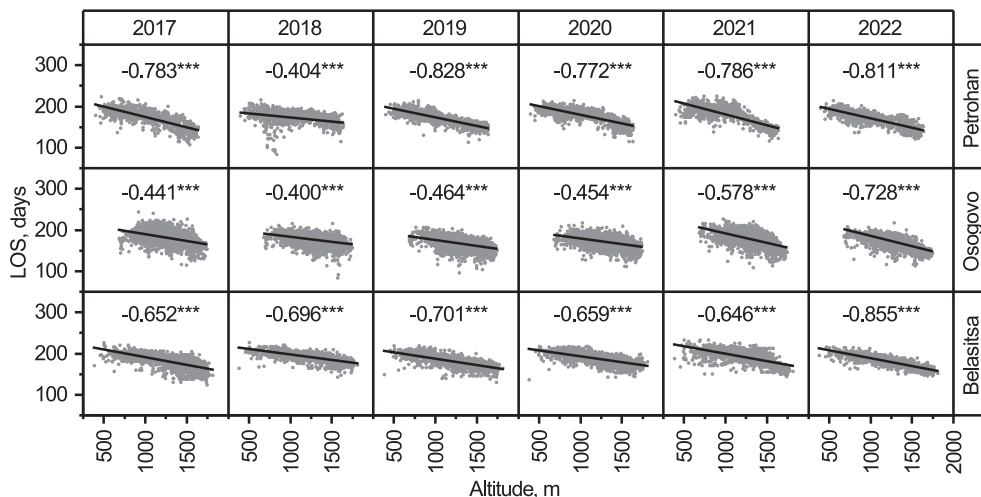


Fig. 6. Length of season (LOS) in relation to altitude during studied period (2017–2022).

Note: Dots present LOS of each stand. The black lines show a correlation between altitude and LOS. Values above the line are Pearson correlation coefficients (***) – p -value < 0.001).

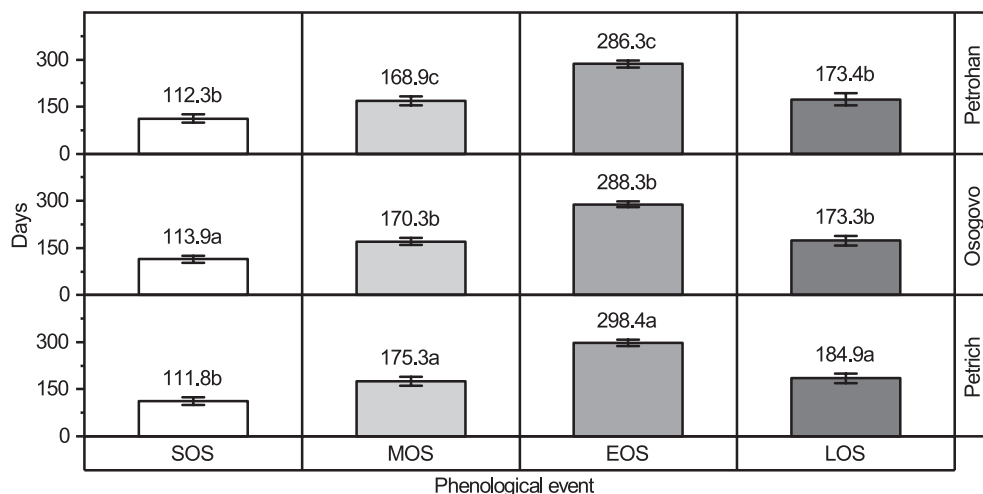


Fig. 7. Average dates (in days of the year) of occurrence of SOS, MOS and EOS and average LOS (in days) for the studied period (2017–2022).

Note: The column and values above are the average phenological events of each object. The whiskers represent the standard deviation. The different letter denotes statistically significant difference averages among objects (one-way ANOVA using Tukey post hoc tests with $\alpha = 0.05$).

calculated (Fig. 7).

The vegetation season of European beech starts on 21 April (23 March – 20 May) in Belasitsa, 23 April (31 March – 18 May) in Osogovo and 22 April (26 March – 18 May) in Petrohan, which is around a week early than leaf unfolding for the same region, observed in our previous study (Tzvetkova and Anev 2014) and in Southern Germany (Dittmar and Elling 2005) but is closer to leaf unfolding in Slovenia (Čufar et al. 2012). In contrast to SOS, which reliably occurs at the latest in Osogovo, MOS and EOS occur the later, the smaller the geographical latitude of the object. MOS occurs on 24 June (23 May – 26 July) in Belasitsa, 19 June (27 May – 13 July) in Osogovo, and 18 June (19 May – 17 July) in Petrohan.

As Gressler et al. (2015) and Kuzmanova (2021) point out, autumn phenophases can be significantly longer than spring due to the considerable distance in

the time of leaf fall along the vertical profile of the assemblage in the forest. However, our results show a shorter period of autumn phenophases compared to spring ones. EOS occurs on 25 October (06 October – 12 November) in Belasitsa, 15 October (29 September – 31 October) in Osogovo, and on 13 October (24 September – 02 November) in Petrohan, versus 18 October from our previous survey (Tzvetkova and Anev 2014). This is probably due to the homogeneous nature of the stands in terms of composition and age, which resulted from the widely applied short-term cutting system in the past. As a result, LOS increases only in Belasitsa – 184 (151–219), while in Osogovo – 173 (144–203), the season lasts as long as in Petrohan – 173 (134–214), regardless of the difference in latitude. However, the growing season of European beech in Western Bulgaria turns out to be considerably longer than in Southern Germany

– 161 and Northern Germany – 154 days (Dittmar and Elling 2005) and significantly closer to that in Slovakia – 128–181 days (Schieber et al. 2013).

Conclusions

A significant correlation was established between the start of season date, max of season date, end of season date, and length of season on the one hand and the altitude and latitude on the other. The established correlations are more significant in the north-sloped mountains and poorer in the Osogovo, where the stands cover the northern, eastern and southern slopes, but also due to the valley character of the climate at the foot of this mountain. Latitude was essential for max of season date and end of season date occurring later the further south the mountain. The latest start of season date at Osogovo, which results in a length of season equalised to that of Petrohan, reduces the influence of altitude on these phenological events. Analysing the spatial patterns of vegetation changes can help identify variations in phenological events in different areas. The information provided by phenological observations will be increasingly valuable in large-scale approaches to forest management and remote methods for establishing phenological events would greatly facilitate their tracking in time and space.

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Efficiency of using a water curtain device in forest fires

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Abstract

The article presents statistics of forest fires in Ukraine, characterizes large-scale forest fires in the world and their consequences. Presented methods of detecting and reducing the intensity of the spread of forest fires and fires in ecosystems that were under previous radioactive or chemical contamination do not always bring the desired result, so the authors suggest using their patented device to create a water curtain. The purpose of the article is to present a mathematical model of irrigation with this device. To conduct the research, a stand was used, with the help of which the results of changes in pressure, flow rate, spray radius were obtained experimentally. Empirical dependencies were established, on the basis of which a mathematical model of irrigation with a water curtain device was built. The model is necessary to determine the parameters of the device and improve the quality of calculations necessary during forest fire extinguishing.

Key words: cloud deposition, fire protection, irrigation intensity, liquid consumption.

Introduction

The issue of preserving forests and protecting them from various harmful factors of both natural and anthropogenic nature is important, complex and large-scale. A prominent place in the highlighted problem is the issue of protecting forests from fires.

Large-scale studies of the long-term dynamics of forest fires have shown a constant increase in their number. In recent history, the period of rapid development of fire and rescue services in the first half of the 20th century, when the

total area of fires in the world decreased, can be considered an exception. However, at the beginning of the 21st century, the number of protracted significant forest fires, which led to human casualties and material damage, continued to grow (Zibtsev et al. 2019, Lahno et al. 2022).

Scientists point to a relationship between fire and climate change that could overshadow the effects of global warming on plant distribution and migration and have significant implications for forests, forestry, human protection and the economy. Scientists call fires the main factor in the restoration of forest stands, which

significantly affects the structure and functions of the forest (Flannigan et al. 2006, Neary and Leonard 2015, Sydorenko et al. 2022).

For example, in 2018, due to the long-term accumulation of a large mass of dry trees in forests and heat, large-scale forest fires occurred in the state of California, USA, as a result of which at least 86 people died, more than 500 people went missing, and more than 7200 buildings were destroyed. As a result of merciless felling, the fires of the 'lungs of the planet' – the Amazonian tropical forests – are regular. In 2019, it was not possible to extinguish the fire for 10 months, 900,000 ha of forest burned. In 2019–2020, during the so-called 'Black Summer' in Australia, forest fires caused by seasonally high temperatures and drought – about 18 million ha were destroyed, more than 30 people died (Word and Deed 2020).

The total area of forest plots belonging to the forest fund of Ukraine is 10.4 million ha, including 9.6 million ha covered with forest vegetation. In 2022, 1009 fires on an area of 15.5 thousand ha were eliminated in the forests of this sphere. The average area of one fire was 15.4 ha, and the damage was 11 million euro. Forest fires occur mainly due to careless handling of fire by the population. In 27 % of cases, the forces and means of the State Emergency Service were involved in extinguishing them (SFRAU 2022).

Domestic scientists, observing a clear trend towards an increase in the area of large forest fires, draw attention to the high combustibility of forests in Ukraine, the key factors of which are considered to be the lack of funding of forest fire services, insufficiently effective training and interaction with operational and rescue units of their employees, as well as non-fulfillment of current legislative requirements regard-

ing fire prevention and their imperfection (Zibtsev et al. 2019).

The negative consequences of fires in forest ecosystems arise from the great importance of forests for society and depending on the scale of their spread include in addition to economic and political losses, and aggravation of social problems – the emergence of environmental problems, namely: the release of harmful combustion products, mostly in the form of aerosols, which can be transported over considerable distances, pollution of the atmospheric air with carbon dioxide and other harmful substances, impoverishment of biological diversity, deterioration of the conditions of natural regeneration of forests, reduction of the fodder base and difficulty in the migration of species, increase in the vulnerability of forests to pests and diseases, changes in the landscape structure and soil erosion, etc.

Thus, the problem of forest fires can be safely considered global, as countries with large and small areas of forests suffer from them.

In order to minimize the consequences of forest fires, it is important to detect them in time, that is, before the fire becomes uncontrollable and spreads over a huge area.

The methods and means of timely detection of fires include constant surveillance, which is carried out by patrolling, inspecting forest areas from fire towers and masts using human resources or video surveillance systems, using manned and unmanned aerial vehicles, observations from space (Lahno et al. 2021).

Unfortunately, these measures do not always bring the desired result, and the forest fire develops to such a level that it is necessary to respond to it, using significant forces and means for its elimination.

Horizontal migration of radioactive

combustion products, depending on the dynamic parameters of the wind, characteristics of the soil, its protection from the wind, etc., can cause radiation pollution or an increase in its density in the surrounding areas of the forest. There is also a danger of secondary radioactive contamination of the territories, which is associated with the density of soil contamination, the effect of wind erosion and the activity of radionuclides in the ash. As a result of such fires, the concentration of radionuclides in the air compared to background values can increase almost 104 times (Sydorenko et al. 2022).

In such cases, it is necessary to remember that the only effective method that reduces the intensity of the spread of combustion products is their deposition. Deposition of combustion products, dust and other aerosols can be effectively carried out using sprayed water jets. It is necessary to carry out such works during the extinguishing of fires in the ecosystems of the exclusion zone.

According to the results of the analysis of the existing methods and devices for the deposition of radioactive aerosol (Lahno et al. 2022), dust and surface irrigation during a ground fire in the exclusion zone, it was established that all the devices and methods of their application available in the emergency and rescue units are effective only when used locally, namely under the time of the rescuer's work with fire water hose.

The problem of extinguishing forest fires is being solved by the researchers in different ways (including water curtain and water mist): they introduced the concept of a fire-extinguishing bomb of water fog, and also offered to use a combined method that combines fire lanes created by explosives, dropping water from the air and drilling wells to obtain and use un-

derground water for extinguishing (Li et al. 2012); expanded current knowledge on the use and effectiveness of air tankers and developed recommendations for improving data collection and aviation management during wildfires in the United States (Calkin et al. 2014); offered to create a network of 30- to 70-meter-wide tunnels for forest safety, supplemented by a mobile sprinkler system to create a water curtain to moisten another tunnel 100 m away (Azari 2010); modeled the process of dropping water in the form of water mist, which it turns into when extinguishing forest fires from a great height (Sato et al. 2004, 2005); substantiated the effectiveness of explosive water mist compared to a water curtain and dropping water from a height (Li and Wang 2011).

A significant number of works are devoted to the issues of modeling the occurrence, development, forecasting of the spread and negative impact on the environment of fires in ecosystems exposed to radioactive contamination. In particular: modeling based on a number of parameters for calculating the ecological and radiation situation under the influence of the intensity and direction of migration of radioactive combustion products using a model based on deflation parameters, as a result, graphical dependencies for the deflation coefficient under different meteorological conditions were obtained (Sydorenko et al. 2022). Determination of the scheme of forming a mathematical model for assessing the ecological impact of negative factors of a forest fire in complex radiation conditions of fire load, and construction of a corresponding block diagram (Azarov et al. 2020). Modeling and substantiation of the dependence of the scattering and deposition of radioactive materials on the ground from past meteorological data, in particular air flows,

proving the significance of their influence on determining the area and scale of response in the case of nuclear accident before carrying out on-site measurements (Hernandez-Ceballos et al. 2020).

A number of studies are devoted to the study of water curtain systems as an effective method of fighting fire, in particular, it is worth mentioning the analysis of water curtains of various configurations regarding the possibilities of protection against the thermal effects of fire due to the ability of water to absorb and disperse thermal radiation (Boulet et al. 2006, Tseng and Viskanta 2007, Turco et al. 2016, Ponziani et al. 2018) and smoke, and weaken the radiation effect (Wen et al. 2008), and also substantiating the viability of Heskestad scale relations for the interaction of water curtain splashes under the condition of a high Reynolds number ($10 \leq Re \leq 500$) based on Froude simulation for large-scale simulation of localization or fire extinguishing with a water curtain (Yu 2012).

The researchers also paid attention to the modeling of extinguishing fires by deposition of a water curtain in a limited space. In particular, in rooms under different conditions (water pressure, location of combustible substance) with the proof of lower water consumption by the curtain compared to the sprinkler system (Pancawardani et al. 2017), in a small chamber using a double fluid system of the water curtain in continuous and pulsed modes (Gupta et al. 2012).

Scientists have devoted a significant amount of research to the use of water curtains to prevent and extinguish fires in tunnels: during their construction (Mehaddi et al. 2020); analysis of the use of sprinkler systems of car tunnel walls (Deng et al. 2023); evaluation of the effectiveness of the fire protection system based on a water

curtain against the spread of toxic smoke and gases in railway tunnels (Terribile et al. 2017); study of the spread of heat and smoke through the tunnel – research by varying the rate of heat release of the fire source, water curtain pressure and the number of rows of the water curtain showed that these indicators affect the smoke blocking by the water curtain system (Chen et al. 2023).

Other areas of use of water curtains in fire safety are their use in fighting fires on cargo ships (Zeinali et al. 2023) and passenger ferries (Hemgård 2015), as well as for protection against vapor cloud explosions in the design of technological premises (Allason et al. 2019).

The subject of interest of scientists was also substantiation of the effectiveness of the water curtain in extinguishing polymethyl methacrylate fires (Yao et al. 2012) and hydrodynamic modeling to estimate the dispersion parameters of liquefied natural gas vapors (the influence of droplet sizes and temperatures and the configuration of water curtain systems was analyzed), which ascertained the effectiveness of the dispersion of LNG vapors by the water curtain system and reducing the fire hazard of gas spills (Rana and Mannan 2010, Kim et al. 2012). Also considered: the modeling of the development of smoldering fires and their elimination by a water curtain, for example, peat fires depending on the intensity of water spraying (the distance between the fire barrel and the surface of the peat), which showed the influence of particle size and permeability of peat on the spread of the smoldering front of combustion and futility of short-term extinguishing of peat fires (Ramadhan et al. 2017), as well as fires in underground coal mines for three types of coal with different ranks and sizes of coal particles, which proved that moisture con-

tent was the dominant factor in the spread of smoldering and coal oxidation temperature (Tang and Huang 2022).

Despite the considerable amount of research, the development of firefighting equipment for aerosol, dust, and surface irrigation that could be used to extinguish fires in ecosystems, especially those exposed to radioactive or chemical contamination, remains an urgent task (Lahno et al. 2020).

As one of the options for such equipment, the author's team consisting of Denys Lagno and others proposed and created a device for creating a water curtain, the intellectual property right of which is registered by Ukrainian patent No. u 2020 05865.

To extinguish forest fires, such devices can be connected in series in a dead-end or ring line built from fire hoses. This method will increase the effectiveness of extinguishing forest fires, reducing the negative consequences for forest areas. However, the operating parameters of the proposed device for creating a water curtain were not investigated.

Taking into account what has been said, the purpose of our research is defined, namely the construction of a mathematical model of irrigation with a device for creating a water curtain.

Materials and Methods

A stand (Fig. 1) was used as a fire engine for a full-fledged study, the main element of which is a pumping unit, which includes an asynchronous three-phase electric motor with a capacity of 18 kW and a centrifugal liquid pump that can provide a flow rate of up to $48 \text{ m}^3 \cdot \text{h}^{-1}$ with a pressure of up to 1 MPa and allows conducting research with various types of hydraulic

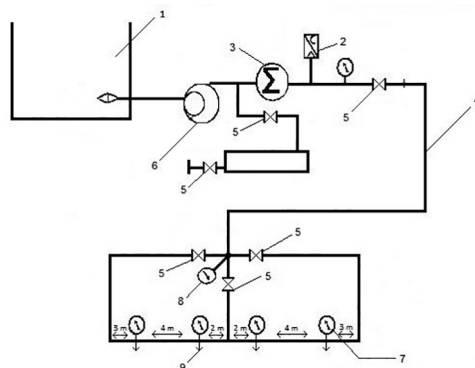


Fig. 1. General scheme of the experimental stand.

Note: The test stand includes: 1 – capacity 1 m³; 2 – analog pressure converter; 3 – electromagnetic fluid flow converter; 4 – water hose Ø51 mm; 5 – shut-off valve; 6 – centrifugal pump.

manual fire-fighting equipment.

The pumping unit (Fig. 2) is connected to the jet forming nozzle through the hydraulic system (flow meter, pressure sensor, pressure pipelines).

The electric motor is controlled using a Danfos VLT 6000 HVAC frequency converter, which allows obtaining the required fluid pressure value.

To obtain flow data, an electromagnetic fluid flow converter SDM-1 was



Fig. 2. Pumping unit (photo Oleh Zemlianskyi).

used, which is capable of working in the flow range from 0.26 to $65 \text{ m}^3 \cdot \text{h}^{-1}$ (0.07 – $18 \text{ L} \cdot \text{s}^{-1}$), of the second class of accuracy, the limit value of the relative error at consumption from $0.65 \text{ m}^3 \cdot \text{h}^{-1}$ ($0.18 \text{ L} \cdot \text{s}^{-1}$) is 2 %.

To measure the pressure an analog pressure sensor HK1100C with a measurement limit of 1.2 MPa was used. Relative error at ambient temperature from $+15$ to $+50 \text{ }^{\circ}\text{C}$ is 1.5 %.

Sensor signal processing is implemented using the Arduino Mega 2560 board – based on the ATmega2560 microcontroller. It has digital inputs/outputs and analog signal inputs. Information output is implemented on the LCD keypad shield 1602 display. It is also possible to output information in real time to a computer via a USB port. For this, the PLX-DAQ plugin for Microsoft Excel was used.

With the help of a pumping unit, a study of the parameters of the device for creating a water curtain was carried out. Experimental data were obtained on changes in pressure, flow rate, spray radius during water supply through the device for creating a water curtain.

Empirical dependences of water flow on pressure and spray radius on pressure were obtained by approximating experimental data in the form of polynomial equations. This, in turn, made it possible to obtain the dependence of the intensity of irrigation on pressure.

To conduct the experiment, a device for creating a water curtain (Fig. 3) is attached to the experimental stand (Fig. 1). Next, the shut-off valves were opened and water was supplied to the device for creating a water curtain.

By increasing the frequency of the current with the help of a frequency converter, an increase in the water pressure in the system was achieved. Flow and

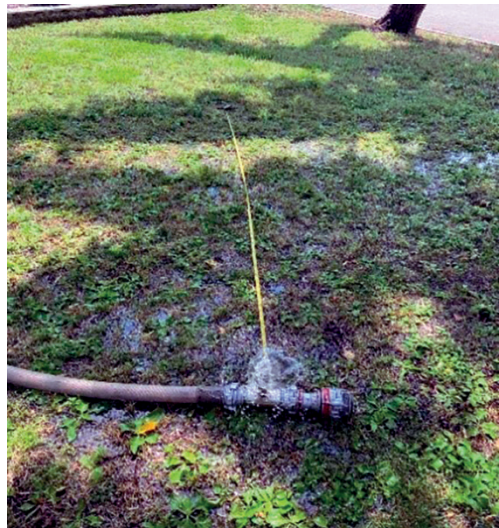


Fig. 3. Spraying radius of fire extinguishing agent (photo Denys Lahno).

pressure data were automatically recorded every second. Starting from a pressure of 1 bar, the radius of the spray zone was measured every 0.5 bar. To obtain a reliable average result and further check with the appropriate statistical apparatus, the experiment was carried out with repetitions. In total, three repetitions of the experiment were carried out with the same starting conditions.

Results and Discussion

Thus, the experimental studies conducted by the authors using the developed device for creating a water curtain demonstrated the dependence of pressure on time (Fig. 4), the dependence of fluid flow on time (Fig. 5) and the irrigation area, fluid flow of the device depending on pressure (Fig. 6).

During practical use, a study that showed the irrigation area, device consumption depending on the pressure was

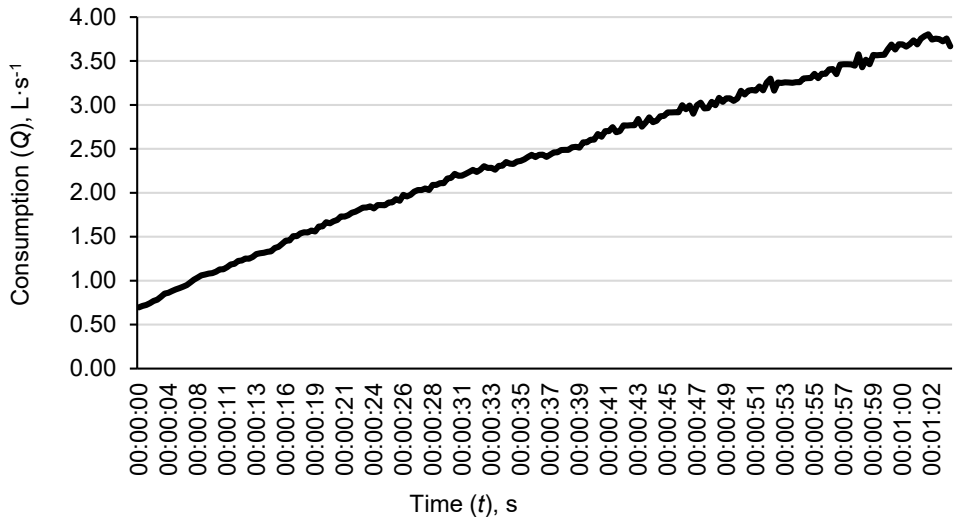


Fig. 4. Dependence of consumption on time.

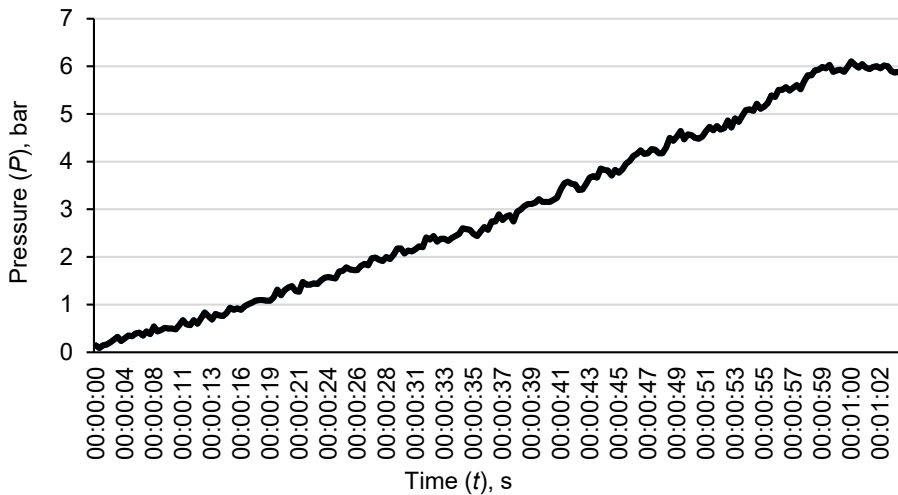


Fig. 5. Dependence of pressure on time.

conducted (Fig. 6).

From the graph (Fig. 6), it is clear the general dependence of the consumption on pressure, and at a maximum pressure of 6 bar, the consumption is about 3.5 L per second, which allows the device to be used both individually and in a group, using existing hydraulic fire equipment for

creation of water curtains, for extinguishing and protection against excessive thermal radiation, as well as during the localisation of accidents associated with the release of toxic and radioactive substances with the purpose of deposition of toxic or radioactive clouds.

To determine the capabilities of devic-

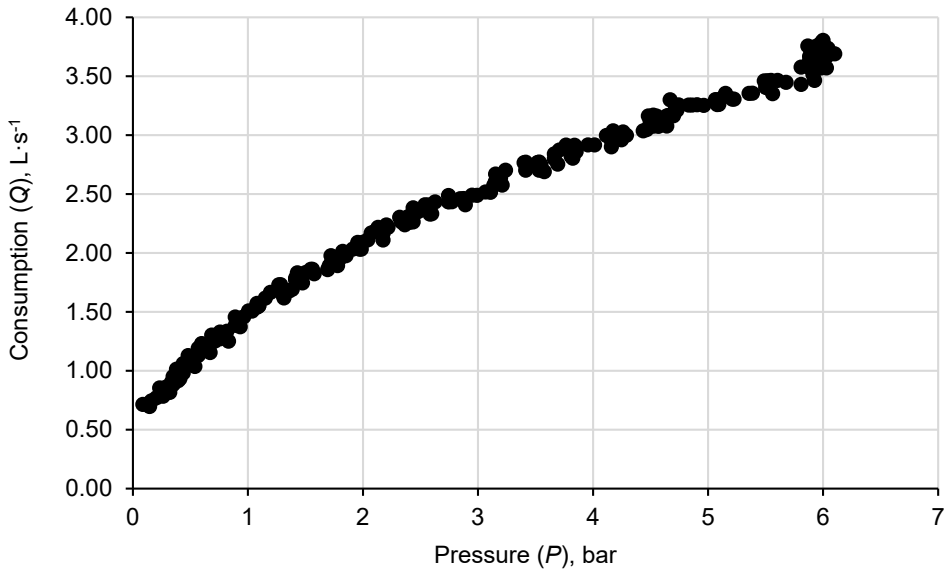


Fig. 6. Dependence of flow rate on pressure.

es for creating a water curtain during surface irrigation, it is necessary to calculate the surface. A irrigation intensity, for this it is necessary to identify the dependence of formula (1):

$$Q = f(Q, R), \quad (1)$$

where: q is irrigation intensity, Q is flow rate, R is radius of the spray zone.

The dependence of the flow rate (Q) on the pressure (P) can be represented as an empirical dependence obtained by approximating the curve (Fig. 7) by formula (2):

$$Q = 0.0126P^3 - 0.1599P^2 + 1.0164P + 0.5986. \quad (2)$$

The results of irrigation intensity calculations depending on the pressure are presented on the graph (Fig. 8).

The obtained results can be used when calculating schemes for extinguishing fires in the surface layers of peat,

The dependence of the radius of the spray zone (R) is similarly obtained by approximating the curve (Fig. 6) by formula (3):

$$R = -0.0125P^3 + 0.1247P^2 + 0.2119P - 0.0433. \quad (3)$$

Taking the simplification that the irrigation intensity in meters of the irrigation zone q is uniform, we obtain the expression in formula (4):

$$q = \frac{Q}{\pi R^2}. \quad (4)$$

Taking into account dependencies (3) and (4), we get formula (5):

$$q = \frac{0.0126P^3 - 0.1599P^2 + 1.0164P + 0.5986}{\pi(-0.0125P^3 + 0.1247P^2 + 0.2119P - 0.0433)^2}. \quad (5)$$

grass fires in forests. Based on them, it is possible to formulate a mathematical model of irrigation with a device for creating a water curtain, which consists of equations of formulas (2), (3) and (5):

$$\begin{cases} Q = 0.0126P^3 - 0.1599P^2 + 1.0164P + 0.5986 \\ R = -0.0125P^3 + 0.1247P^2 + 0.2119P - 0.0433 \\ q = \frac{0.0126P^3 - 0.1599P^2 + 1.0164P + 0.5986}{\pi(-0.0125P^3 + 0.1247P^2 + 0.2119P - 0.0433)^2} \end{cases}$$

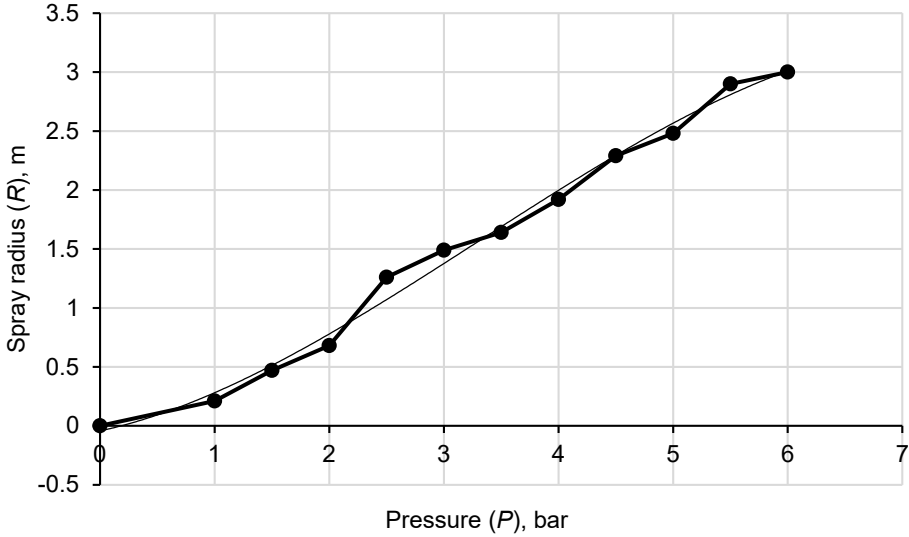


Fig. 7. Dependence of spray radius on pressure.

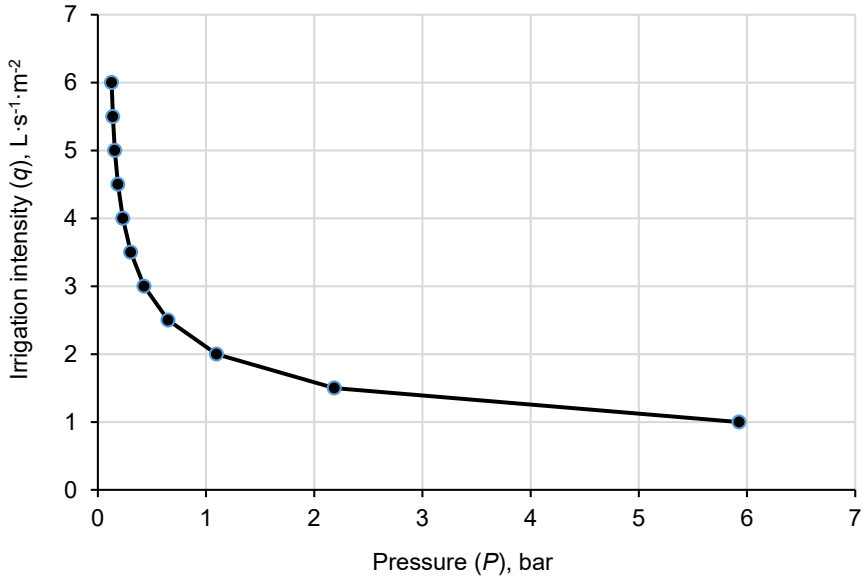


Fig. 8. Irrigation intensity depending on pressure.

Analysing the reproducibility of experiments requires quantitative measures of test adequacy. The adequacy check was performed on the basis of experimental information obtained during the experiment and its repetitions.

In order to find out the adequacy of the results of the experimental data during the tests, a number of criteria were selected, which are described below.

Fisher's F-test is used for sequential comparison of variances of indicators. Its application enables the verification of the hypothesis about the equality of general variances, the distribution of parameter values at each minute of the tests. We calculate the criterion according to the formula (6):

$$F = \frac{S_{ad}^2}{S_y^2}, \quad (6)$$

where: S_{ad}^2 – adequacy variance, S_y^2 – reproducibility variance.

The dispersion of flow adequacy is calculated as the deviation between the flow rates at the same pressure value and is presented in the formula (7):

$$S_{ad}^2 = \frac{\sum_{i=1}^n (Qs_i - Q_i)^2}{n}, \quad (7)$$

where: n – number of flow measurements, Qs_i – the average value of the flow at the same significant pressure, Q_i – data during the test.

The dispersion of reproducibility is calculated as the deviation of the flow and the average value of the flow at different pressure values (taking into account the error of the flow meter). This indicator is calculated according to the formula (8):

$$S_y^2 = \frac{\sum_{i=1}^n [Q_i - (1 + \delta)\bar{Q}]^2}{n}, \quad (8)$$

where: n – number of measurements; $(1 + \delta)\bar{Q}$ – average flow rates, taking into account the relative error δ ; Q_i – flow rates at a given pressure.

Next, the adequacy variance was compared with the reproducibility variance and Fisher's test was calculated (F) (tables 1 and 2).

Table 1. Dispersion parameters of the results of determining the flow rate based on the results of three experiments.

Maximum deviation, $L \cdot s^{-1}$	Average deviation, $L \cdot s^{-1}$	Relative deviation, %	F-criterion	Critical value of F-criterion
0.093	0.018	0.91	1.35	7.26

Table 2. Dispersion parameters of the results of determining the radius of the spray zone based on the results of three experiments.

Maximum deviation, $L \cdot s^{-1}$	Average deviation, $L \cdot s^{-1}$	Relative deviation, %	F-criterion	Critical value of F-criterion
0.19	0.067	15.5	2.15	2.36

Similarly, the determination of the dispersion of adequacy compared to the dispersion of reproducibility was carried out and the Fisher criterion (F) was calculated during the determination of the spraying zone.

According to tables 1 and 2, the calculated adequacy criteria do not exceed critical values.

Therefore, a mathematical model of irrigation with a water curtain device has been developed and published for first

time, which can be used to calculate the irrigation zones of each individual sprinkler in a system with a series connection for extinguishing forest fires. The model will allow, after the hydraulic calculation of the pump-hose system using serially connected nozzles, to determine the parameters of such a system, in particular, the input pressure in the system and the distance between the nozzles.

Prospects for further research include the determination of the effective intensity of irrigation and the determination of possible options and maps for the placement of sprinklers to ensure the necessary efficiency of the deposition of harmful substances in the air, provided that the effective intensity of irrigation is ensured in horizontal and vertical projections.

Conclusions

The obtained results can be used during modeling of areas of spraying of fire-extinguishing liquids by devices for creating a water curtain for extinguishing forest fires or deposition of clouds with radioactive and poisonous substances. However, in order to qualitatively solve the problem of precipitation of clouds with radioactive and poisonous substances, it is necessary to conduct experimental studies on the formation of the vertical projection of the spray zone by the proposed device.

Similarly, studies can be conducted with different types of sprayers and water curtain devices to obtain empirical relationships similar to (2) and (3). Thus, the approach considered in this work can be used to obtain mathematical models of irrigation with other types of sprinklers, similar to the represented model.

The mathematical model obtained as a result of the research is an important as-

pect of the forest fire extinguishing methodology, as it allows you to calculate the operating parameters of the device for creating a water curtain. The model and similar models are necessary for the hydraulic calculation of the pump-hose system when extinguishing forest fires with the use of serially connected sprinklers.

The use of research results will improve the quality of calculations required during forest fire suppression and the deposition of clouds of radioactive and poisonous substances. This, in turn, will make it possible to use available forces and means more efficiently and, as a result, reduce the negative effects of fires on forest plantations.

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Peculiarities of middle-aged Scots pine forests development after surface fires in Kremenchuk green area, Ukraine

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Abstract

The aim of the study was to establish the effects of different levels of damage by surface fires on middle-aged Scots pine (*Pinus sylvestris* L.) stands in the green area of the city of Kremenchuk under increased recreational pressure. We used data from the sample plots established in Hradyzk Forestry in Kremenchuk Forest Economy Branch 3 years after a surface fire in a fairly common type of forest site conditions – fresh relatively poor forest site type. The main mensuration characteristics as well as impact features and impact of damage to Scots pine trunk with different level of severity were determined, taking into account the rough bark height and Kraft classes. The tree health dynamic and trees mortality several years after the fire were analysed. The possibilities for the tree regeneration and condition improvement were assessed, considering the long-term recreational pressure. A very strong correlations were found between the tree condition deterioration and the bark char height increase ($r = 0.95$) and the degree of thin bark burn injury ($r = 0.98$). The dependence of the tree mortality on the bark char height was also very strong ($r = 0.94$). A strong significant correlation ($r = 0.84$) was established between the proportion of dying trees and the degree of thin bark burn injury. Based on these data, it was possible to clearly trace the consequences and features of the most critical damages as well as to establish the values at which the trees almost completely survived.

Key words: bark char height, forest fires, health condition index, Kraft class, recreational pressure, rough bark height, thin bark burn injury.

Introduction

Green areas are always the most essential element in the structure of any city. Forests in the green area of Kremenchuk suffer not only from intensive industrial

emissions due to a large number of nearby industrial plants (a total of 86 enterprises), but also a powerful recreational pressure. The green area of the research city includes 8 parks, 24 public gardens, and boulevards. It also includes Scots pine

stands in the northeastern edge of the city and islands adjacent, as well as street and local plantings. They all form an integrated green area of the city, the functions of which are aimed at improving the ecological situation both in Kremenchuk and in the adjacent areas, as well as at enriching its recreational resources. Such areas require special attention for protection and conservation (Wieniawska-Raj 2010, Boychenko et al. 2020, Nikiforov and Galchenko 2020).

The intensive industry and transport development and the related urbanisation process have increased the impact of negative factors on forests. This problem is particularly acute both in Ukraine (ME-PNRU 2018) and elsewhere in the world (Alcamo et al. 2003, Klymenko and Zaleskyi 2010, Farcy et al. 2018).

Increasing recreational pressure and trampling in forests cause a stand deterioration and a stock and density decrease (Gensiruk et al. 1987, Hirs et al. 2004, Voron 2011). At the same time, the health of such stands is even more negatively affected by forest fires with the threat of rapid tree decline and even dieback. This problem is especially acute for Scots pine (*Pinus sylvestris* L.) forests (Leshechenko 2013, Badik et al. 2018, Melnik 2019, Sydorenko et al. 2020, Voron et al. 2021).

The main cause of fires is the human activity. Therefore, the forests in green belts around large cities with a high population density have a particularly high level of fire hazard and a large number of arsons (Doerr and Santín 2016, Melnik 2019, Tokareva et al. 2022). In contrast to the increased recreational impact, which also greatly affects green area forests, wildfires lead to even greater and faster negative changes in fire-damaged stands. At the same time, the wildfire impact depends on the type of the fire, the quan-

titative and qualitative characteristics of forest fuel, damage type and its intensity, and the fire resistance of individual trees and a stand as a whole (Usenya et al. 2011, Voron et al. 2021).

A fire impact and its consequences for stands can be assessed at the level of an individual tree, that is, by determining its fire resistance (Sheshukov et al. 1978, Usenya et al. 2011, Voron et al. 2021). After the fire damage to a tree trunk, roots, and crown by the combine effect of convective flow, thermal radiation, and thermal conductivity, the consequences can be significantly different for the different types of forest fires (surface, crown or ground ones) (Tsvetkov 2006, Kuzyk and Tovaryansky 2017, Wagtendonk et al. 2018). It is therefore necessary to clearly distinguish the most influential fire characteristics that have different consequences for specific types of Scots pine stands (depending on composition, age, forest site type, etc.). At the same time, it is important to understand what will primarily affect the further development of the stands.

According to many studies (Sheshukov et al. 1978, Tsvetkov 2006, Voron et al. 2021), damage to pine trunks by fire is the main indicator of negative consequences that will lead to trees dieback. If the bark char height exceeds the height of the rough bark for most trees in the stand, this brings to high rate of mortality for the entire stand, i.e., the proportion of dead trees increases dramatically (Voron et al. 2021). Therefore, a further study and analysis of post-fire patterns under different natural conditions as well as under side effect of other stressors (recreational pressure) and to build a complex framework of postfire models for different types of forests taking into account vulnerability of this stands.

The relevance of the present study was determined by the need to assess

the post-fire consequences in more detail and to more accurately predict the further development of individual trees in Scots pine stands of green belts. This in turn will allow to reduce economic losses because of timely and sound selective sanitation felling as well as to preserve minimally damaged trees.

The aim of the study was to determine the effects of a surface fire on middle-aged Scots pine stands with an increased level of recreational impact in the green area of the city of Kremenchuk, Ukraine, and to find out the specificities for the deterioration and post fire tree mortality over a long post fire period.

Object and Methods

The study was carried out in the forests grown in Kremenchuk Forest Economy

Branch in Poltava region on the border of forest-steppe and steppe, Ukraine (Fig. 1) (Myroniuk et al. 2020). All the forests perform useful ecosystem services for the city of Kremenchuk and other settlements. Despite it these areas are affected by fires every year.

The city of Kremenchuk is one of the largest industrial centers not only in Poltava region, but also of the whole Ukraine. It is located in the zone of temperate continental climate on the border of forest-steppe and steppe within Dnipro lowland and the middle course of Dnipro river on its left and right banks. The area of the city is 9586 ha and the length from north to south is approximately 30 km; it has a population of approximately 217,000 inhabitants (Boychenko et al. 2020).

The typical middle-aged Scots pine forests, which are most common for study region, were chosen for laying out sam-



Fig. 1. Diagram-map of the research region of Ukraine.

pling plots. In this region grass fires of different intensity were recorded and typically spreaded to forests. At the same time, they have a fairly substantial stage of recreational digression (III stage) (Voron et al. 2011), which is explained by their proximity to settlements and high population density.

The object of the study was pure middle-aged Scots pine stands damaged in 2019 by surface fires of various intensity under increased recreational impact. Their geographic coordinates are 49°05'40" N, 33°22'25" E (Fig. 1) (Myroniuk et al. 2020). For the study, in September 2022, five temporary sample plots were laid out in the middle-aged Scots pine stands in Hradizk Forestry in Kremenchuk Forest Economy Branch three years after a surface fire in the fresh relatively poor forest site.

The main stand characteristics were calculated for each sample plot with different degrees level of fire damage (according to the bark char height). All characteristics determined for the sample plots were compared with each other and with those from the control sample plot. As a control we used a sample plot without fire damage but with a recreational impact. All sampling plots were similar in terms of the degree of recreational influence and forestry characteristics; they had III stage of recreational digression but in the same time they were damaged by surface fires with different intensity.

Recreational degradation is a process of changing the natural environment as a result of anthropogenic factors, marked by soil compaction, trampling and destruction of forest litter, grass cover, and undergrowth, as well as damage to trees. For natural forest complexes, five stages of recreational degradation have been substantiated, depending on the recre-

ation coefficient and the condition of the stand, undergrowth, shrubs, grass and moss cover, and forest litter (Cherchyk and Mishchenko 2009).

The sample plots were laid out in accordance with the standard methods used in Ukrainian forestry and forest mensuration (Vorobyov 1967, Corporate standard 02.02-37-476:2006 2007, Hrom 2010). Mensuration and morphological characteristics of trees were determined, namely: tree height (H_{ave} , m), diameter at breast height (D_{ave} , cm), is stock volume per 1 ha (V_{ave} , $m^3 \cdot ha^{-1}$), number of trees per ha (N , $trees \cdot ha^{-1}$), Kraft class, and a rough bark height. All these indicators on SP damaged by surface fire were measured already after the fire, and were compared with the control sample plot, i.e., similar in all forestry characteristics that was not damaged by fire. Main mensuration changes as well as the consequences of fires were assessed by comparing the differences between the damaged stand and the control sample plot. We have also considered that these sites are additionally constantly exposed to the increased recreational impact, which is also a factor that negatively influences the stand condition and growth (Gensiruk et al. 1987, Derekh 2008). Therefore, to compare the impact of fires of various intensities on the structure and beneficial functions of pine stands under increased recreational impact, we selected sites with the same degrees of recreational digression and almost identical biogeocenotic conditions. The stages of recreational digression were defined according to the Regulatory Reference Materials for the Inventory of Forests in Ukraine and Moldova (Shvidenko et al. 1987, USFMPA 2006).

In the studied area, road-based recreation activity was registered in the vast majority of cases, that is most character-

istic for forests with developed infrastructure (Moiseev et al. 1990). Tourists here travel along the roads and trails both on foot and by bicycle. To investigate this issue, we determined not only the degree of recreational digression but also measured the trampled area proportion.

The trampled areas were compared using recreation factor K_r . It was defined as the ratio of the compacted and trampled area to the total area of the plot and expressed in fractions of a unit (Gensiruk et al. 1987).

The detailed investigation of damage for each individual tree differing in diameter, Kraft class and the rough bark height allowed analysing the influence on the tree condition of such characteristics as the bark char height and degree of thin bark burn injury. We assessed correlational dependences of changes in health condition index and standing dead trees percentage on both of these indicators for separate groups of similar trees.

The tree condition was assessed by the stand health condition index according to the recommendations developed in the Laboratory of Forest Ecology, Ukrainian Research Institute of Forestry and Forest Melioration (Voron et al. 2011).

During the survey, we assessed the stand condition by the morphological changes in the trees, considering such bioindicative signs as defoliation (loss of needles) and decolouration (change in colour) of tree crowns. Also, tree health condition categories were determined.

The damage degree for the stands, that is, the health condition index I_c , was determined based on these indicators. It was calculated as a weighted mean indicator according to formula (1) (Voron et al. 2021):

$$I_c = \frac{K_1 \cdot n_1 + K_2 \cdot n_2 + \dots + K_6 \cdot n_6}{N}, \quad (1)$$

where: I_c – health condition index of the stand; $K_1, \dots, K_6$ – category of the health condition of the trees (from 1 to 6); $n_1, \dots, n_6$ – number of trees of the given health condition category; N – total number of recorded trees in the sample plot.

The damage degree was determined according to the health condition index, taking into account the following scale of health condition indices: 1.0–1.5 – healthy stand, 1.6–2.5 – weakened stand, 2.6–3.5 – severely weakened, 3.6–4.5 – dying stand, 4.6–6.0 – dead stand.

The health condition index of the stand (I_c) and the proportions of dying and standing dead trees (4th, 5th and 6th health condition categories) were found based on general data from all sample plots, and for each bark char height level (0.5 m each) and Kraft class.

The consequences of surface fire damage to the studied pine stand were investigated based on the thermal radiation effect, i.e. damage to a trunk (the bark char height H_{char}). The fire intensity was determined by the flame height in meters: up to 0.5 m – low intensity fire, 0.5–1.5 m – medium intensity fire, and above 1.5 m – high intensity fire (Cabinet of Ministers of Ukraine 2022).

For a more detailed study of damage to a trunk and its effect on further tree development, we measured the bark char height and the rough bark height. The degree of the thin bark burn injury was calculated using these data according to formula (2) for an additional assessment of the trunk damage (Voron et al. 2021):

$$H_{\text{inj}} = (H_{\text{char}} - H_{\text{rough bark}}), \quad (2)$$

where: H_{inj} – degree of the thin bark burn injury, m; H_{char} – mean bark char height, m; $H_{\text{rough bark}}$ – rough bark height, m.

Determination of features for fire protection for trees of various diameters was carried out by establishing a correlation

between the height of bark transition area, where the bark changes from thick to thin, and the diameter of trees of various thickness degrees. This value was additionally used in the diagnosis of fire damage to trees, to determine the degree of the thin bark burn injury, and when comparing the characteristics of trees of different Kraft classes.

Statistical data processing was carried out according to generally accepted methods (Atramentova and Utevska 2007, Daniel and Cross 2018, Shalabanov and Roganov 2008), using MS Excel 2013 and Statistica 10 computer applications. Correlation and regression analyses were done according to common methods. During correlation analysis, the relationship is functional if the correlation coefficient is 1.00, very strong – 0.90–0.99, strong – 0.70–0.89, significant – 0.50–0.69, moderate – 0.30–0.49,

weak – 0.10–0.29. Mean absolute errors and experiment accuracy were calculated according to standard methods (Atramentova and Utevska 2007, Daniel and Cross 2018, Shalabanov and Roganov 2008).

Results and Discussion

All the sample plots were established in 55-year-old stand and almost did not differ in terms of the main stand indicators (Table 1). The impact of recreational pressure in the form of trampled paths was recorded in all the sample plots. The mean tree diameters and heights in the sample plots varied within 10 %, the densities were from 931 to 1501 trees·ha⁻¹, the growing stocks were from 403 to 496 m³·ha⁻¹. All the sample plots had the same 2nd growth class (Hrom 2010), as well as similar relative densities of stocking of about 0.8–0.9.

Table 1. Stand characteristics in established sample plots.

Sample plot	Location of SP	H_{ave} , m	D_{ave} , cm	Growth class	V_{ave} , m ³ ·ha ⁻¹	N , trees·ha ⁻¹	Relative density of stocking
1	49°05'40.4" N 33°22'25.3" E	15.1	30.9	2	202	931	0.79
2	49°05'40.2" N, 33°22'25.9" E	15.4	29.2	2	209	970	0.74
3	49°05'39.8" N, 33°22'27.2" E	15.2	28.8	2	218	938	0.82
4	49°05'39.4" N, 33°22'28.2" E	14.9	25.8	2	244	1,051	0.88
Control	49°05'42.8" N, 33°22'19.9" E	15.7	26.5	2	218	941	0.82

Note: H_{ave} is height, D_{ave} is diameter, V_{ave} is stock volume, N is number of trees.

All of the sample plots had the same stage of recreational digression (Table 2); however, the control plot had two times lower trampled area percentage than all four damaged plots. Thus, it was difficult to clearly determine how much this factor af-

fects due to similarity of recreation impact on all the sample plots. Therefore, the fire damage itself was investigated and analyzed much more thoroughly. It should be noted that a few healthy trees were found only in control plot (1st health condition

Table 2. Condition of middle-aged pine stand in the sample plots under the recreational pressure and damaged by surface fire.

Sample plot	Percentage of trampled area	Recreation factor K_r	Degree of recreational digression	Mean bark char height H_{char} , m	Mean rough bark height $H_{\text{rough bark}}$, m	Health condition index	Health condition	Distribution of trees by health condition categories, %					
								1	2	3	4	5	6
1	14	0.14	III	0.48	5.38	2.60	Severely weakened	0	42	52	3	0	3
2	16	0.16	III	0.92	4.87	3.14	Severely weakened	0	15	70	6	2	7
3	16	0.16	III	1.68	4.66	3.25	Severely weakened	0	2	80	8	1	9
4	16	0.16	III	2.51	4.75	3.62	Dying	0	3	60	9	6	24
C	8	0.08	II	-	5.10	2.42	Weakened	5	50	43	2	0	0

category – 5 %). Weakened (50 %) and severely weakened (43 %) trees prevailed there, while standing dead trees (5th–6th health condition categories) were not recorded. Dying trees made up an insignificant part (4th health condition categories – 2 %). At the same time, dying and dead trees appeared in rare cases as a result of their natural differentiation, that is, the dieback of weakened trees.

Assessment of the stand characteristics in fire-damaged sample plots showed that they differed (Table 2). The health condition index fluctuated noticeably in the range of 2.60–3.62. The value increased with an increase in the bark char height. Thus, the least fire-damaged sample plot 1 ($H_{\text{char}} = 0.48$ m, i.e. low-intensity surface fire) had the health condition index of 2.60, indicating ‘severely weakened’ stand in terms of health condition. It should be noted that stands in both sample plots 2 and 3 also were assessed as the ‘severely weakened’ ones in terms of health condition, but the health condition index there was significantly higher (3.14 and 3.25, respectively), which is

explained by a stronger damage in these plots. In the sample plot 2, the mean bark char height $H_{\text{char}} = 0.92$ m, that testifies to a medium intensity surface fire. In the sample plot 3, $H_{\text{char}} = 1.68$ m, indicating strong intensity surface fire. Sample plot 4, with the highest value of H_{char} of 2.51 m, belonged to the ‘dying’ stand in terms of health condition.

A detailed analysis of the tree distribution by condition categories showed that deterioration was recorded in all damaged plots, which is confirmed by the complete absence of healthy trees (1st health condition category) and the presence of dying (4th health condition category) and dead (5th and 6th health condition categories) trees (Table 2). In sample plots 3 and 4, where the mean bark char height was greater and at the same time a height of the rough bark transition was lower, the proportion of trees of the 4th and 5th health condition categories and the mean health condition index were significantly higher. Thus, it is noticeable that the rough bark protects the trunk from thermal radiation.

Based on the graph (Fig. 2), it can be seen from the comparison of these indicators for all four fire-damaged sample plots that the height of the bark transition area clearly depends on the tree diameter. That is, it is clearly visible that at the smallest thickness degree of 18 cm, the

lowest height of the bark transition area is observed – 3.8 m only. The maximum value of 5.9 m is observed at the largest thickness degree of 42 cm. A very strong ($r = 0.91$) positive significant correlation ($t_f = 4.63 > t_{st,0.01} = 3.10$) was found between the height of the rough bark and diameter.

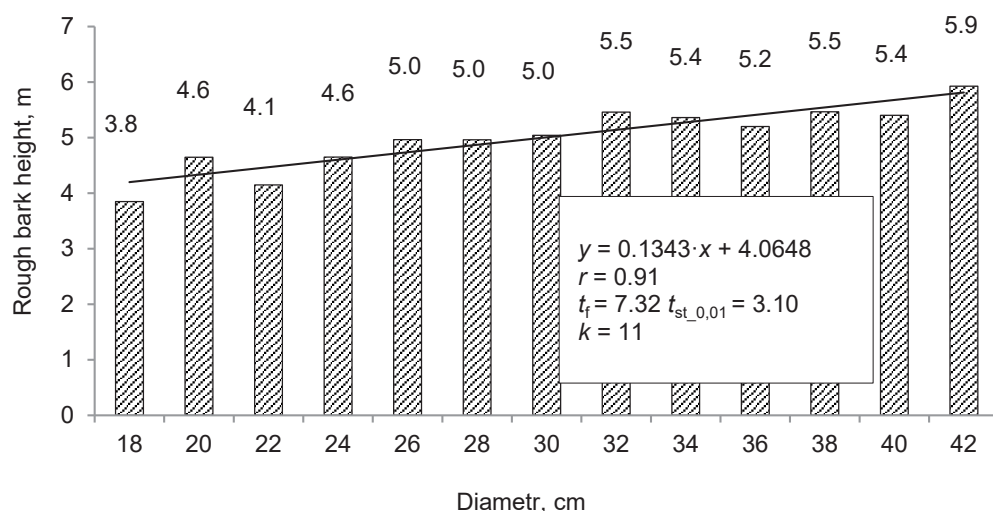


Fig. 2. Dependence between bark transition height area and diameter.

This distribution showed well how trees of different Kraft classes were affected by fires of different intensities. Determining the mean rough bark height separately for each Kraft class made it possible to compare the differences in the consequences, taking into account this characteristic as well (Table 3).

The least negative impact for the trees of all five Kraft classes were caused by the damage with a minimum bark char height (up to 0.5 m, i.e., a fire of low intensity). The proportion of standing dead trees did not exceed 2.2 % for III Kraft class. For trees of I, II and even IV–V Kraft classes, no dieback was noted and the health condition index was similar (2.5–3.0 m).

When comparing bark char height from 0.5 to 1.0 m, a dieback was noticeable for

trees of IV–V Kraft classes, but it was not so significant. Their mean health condition index was 3.0, while for other groups the health condition was not much better – 2.7.

For trees of IV and V Kraft classes, even when the bark char height did not exceed the mean height of the rough bark, the damage led to massive dieback already at H_{char} of 1–1.5 m (medium intensity fires) and above 1.5 m (high intensity fires), i.e. with such damage the proportion of dying and standing dead trees was 100 % in almost all cases. Trees of III Kraft class reacted quite negatively to such damage; in this case, the proportion of standing dead trees was 25 %. Critical for such trees was the bark char height of 3.5 m (50–100 % of standing dead trees),

Table 3. Distributions of the mean health condition index and dying and standing dead trees depending on the bark char height for various Kraft classes.

Bark char height, m	I_c by Kraft classes				Percentage of dying and standing dead trees by Kraft classes			
	I	II	III	IV-V	I	II	III	IV-V
0.5	2.7	2.5	2.9	3.0	0	0	2.2	0
1	nd	2.7	2.7	3.0	nd	0	0	16.7
1.5	2.5	2.7	3.2	4.0	0	0	25	100
2	3.0	3.0	3.3	5.0	0	6.2	27.3	100
2.5	3.5	2.7	3.5	4.0	0	0	30.8	50
3	3.0	3.7	3.7	5.0	50	40	33.3	100
3.5	nd	4.0	5.0	nd	nd	50	100	nd
4	nd	nd	3.5	5.0	nd	nd	50	100
4.5	nd	nd	5.0	nd	nd	nd	100	nd
Mean rough bark height, m	6.82	5.25	4.72	4.03	6.82	5.25	4.72	4.03

Note: nd – no data.

which was very close to the the mean rough bark height (4.7 m). Under such severe damage, the situation was different for trees of I and II Kraft classes. Such trees had a noticeably larger rough bark height (5.25 and 6.82 m). At a maximum bark char height of 3.5 m, only up to 50 % of dying trees were recorded. With a lower bark char height but with high fire intensity, there was a complete absence of trees IV, V and VI Kraft classes. Such data showed clear differences in the health deterioration for trees of different Kraft classes. Thus, the best post-fire health condition was observed for dominant trees (I and II Kraft classes), in which the higher rough bark can better protect the tree from fire damage. This further confirms the importance of taking this characteristic into account when determining the consequences of damage to such middle-aged pine stands by surface fires.

The analysis of the correlations between the bark char height and I_c , as well as the percentage of dying and standing

dead trees showed a very strong ($r = 0.95$ and 0.94) and significant correlation dependence, which was confirmed in both cases ($t_f > t_{st,0.01}$). Thus, there is a clear pattern: an increase in the mean pine stand health condition index and the percentage of dead trees with an increase in the bark char height. Therefore, it can be claimed that under the given conditions in such pine stands, the bark char height is the key indicator in determining the impact of surface fires of varying intensities (Fig. 1).

A strong correlation between the bark char height and such characteristics as the health condition index and the percentage of standing dead trees was found for the entire stand as a whole (Fig. 3). This is evidenced by a high correlation coefficient and an excess of the Student t_f significance level over $t_{st,0.01}$.

We have found that also found that it is quite effective to analyse the surface fire impact and propose the priority measures necessary to cut down the most

damaged trees by determining the degree of thin bark burn injury (see Fig. 4). The correlation between this characteristic

and the health condition index was found to be even higher ($r = 0.98$), even with a higher value of the number of degrees of

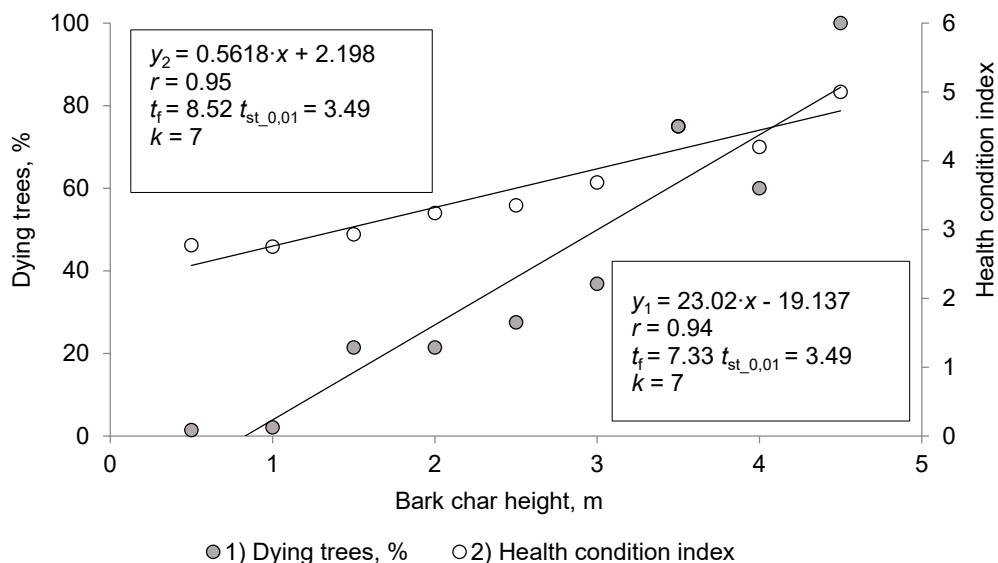


Fig. 3. Dependence of the mean health condition index and the percentage of dying trees on bark char height.

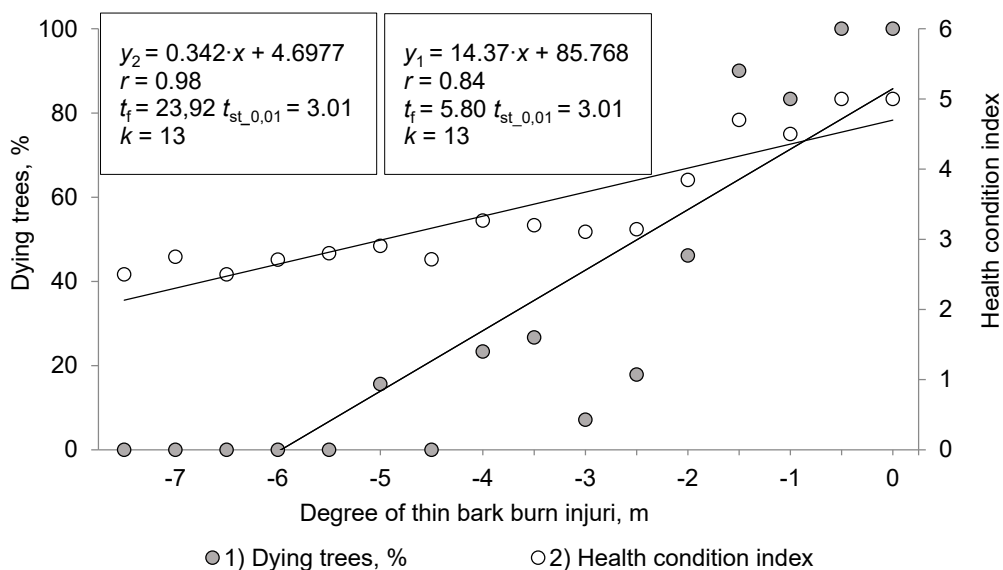


Fig. 4. Dependence of the mean health condition index and the percentage of dying and dead trees on the degree of thin bark burn injury.

freedom ($k = 13$). Although a less close ($r = 0.84$) strong significant correlation dependence was established when comparing the degree of thin bark burn injury and the proportion of dying trees, but two important points can be clearly distinguished based on these data. First: it is possible to track the consequences and features of the most critical damages. The graph (Fig. 4) clearly shows a 100 % probability of tree deaths when the bark char height reaches the maximum level of the rough bark height ($H_{inj} = 0$). Also, we can see the critical damage level (H_{inj} is from -0.5 to -1.5 m) with the probability of almost complete dieback (80–100 %) of any trees. For such injuries, the trees must be prescribed for sanitation felling, immediately after the fire. Secondly: this comparison clearly shows the trees that will survive. For example, dying and dead trees were completely absent when the degree of thin bark burn injury varied from -5.5 to -7.5. This is also an important limit for the preservation of such forests during post-fire sanitation interventions.

Similar studies have already been conducted in the mid-aged pine forests of Ukraine, but in Kharkiv region (Sydorenko 2017, Melnyk 2019, Sydorenko et al. 2020, Voron et al. 2021). Under these conditions, during the exposure to surface fires of varying intensity, no severe damage by convective heat flow was recorded, i.e. there was no burning of branches and needles. The main indicator for assessing the impact of surface fires is the effect of thermal radiation, i.e. the height of the bark char. Many studies have found a direct significant correlation between the average height of bark char and tree health ($r = \geq 0.6$ –0.9), as well as the degree of thin bark burn injury. Also, according to such studies, in the conditions of the forest-steppe part of Kharkiv region, in

a pine plantation similar in average such as diameter at breast height (DBH), three levels of damage and negative changes were established, that is, the mortality of trees depending on the increase in the degree of burn of the thin bark: 1) when the height of the char did not exceed the height of rough bark (H_{inj} from -9 to -4 m), and the trees almost did not react to such damage; 2) when the char was a few meters from the transition bark zone ($H_{inj} = -4$ to -1 m), while the proportion of dead trees noticeably increases to 30 %; 3) the height of the char is very close to the transition zone from coarse bark to thin one (H_{inj} from -1 to 0 m), as a result the condition index deteriorates sharply and the proportion of dead trees exceeds 50 to 100 %. Almost the same patterns and results were obtained in our current research in the green zone of the city of Kremenchuk (Fig. 4). In both studies, the levels of damage and potential consequences were more or less similar. Thus, the minimum share of dead trees from 0 to 15 % was noted at the first level, i.e. H_{inj} is from -7.5 to -4.5 m. The increase in the share of dead trees to 46 % at H_{inj} values from -4 to -2 m. But almost complete death from 83 to 100 % of trees at H_{inj} from -1.5 to 0 m. Thus, in the conditions of the Left Bank forest-steppe, an additional stress factor (recreational pressure) is not decisive and does not significantly affect the post-fire development of damaged stands.

It can also be noted that in the conditions of the left-bank Forest Steppe, for a better comparison and obtaining more reliable post fire mortality prediction, it is necessary to take into account the class of tree growth according to Kraft and the height of the coarse bark, with the further determination of the degree of of the thin bark injury.

The obtained data and conclusions

recommended to be used in similar conditions for pine stands in the Forest Steppe.

The research of Tkach (2019) in the Mixed-forest zone (Ukrainian Polissia) in similar mid aged Scots pine stands under conditions of fresh forest showed intensive dieback (more than 50 %) of such stands even with minimum values of the height of the bark char (up to 0.5 m). In the conditions of Ukrainian Polissia this happened due to severe damage to the surface root system that are typically forming in such conditions, second important factor was a significant litter reserves that was lead to smoldering fire (Tkach 2019). This phenomenon is especially negatively manifested in wet and humid hygrotops in abnormally dry years when all litter as well as a duff layer were burnt. While in our research the conditions of the left-bank Forest Steppe, only 2 % dead trees share was recorded at this height of the bark char, i.e. impact of fire was low (Fig. 3). Therefore, the study of the fire impact, considering natural zones and their specific natural features, is very important.

Bark thickness is an important indicator of tree trunk resistance to damage from surface fire (Lawes et al. 2012, Voron et al. 2021). In our study, due to the comparison of the rough bark height for trees of different diameters and investigation of the effect of fires of different intensities, it was possible more accurately to determine certain regularities of the changes in tree condition and dieback.

The bark char indicator is widely used in the world, both alone and in combination with crown scorch, to predict post-fire mortality of pine forests (McHugh and Kolb 2003). However, a study of fire impact on pine forests in the Intermountain West in the USA showed that the strength of crown scorch and crown consumed volume are quite important and accurate

indicators for determining tree mortality (Sieg et al. 2006). Other indicators, such as DBH and maximal bole scorch height, ground fire severity rating, the presence of insects and a number of other characteristics, only by a few percent increased the accuracy of determining the death of the studied pine trees in a given area in the following 3 years postfire.

It is necessary to implement ecologically-based forest management with the preservation of trees, taking into account the natural features of a certain region. This is particularly important in the green areas of large industrial cities. Our study showed that the tree health assessment could be improved. We recommend using in such conditions not only the bark char height but also the degree of thin bark burn injury, especially during surface fires with high intensity.

Conclusions

In the green area of the city of Kremenchuk after surface fires in middle-aged pine stands in relatively poor forest sites, the degree of fire damage to the trunk (bark char height) was immediately driving the deterioration of the stand health. Such indicators as the rough bark height and Kraft class were found to be essential for assessing damage and predicting negative changes. These characteristics indicate the degree of tree protection and resistance to the impact of a surface fire.

Middle-aged pine stands with an increased level of recreational impact (the 3rd stage of recreational digression, the trampled area percentage 14–16 %) in fresh relatively poor forest sites in the studied area were resistant to minimum intensity surface fires (bark char height was up to 0.5 m) and medium intensity

surface fires (bark char height was from 0.5 to 1.5 m). However, the maximum intensity surface fires with more than 1.5 m bark char height caused an increase in deterioration and dieback even among dominant trees of I and II Kraft classes. An important indicator of the protection of trees from fire is the rough bark height, which has larger values in trees with a higher Kraft class and a larger diameter.

The results of this study can be used not only to reduce losses due to timely sanitation felling but also to preserve individual trees that will probably survive.

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Gas-exchange responses to light variation of tree species in urban landscaping

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Abstract

Some modifications of the urban environment, such as changes in light intensity resulting from anthropogenic activities in the cities, affect the plant's physiology. Examining physiological processes reveals the current state of plants and their potential for adaptation under changing environmental conditions. In a field study, we investigated the gas-exchange responses of seven tree species used in urban landscaping (*Betula pendula* Roth, *Ailanthus altissima* Swingle, *Tilia tomentosa* Moench, *Tilia platyphyllos* Scop., *Tilia cordata* Mill., *Quercus robur* L., and *Paulownia tomentosa* Siebold & Zucc) to variations of light using infrared gas analysis. Leaf light-saturated photosynthesis, dark respiration, and light use efficiency were obtained from the light-response curves. Carbon use efficiency was also determined. In this study, the highly shade-intolerant species, except for *P. tomentosa*, show lower carbon use efficiency. This suggests that the existing environmental conditions are not conducive to intensive growth for species that demand substantial solar radiation. In contrast, *P. tomentosa* stands out as an exceptionally resilient and potentially productive species, capable of adapting to various changes in the current environment, even when they do not align with its specific ecological requirements. Nevertheless, *P. tomentosa*'s high carbon use efficiency compared to the native experimental species suggests its potential invasiveness.

Key words: carbon use efficiency, dark respiration, environmental stressors, light-saturated photosynthesis, light use efficiency.

Introduction

The photosynthetic activity of plants is highly correlated with solar radiation and thus net carbon gain and biomass production, if other factors are optimal, such as water and nutrient supply. The survival and growth of plants rely on their carbon balance. Two significant flows primarily

govern the carbon balance of vegetation: the input of carbon through photosynthesis and the output through respiration. The value of daily whole-plant gross CO₂ assimilation is positively correlated with growth irradiance and there is supporting evidence indicating an irradiance-dependent relationship with respiration, as well (Pons and Poorter 2014). Achieving

the maximum net photosynthetic carbon gain relies significantly on acclimating leaf physiological traits (Björkman 1981, Givnish 1988) as a vital strategy.

Species adapted to high irradiance, which are shade-intolerant, tend to invest significantly in leaf traits that maximize the photosynthetic rate and photoprotective mechanisms, relative to those associated with light absorption (Valladares and Niinemets 2008, Dusenge et al. 2015, Anev and Marinova 2021). Schulze et al. (2002) indicated that when plotting the rate of photosynthesis in relation to increasing light, the initial slope of the light response curve is linear before the rate levels off and becomes constant as photosynthesis saturates. Excessive light can be absorbed by chloroplasts but may not be effectively utilized for assimilation, fluorescence or dissipation as heat, potentially causing severe oxidative stress. High leaf temperatures can lead to stomatal closure and limited photosynthesis (Yamori 2016).

In low light environments, photon absorption becomes a limiting factor for photosynthetic rates. As a result, shade-tolerant species proportionally invest more in structural components and pigments, leading to greater light absorption compared to shade-intolerant species (Feng et al. 2004, Valladares and Niinemets 2008). Within a species, plants grown in shaded locations, as opposed to those growing in well-lit environments, tend to have leaves with a low dark respiration rate, light-compensation point, light-saturation point, net photosynthetic rate, and electron transport rate, primarily due to the low concentration of photosynthetic enzymes in the leaves (Craine and Reich 2005, Valladares and Niinemets 2008, Kolev and Anev 2022). These shade-tolerant plants achieve their maximum rates of photosynthesis at lower light intensities

and may also photosynthesize more efficiently at low light levels, although this efficiency aspect is less well-established (Baker 1950). The research conducted by Kubiske and Pregitzer (1996) demonstrated that the alterations induced by various levels of CO₂, which gas is significantly elevated in an urban environment (Liu et al. 2011), in the parameters associated with how plants respond to light interacted in a manner that resulted in distinct predictions for the carbon balance at the leaf level, especially under different light conditions. Notably, these effects of shade were most prominent in plant species that possess a high degree of shade tolerance. Bazzaz and Carlson (1982) observed in their study that late-successional species demonstrated greater CO₂-induced growth enhancements in shade compared to full sun conditions. Additionally, Takagi and Gyokusen (2004) indicated that in their study the shade-tolerant species *Ilex rotunda* showed high photosynthetic performance under low photosynthetic active radiation. On the other hand, Kjelgren and Clark (1992) found a reduction in photosynthesis of shade-intolerant species *Liquidambar styraciflua* L. due to shadowing by tall buildings. However, it should be emphasized that *Liquidambar styraciflua* L. and *Ilex rotunda* Thunb. have different light requirements. The varying physiological responses of tree species to light conditions, which are influenced by their ecotype, states that appropriate selection of tree species can therefore change potential stress factors into favourable conditions.

The study of physiological response to light shows the current state of the experimental trees and their potential for adaptation under urban environmental conditions. However, there are few studies on the effects of the urban microenvironment

on trees (Bassuk and Whitlow 1987, Whitlow and Bassuk 1988, Takagi and Gyokusen 2004, Anev 2016, Wang et al. 2019). Fortunately, advanced instruments, such as infrared portable gas analysers, allow more photosynthetic parameters to be measured in the field. We aimed to investigate the various responses of the photosynthetic parameters in different tree species to the urban environment to provide references for improving the growth conditions of the trees in the cities. We anticipated that each tree species would exhibit distinct light curves, reflecting the fine details of their adaptation to the challenging conditions of an urban environment.

Materials and Methods

In June 2023, a field experiment was conducted on the territory of the University of Forestry located next to the large boulevard St. Kliment Ohridski in the city of Sofia, Bulgaria (42°41'57" N, 023°19'21" E). The area is in the temperate climate zone and has a humid continental climate with warm summers – average monthly temperatures fall below 0 °C and do not exceed 22 °C, with more than 3 months having an average temperature above 10 °C. The mean annual temperature is 10.6 °C, and the mean annual precipitation is 581.8 mm, reaching its maximum in late spring and early summer when thunderstorms are not uncommon (NOAA 2021). The average monthly June temperature was 18.5 °C, the average monthly June precipitation was 161.4 mm (NIMH 2023).

Seven tree species used for landscaping were selected: *Ailanthus altissima* Swingle, *Betula pendula* Roth, *Paulownia tomentosa* Siebold & Zucc, *Quercus robur* L., *Tilia cordata* Mill., *Tilia platyphyllos* Scop. and *Tilia tomentosa* Moench for

the measurements. The age of the trees in the study ranged from 40 to 60 years. Apart from *P. tomentosa*, all experimental trees are located within the yard, positioned between the two university buildings. In contrast, *P. tomentosa* is situated independently near a small building adjacent to the park area.

Gas-exchange measurements were made using a portable photosynthesis system (LI-6400®, LI-COR, Lincoln, NE, USA) with an infrared gas analyser (IRGA) connected to a 6400-02B measuring chamber with a LED light source. During the measurements, we strictly adhered to the PrometheusWiki Gold Leaf Protocol (Evans and Santiago 2014). This protocol provides detailed instructions on how to perform basic measurements using the LI-COR 6400 gas exchange instrument. The measurements of net photosynthesis in response to photosynthetic photon flux density (PPFD) were conducted on sunny days, between 10:00 and 13:00. The measurements were carried out *in situ* by collecting three branches from various exposures of the middle section of the crown of each of the studied tree individuals. From each branch, the third leaf, counting from the tip of the branch, was chosen for the measurements (Evans and Santiago 2014). The leaves were exposed to ambient CO₂ levels and saturating PPFD conditions, set at 2000 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, until both net photosynthesis and intercellular CO₂ concentration had stabilized. The time provided for leaf adaptation when PPFD changes was between 60 and 120 s. Subsequently, the PPFD was systematically reduced in incremental steps, including 2000, 1000, 500, 250, 100, 50, 25 and 0 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ changed by the auto program 'Light_curve'. Net photosynthesis was recorded at each of these PPFD levels once the leaves had reached a steady-

state condition, as described earlier.

The results of the measurements for the light curves from each species were processed using a special software – Photosynthesis tool, which regressively smooths the light dependence of photosynthesis according to the model described in Li-Cor Application Note #105 (Norman et al. 1991) to determine some physiological parameters of the experimental trees, such as light-saturated photosynthesis ($A_{\max}$), dark respiration (R_d) and light use efficiency (LUE). Carbon use efficiency (CUE) was calculated as the ratio of light-saturated photosynthesis to dark respiration. One-way ANOVA tests and Tukey post hoc analysis were performed to determine the difference between the average values of $A_{\max}$, R_d , LUE, and CUE.

Results and Discussion

This study investigated the impact of fluctuations in photon flux density on the parameters of the light photosynthetic curve for various trees used in urban landscaping (Fig. 1).

The response of tree species to changes in light can be observed through the analysis of generalized parameters of light curves.

Light-saturated photosynthesis

We observed (Fig. 2) significant differences in the light-saturated photosynthesis among the studied tree species, indicating substantial variations in their photosynthetic capabilities (one-way ANOVA, $F = 12.843$, $P < 0.001$). *Q. robur* has the highest levels of $A_{\max}$ compared to the

other experimental species. The other tree species in the experiment also have a high light-saturated photosynthesis rate, although not as high as that of *Q. robur*. Among them, *T. cordata* stands out, which has significantly higher light-saturated photosynthesis than *P. tomentosa* and *T. tomentosa* and similar levels of $A_{\max}$ to *A. altissima* and *B. pendula*.

Q. robur biological features (tall, long-lived, forming large and spread crown) and ecological needs (shade-intolerant) are a prerequisite for reaching high levels of photosynthesis under suitable environmental conditions (Schulze et al. 2006). Elevated nocturnal temperatures in the cities can also stimulate night-time respiration in some trees, which can lead to increased photosynthesis the following day (Turnbull et al. 2002). In our study, *Q. robur* demonstrated a higher assimilation rate compared to previous research (Čater and Levanič 2015, Gardner et al. 2021) findings. The high $A_{\max}$ observed in *Q. robur* could be also attributed to the beneficial effects of increasing carbon dioxide levels in urban environments (Kubiske and Pregitzer 1996, Liu et al. 2011) on photosynthesis. Such results indicate that the lighting conditions for *Q. robur* are conducive to supporting intense photosynthesis. Likewise, Lukowski and all. 2020 find in their study that *Q. robur* exhibits better resistance to air pollutants compared to other tree species studied in our experiment, which aids in mitigating the negative impact of these pollutants on photosynthesis rates.

It is interesting that in our study *T. cordata*, which is commonly acknowledged as a shade-tolerant species (Pigott 1991, Eaton et al. 2016), which characterizes it with a lower photosynthetic capacity than shade-intolerant species (Mathur et al. 2018), has similar levels of $A_{\max}$ to the

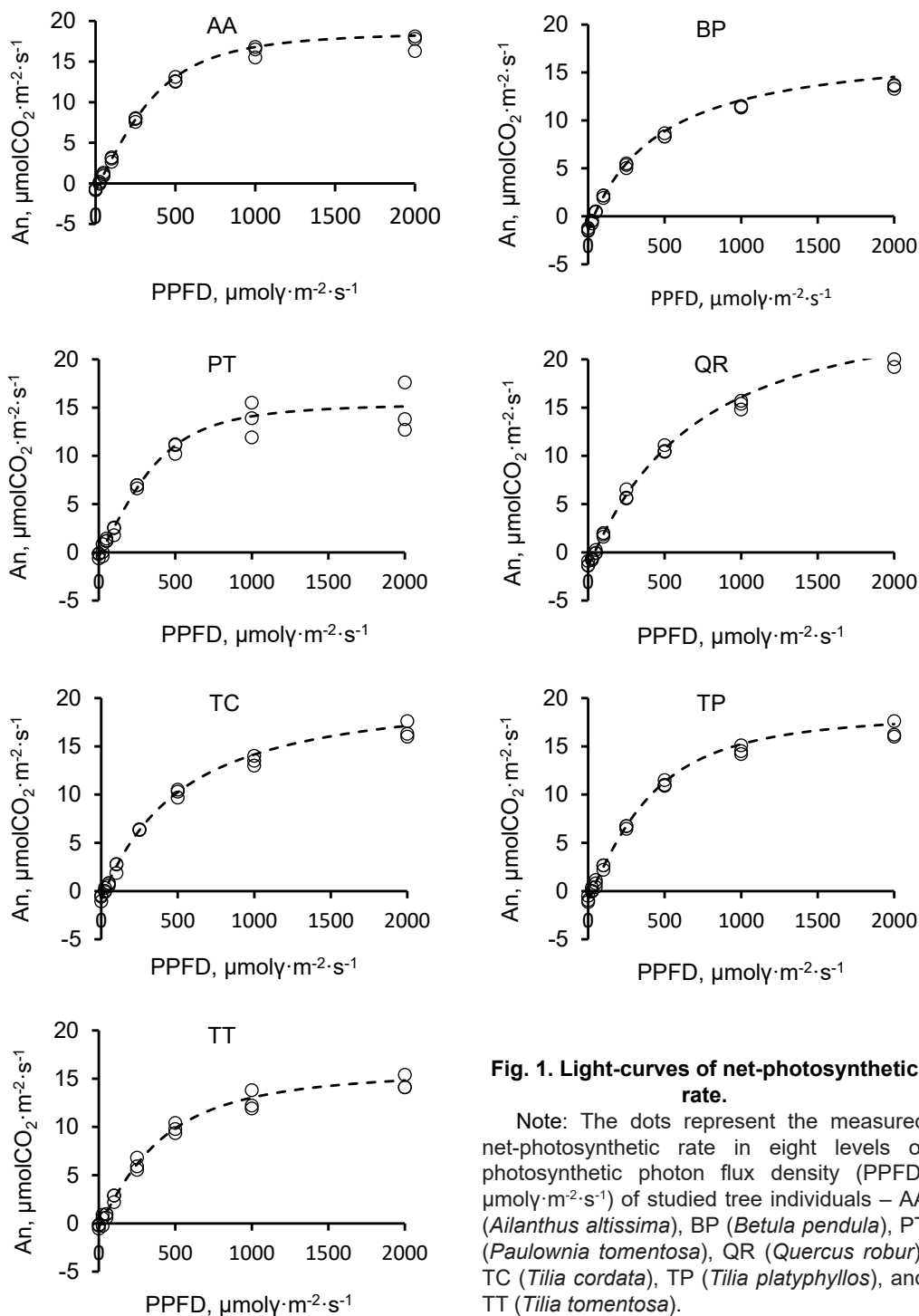


Fig. 1. Light-curves of net-photosynthetic rate.

Note: The dots represent the measured net-photosynthetic rate in eight levels of photosynthetic photon flux density (PPFD, $\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$) of studied tree individuals – AA (*Ailanthus altissima*), BP (*Betula pendula*), PT (*Paulownia tomentosa*), QR (*Quercus robur*), TC (*Tilia cordata*), TP (*Tilia platyphyllos*), and TT (*Tilia tomentosa*).

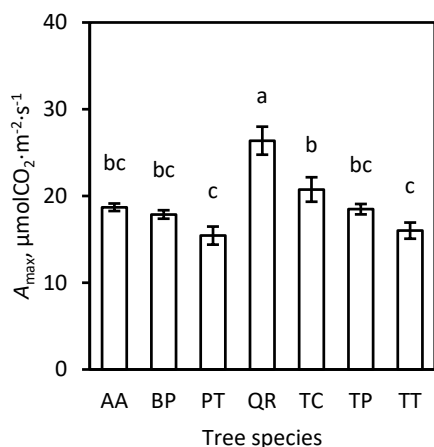


Fig. 2. Light-saturated photosynthesis.

Note: The letters below the columns represent the studied tree individuals – AA (*Ailanthus altissima*), BP (*Betula pendula*), PT (*Paulownia tomentosa*), QR (*Quercus robur*), TC (*Tilia cordata*), TP (*Tilia platyphyllos*), and TT (*Tilia tomentosa*). The columns are the average light-saturated photosynthesis ($A_{\max}$) measured from the leaves of each tree species. The whiskers represent the standard error. The different letter denotes statistically significant difference averages among objects (one-way ANOVA using Tukey post hoc tests with $\alpha = 0.05$).

shade-intolerant tree species in the experiment (*A. altissima* and *B. pendula*) (Beck et al. 2016, Knusel et al. 2016) except for shade-intolerant *Q. robur* (Ellenberg 1988) and even higher $A_{\max}$ than moderately shade-tolerant *T. tomentosa* (Radooglou et al. 2009) and shade-intolerant *P. tomentosa*. Proceeding from the fact that shade-tolerant plants achieve their maximum rates of photosynthesis at lower light intensities and may also photosynthesize more efficiently at low light levels (Baker 1950), it can be assumed that this high $A_{\max}$ that archives *T. cordata* is probably a result of insufficient solar radiation for intensive photosynthesis in light-loving species, but sufficiently favourable

for shade-tolerant ones. *Q. robur*, which is a shade-intolerant tree species, doesn't necessarily invalidate this presumption. In a study by Van Hees (1997), it is observed that when comparing the effects of shading on growth and/or morphology between the shade-tolerant beech and the shade-intolerant pedunculate oak, their responses are surprisingly similar. This suggests that different tree species can exhibit convergent responses to shading conditions, despite their inherent shade tolerance or intolerance characteristics. These findings highlight the complexity of how various tree species adapt to light environments and how their responses may not always align with general expectations based on shade tolerance.

Light use efficiency

No significant differences between experimental tree species were observed in the light-use efficiency (LUE) values (one-way ANOVA, $F = 1.018$, $P = 0.434$) (Fig. 3).

Controversy, Percy et al. (2004) found that there were a few significant differences in light capture efficiency among the species in their study. Shade-tolerant plants generally have improved light absorption efficiency than shade-intolerant species (Bongers and Popma 1988, Evans 1989, Kitajima 1994, Kolarov and Tzvetkova 2006). However, in Kim et al. (2008)'s study results, certain *Quercus* species, which are not shade-tolerant species, exhibited an improved ability to absorb and utilize light under low light conditions. Based on the findings from the studies mentioned earlier in our study, the absence of significant differences between experimental tree species may be related to the likely insufficient average monthly solar radiation, which could have equalized the light use efficiency between

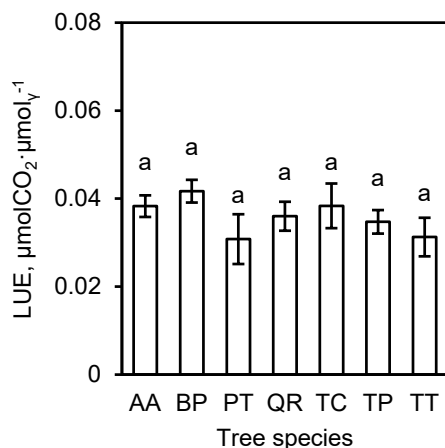


Fig. 3. Light use efficiency.

Note: The letters below the columns represent the studied tree individuals – AA (*Ailanthus altissima*), BP (*Betula pendula*), PT (*Paulownia tomentosa*), QR (*Quercus robur*), TC (*Tilia cordata*), TP (*Tilia platyphyllos*), and TT (*Tilia tomentosa*). The columns are the average LUE from the leaves of each tree species. The whiskers represent the standard error. The different letter denotes statistically significant difference averages among objects (one-way ANOVA using Tukey post hoc tests with $\alpha = 0.05$).

the shade-tolerant and shade-intolerant species in the experiment.

Dark respiration

There were notable differences in dark respiration (R_d) when comparing the tree species studied (one-way ANOVA, $F = 3.452$, $P = 0.011$) (Fig. 4). *Q. robur* and *B. pendula* demonstrated significantly higher values of R_d in comparison to *T. tomentosa* and *P. tomentosa*, while the remaining species exhibited similar dark respiration rates.

The higher R_d values of *Q. robur* and *B. pendula* compared to *T. tomentosa* and *P. tomentosa* suggests that *Q. robur* and *B.*

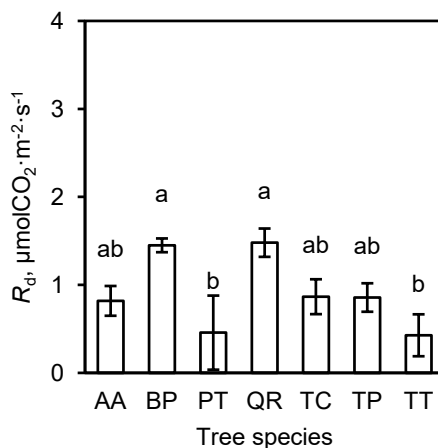


Fig. 4. Dark respiration.

Note: The letters below the columns represent the studied tree individuals – AA (*Ailanthus altissima*), BP (*Betula pendula*), PT (*Paulownia tomentosa*), QR (*Quercus robur*), TC (*Tilia cordata*), TP (*Tilia platyphyllos*), and TT (*Tilia tomentosa*). The columns are the average R_d from the leaves of each tree species. The whiskers represent the standard error. The different letter denotes statistically significant difference averages among objects (one-way ANOVA using Tukey post hoc tests with $\alpha = 0.05$).

pendula may have higher nighttime metabolic activity compared to *T. tomentosa* and *P. tomentosa*. As noted by Turnbull et al. (2002), Kanno et al. (2009) and Searle et al. (2011), elevated night temperature within the city could stimulate respiration and, consequently, photosynthesis. Colalti et al. (2019) observed that the low photosynthetic rates correspond to low respiration rates and the opposite, which we observe in our study, as well. The fact that *B. pendula* does not achieve correspondingly high levels of A_{max} despite having higher R_d rates can be an interesting observation. This suggests that while *B. pendula* may have higher metabolic activity in terms of respiration, it may not be utilizing this higher metabolic activity

to achieve a proportionally higher photosynthetic capacity. The low photosynthesis of *B. pendula* can likely be attributed to air pollutants in the cities, which act as leaf shading and negatively affect photosynthesis of trees (Weber et al. 2002, Przybysz et al. 2014, Popek et al. 2017). Łukowski et al. (2020) indicate that the foliage of *B. pendula* collected a high amount of particulate matter. Dzierżanowski et al. (2011) indicated that in contrast to *Q. robur*, *B. pendula* is more susceptible to air pollutants, particularly of their photosynthetic rates and stomatal conductance (Łukowski et al. 2020). The high intensity of R_d observed in *Q. robur* and *B. pendula* can disrupt carbon balance because plant respiration can release up to about half of the assimilated carbon by photosynthesis daily, as shown by Bruhn (2002). Reduced respiration rates in *T. tomentosa* and *P. tomentosa* are a prerequisite for more efficient carbon assimilation (Griffin et al. 2001, Schulze et al. 2006).

Carbon use efficiency

There were significant differences in carbon use efficiency (CUE) when comparing the studied tree species (one-way ANOVA, $F = 203.598$, $P < 0.001$) (Fig. 5). *T. tomentosa* had the highest carbon use efficiency among the studied tree species, followed by *P. tomentosa*. *A. altissima*, *T. cordata*, and *T. platyphyllos* exhibited moderate levels of CUE, while *Q. robur* and *B. pendula* had the lowest values of this indicator.

T. tomentosa and *P. tomentosa* have moderate A_{max} but, at the same time, maintain low R_d , which provides a high CUE. Maintaining a favourable balance of carbon elements means that *T. tomentosa* and *P. tomentosa* capacity to withstand and adapt to the urban light conditions

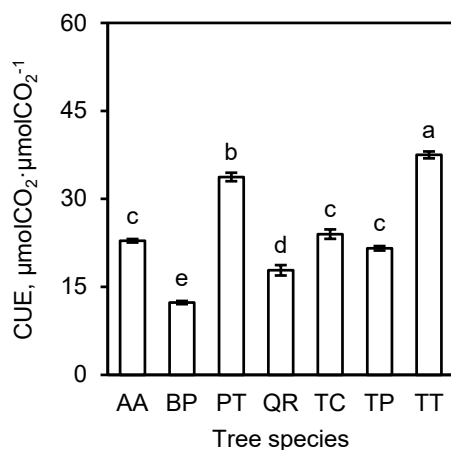


Fig. 5. Carbon use efficiency.

Note: The letters below the columns represent the studied tree individuals – AA (*Ailanthus altissima*), BP (*Betula pendula*), PT (*Paulownia tomentosa*), QR (*Quercus robur*), TC (*Tilia cordata*), TP (*Tilia platyphyllos*), and TT (*Tilia tomentosa*). The columns are the average CUE from the leaves of each tree species. The whiskers represent the standard error. The different letter denotes statistically significant difference averages among objects (one-way ANOVA using Tukey post hoc tests with $\alpha = 0.05$).

reach higher CUE than all other experimental species, which underscores its resilience, as it remains well-suited to its specific environment and is relatively unaffected by less favourable environment. Compared to *T. tomentosa* and *P. tomentosa*, *A. altissima*, *T. cordata* and *T. platyphyllos* exhibit moderate levels of carbon use efficiency. Similar to *P. tomentosa*, *A. altissima* does not attain its full photosynthetic potential as a highly shade-intolerant species (Stratton and Goldstein 2001, Lamarque et al. 2011). However, unlike *P. tomentosa*, *A. altissima* does not achieve the same level of balance among its carbon balance elements, resulting in a lower CUE comparable to that

of the shade-tolerant species in the experiment. The lower levels of CUE that *A. altissima* achieves indicates that it is more responsive to environmental conditions and is comparatively more sensitive as a species. The high energy needs of *Q. robur*, resulting from high R_d values, reflects the increased cost element of the carbon balance, leading to the inefficient use of carbon, which lower CUE. Unlike *Q. robur*, *B. pendula* does not exhibit high A_{max} values but shares similar R_d values, which renders it less carbon efficient. Regarding *B. pendula*, its comparatively lower CUE suggests it may face more significant challenges in adapting to the environmental conditions.

Conclusion

Various tree species in our experiment display unique light response curves, which reveal the intricate aspects of their adaptation to the demanding conditions of an urban environment. *B. pendula* is the most shade-intolerant tree species among the native species in the experiment and having low CUE characterizes it as a species that faces comparatively greater challenges in adapting to the environment compared to the other studied species. Despite having the highest rates of A_{max} , the shade-intolerant *Q. robur* also exhibits low CUE, which, similar to *B. pendula*, puts it at a disadvantage for adapting to environmental conditions. *T. platyphyllos*, *T. cordata* and *A. altissima* exhibit moderate CUE. While the light environmental conditions support their presence, their potential for productivity is expected to be comparatively lower than some of the other experimental species. Furthermore,

the observation that the shade-intolerant *A. altissima* exhibited comparable CUE to the shade-tolerant species in the experiment suggests that the combination of ecological factors was not conducive for it to fully realize its high photosynthetic potential. It seems that *A. altissima* is more sensitive to the light environmental conditions compared to shade-tolerant *T. platyphyllos* and *T. cordata*. *T. tomentosa* has the most favourable combination of carbon balance components, leading to a high CUE, which designates its environment as conducive to rapid growth and elevated productivity. This suggests that *T. tomentosa* would be a suitable choice for landscaping in an urban environment. *P. tomentosa* also has a high CUE. Even though its photosynthesis rates are relatively lower, possibly due to limited solar radiation, it effectively integrates the components of its carbon balance in a beneficial manner that underscores *P. tomentosa*'s exceptional adaptability to the urban environment, also indicated by other authors (Stojičić et al. 2010, Ivanova et al. 2019, Gyuleva et al. 2021). However, the achievement of almost the highest levels of CUE by the non-native *P. tomentosa* compared to the native experimental species suggests a potentially invasive nature, which landscapers should carefully consider. Conducting a comprehensive study on the response of various tree species to a wider range of ecological factors would be valuable for a more accurate assessment of their ability to adapt to the challenging conditions of an urban environment. Such research could provide valuable insights to assist landscapers in making informed decisions when selecting tree species for landscaping in urban areas.

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Using the regression model to estimate the infiltration rate from soil properties after shifting cultivation in Vietnam

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Abstract

The aim of the study was: (i) to measure the different soil properties and infiltration rate; (ii) to determine the optimum soil infiltration rate model based on soil properties (soil porosity, bulk density, soil moisture, organic matter, clay, silt and sand) after shifting cultivation in Vietnam. Infiltration rates were measured using a double-ring infiltrometer at 36 sampling points, and the measurements were taken from February to June 2020. Location of each infiltration stations were marked using GPS device. The results showed that the infiltration rate in vegetation recovering (grassland, shrubland and small regenerating trees) after shifting cultivation varied from 2.41 to 3.23 mm·min⁻¹, with an average measured infiltration rate of 2.87 ± 0.22 mm·min⁻¹. The soil porosity, organic matter content and sand have a positive correlation with infiltration rate, whereas bulk density, soil moisture, clay, silt have a negative one. The analysis performed for five models considering the combination of soil properties and subjected to regression analysis. Result showed that in order to predict soil infiltration rate based on few properties of soil with four independent variables, multi-linear regression model $IR = 1.745 + 0.026 (SP) + 0.016 (OM) - 0.026 (SM) + 0.003 (sand)$ with the coefficient of determination $R^2 = 0.856$, Bayesian Information Criterion (BIC) = -55.77 and posterior probability = 15.5 % is the best model for the estimation of infiltration rate and recommended for the research area.

Key words: bulk density, multi-linear regression, organic matter, soil moisture, soil porosity.

Introduction

Soil infiltration plays an important role in water storage for crops due to its direct effect on rainfall and crop yields and volume, transport routes and agricultural drainage quality (Huang et al. 2017). In arid and semi-arid regions, where pre-

cipitation is lower than evaporation, managing to get enough water is essential to sustaining plant life (Tang et al. 2018). In addition, soil infiltration is related to the risk of water erosion, as the main impact of soil erosion is runoff and residual water content on the soil surface after infiltration (Moazeni-Noghondar et al. 2021).

The initial infiltration rate, average infiltration rate, stable infiltration rate, or infiltration rates of several different stages were used to evaluate the stage characteristics of the infiltration process (Li et al. 2013, Zhao et al. 2013, Tang et al. 2018, Zhu et al. 2020). Neris et al. (2012) used the steady-state infiltration rate to study the effect of vegetation types on soil-water infiltration. Reynolds and Reddy (2012) used the average infiltration rate to assess the soil infiltration capacity in reclaimed surface coal mines. However, soil infiltration processes cannot be well described by one or two types of infiltration rates because they contain different information.

Traditional studies indicated that soil infiltration was affected by soil texture and structure (Saputra et al. 2022). It is one of the primary factors affecting infiltration characteristics. However, subsequent studies showed that infiltration was not only affected by soil texture but also by soil properties (Tang et al. 2018, Karahan and Yalim 2022). Soil bulk unit weight has an inverse correlation with infiltration rate. Higher soil bulk density reduces soil porosity, leading to decreased infiltration characteristics. Initial moisture content is a critical parameter that affects water retention and transmission in soil. According to Pandey and Pandey (2018), the hydraulic conductivity of sandy soil decreases with depth. Hence, the initial moisture content is a key input variable for modelling soil infiltration characteristics. Characterizing infiltration at the field scale is challenging due to the need for multiple measurements (Khatri and Smith 2005). Estimating infiltration features is difficult because of significant spatiotemporal variability. To address these challenges, researchers globally (Mirzaee et al. 2014, Parhi 2014, Tuffour and Bonsu 2015) have suggested using infiltration models as an alternative

to field-based measurements. Linear and non-linear regression are widely used approach (Rahmati 2017).

Shifting cultivation affects the hydrologic balance, creating unregulated stream flows and increasing the risk of soil erosion, floods and droughts (Schröder et al. 2023). The main cause of these problems is increased runoff due to low infiltration rate and a decrease in soil water retention (Morbideilli et al. 2018). Many studies have reported the changes in soil infiltration and soil properties after forest clearing for agricultural purposes (Sajjadi et al. 2016, Patle et al. 2018, Sun et al. 2018, Dionizio and Costa 2019, Karahan and Yalim 2022).

In view of above, an attempt was conducted to predict the soil infiltration rate of vegetation recovered after shifting cultivation using the Multiple Linear Regression Analysis with the following objectives: (i) to measure the different soil properties and infiltration rate of vegetation recovered after shifting cultivation; (ii) to determine the optimum soil infiltration rate model based on soil properties.

Materials and Methods

Study area

The study area is a mountainous district located in the southwest of Nghe An province, Vietnam (19°18'28" N and 104°28'36" E), and was performed from February to June 2020. Nghe An is directly affected by the tropical monsoon climate. The average temperature varies from 23–25 °C. The average rainfall is 1450 mm but unevenly distributed in space and time. The shifting cultivation area is 50,000 ha. As the vegetation in the area is mainly composed of grasslands and shrublands

growing on fallow swidden, these areas will be the focus of development and rehabilitation measures in the coming period. The aim of these efforts is to promote the forest protection function and provide sustainable land use practices.

Thirty-six study sites corresponding to the three different vegetation types after shifting cultivation (grassland, shrubland and small regenerating trees) were selected within the area described above (Fig. 1). As shown in Figure 1, twelve of the sites were grasslands that had formed after 1–3 years of fallow in shifting cultivation. Fifteen of the sites were shrublands where the number of regenerating trees was less than 500 trees·ha⁻¹ and they had formed after 4–6 years of fallow. Nine of the sites were small regenerating trees; the number of regenerating trees with a height over 1 m was 1000 trees·ha⁻¹ and they had formed after 7–9 years of fallow.

Soil sampling and analysis

Thirty-six surface soil samples were collected from the topsoil (0–20 cm soil layer) with a steel cutting ring (5 cm in diameter and 5 cm in depth) for further analysis of basic soil properties. The collected soil samples were placed in plastic-lined soil bags and transported to the laboratory. Moist soil samples were air-dried at room temperature and large roots were removed.

Soil bulk density (*BD*) was measured by a soil bulk sample with a 5 cm diameter and a 5 cm-high stainless steel cutting ring (three replicates). It was calculated by formulas (1):

$$BD = \frac{W_2 - W_1}{V}, \quad (1)$$

where: *BD* is bulk density, g·cm⁻³; *W*₁ is the weight of core cutter, g; *W*₂ is the weight of core cutter and soil, g; *V* is the volume of

core cutter, cm³ (Patle et al. 2019).

A soil sample for estimating soil moisture (*SM*) was collected nearby before infiltration and *SM* was determined using the oven drying method, keeping soil samples at 150 °C for 24 h. The *SM* was calculated by formulas (2):

$$SM = \frac{M_0 - M_1}{M_0}, \quad (2)$$

where: *SM* is soil moisture content, %; *M*₀ is weight of soil, g; *M*₁ is weight of dried soil, g (Patle et al. 2019).

Soil porosity (*SP*) was calculated by formulas (3):

$$SP = \left(1 - \frac{BD}{RD}\right) \cdot 100, \quad (3)$$

where: *SP* is the total soil porosity, %; *BD* is the soil bulk density, g·cm⁻³; *RD* is relative density, g·cm⁻³.

Determination of particle size distribution of soil samples has been analysed by Pipette method (Gee and Bauder 1986). The particle size distribution was calculated by formulas (4–6):

$$\text{Clays} = \frac{(m_2 - m_B) \cdot 10^5}{V_p \cdot m \cdot K}, \quad (4)$$

$$\text{Silts} = \frac{(m_1 - m_2) \cdot 10^5}{V_p \cdot m \cdot K}, \quad (5)$$

$$\text{Sands} = \frac{100 \cdot m_3}{m \cdot K}, \quad (6)$$

where: *m* is mass of soil sample (air dried); *m*₁ is mass of first sample (clay + silt) after drying 105 °C; *m*₂ is mass of second sample (clay) after drying 105 °C; *m*₃ is mass of total sands after drying 105 °C; *K* is moisture correction coefficient = mass sample after drying at 105 °C·m⁻¹; *V*_p is volume of the sample; *m*_B is mass of blank (reagents without sample) after drying 105 °C.

The measurement of soil organic matter (*OM*) content was determined by oxidation with the potassium chromate method by formulas (7 and 8):

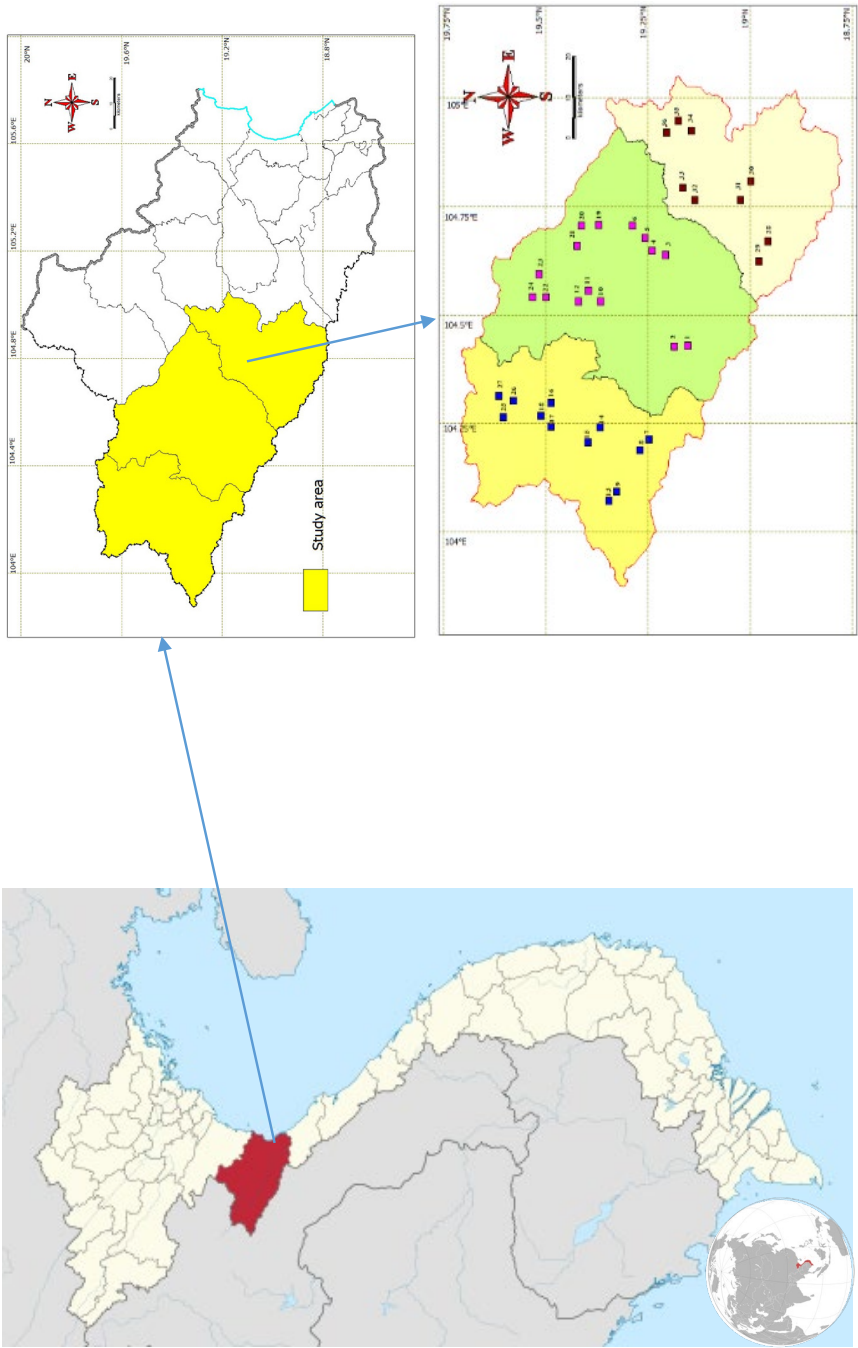


Fig. 1. Map of study area and experimental plots.

Note: Twelve of the dark blue boxes represented grassland sites that had developed after 1–3 years of fallow in shifting cultivation; fifteen of the pink boxes represented shrublands sites that had developed after 4–6 years of fallow in shifting cultivation; nine of the brown boxes represented shrublands sites that had developed after 7–9 years of fallow in shifting cultivation.

$$\begin{aligned} \text{Organic carbon (\%)} &= \\ &= 1.334 \cdot \frac{(V_b - V_s) \cdot 0.3 \cdot M}{W_t}, \end{aligned} \quad (7)$$

$$\begin{aligned} \text{Organic matter (\%)} &= \\ &= 1.724 \cdot \text{organic carbon}, \end{aligned} \quad (8)$$

where: V_b and V_s are the titration volume of blank sample and volume of soil sample respectively, mL; $0.3 \cdot M$ is the molarity of $(\text{NH}_4)_2\text{SO}_4$ and $\text{FeSO}_4 \cdot 6\text{H}_2\text{O}$ solution used in the titration; W_t is the soil sample weight, g (Farid et al. 2019).

Infiltration rate measurement

Infiltration rates were measured by using a double-ring infiltrometer on 36 sample plots. A constant head of water 3 cm deep was maintained in both the 20 cm diameter inner ring and the 30 cm diameter buffer (outer) ring. The average infiltration rate during the 0–110 min period is defined as the overall average infiltration rate (IR) (Wu et al. 2016). Calculating soil-water infiltration rate by formula (9):

$$IR = \frac{Q \cdot 10}{S \cdot T}, \quad (9)$$

where: IR is the water infiltration rate of soil, $\text{mm} \cdot \text{min}^{-1}$; Q is the amount of water absorbed, cm^3 ; S is ring cutter cross-section area, cm^2 ; T is penetration time, min.

Statistical analysis

Prediction model using multiple linear regression (MLR) analysis

A typical multiple-variable linear regression model is expressed as formula (10):

$$y = k + k_1 \cdot x_1 + k_2 \cdot x_2 + \dots + k_n \cdot x_n, \quad (10)$$

where: y is dependent variable is soil infiltration rate, $\text{mm} \cdot \text{min}^{-1}$; $x_1, x_2, \dots, x_n$ are independent variables are bulk density ($\text{g} \cdot \text{cm}^{-3}$), soil porosity (%), soil moisture

(%), organic matter (%), clay (%), silt (%), and sand (%); $k, k_1, k_2, \dots, k_n$ are regression coefficients.

Using all these parameters basic infiltration rate prediction model was developed using package Bayesian Model Averaging (BMA) in R (programming language).

Bayesian model averaging

Bayesian model averaging (BMA) is a statistical scheme to infer a probabilistic prediction that possesses more skill and reliability than the original ensemble members produced by several competing models (Duan et al. 2007). BMA has been used primarily in generalized linear regression applications. Recently, Bayesian model averaging has gained popularity in diverse fields such as statistics, management science, medicine and meteorology (Fernandez et al. 2001, Raftery et al. 2005).

The key idea behind BMA is to consider a set of models, each with its own set of parameters, and to assign a prior probability to each model. Given the observed data, the posterior probability of each model can then be computed using Bayes' theorem, which takes into account both the likelihood of the data given the model and the prior probability of the model.

Once the posterior probabilities of each model have been computed, they can be used to compute the weighted average of the predictions from each model. This produces a single prediction that takes into account the uncertainty in model selection. The weights used in the averaging process are proportional to the posterior probabilities of each model, so that models with higher posterior probabilities contribute more to the final prediction.

Bayesian information criterion

In inferential statistics, we compare model selections using p -values or adjusted R^2 . Besides, in this study, we will take the Bayesian predictive model. Analysis of Bayesian model selections using the Bayesian information criterion (BIC). BIC is defined to be as in formula (11):

$$BIC = n \cdot \ln(1 - R^2) + p \cdot \ln(n), \quad (11)$$

where: n is the number of observations in the model, and p is the number of predictors (not including the intercept) in the model.

When the smaller BIC value is (more negative), the better the fit of models selected (Schwarz 1978).

Standard deviation (SD) and coefficient of variation (CV)

SD and CV are types of measures of dispersion. SD is an absolute measure and CV is a relative measure. SD and CV are calculated by formulas (12) and (13):

$$SD = \frac{1}{n} \sqrt{\sum_{i=1}^n (x_i - \bar{x}')^2}, \quad (12)$$

$$CV = \frac{SD}{\bar{x}'} \cdot 100, \quad (13)$$

where: x_i is measured value; $\bar{x}'$ is mean of measured value; n is number of the measured value.

Results and Discussions

Soil infiltration rate

In the sloping land from medium to high rainfall, water infiltration is important for soiling protection and watering retention (Morbideilli et al. 2018). In this study, it was found that the infiltration rate on vegetation types after shifting cultivation (grassland, shrubland and small regenerating trees) varies from 2.41 to 3.23 $\text{mm} \cdot \text{min}^{-1}$ with a measured average infiltration rate $2.87 \pm 0.22 \text{ mm} \cdot \text{min}^{-1}$ (Table 1). Variations in soil infiltration can be induced by vegetation growth and the intrinsic spatial variability of soils. In this study, all vegetation types were restored from shifting cultivation. These shifting cultivation lands were abandoned gradually due to policy-driven factors. The vegetation restoration process improved soil infiltration capacity (Li and Shao 2006, Wang et al. 2012). The improvement in soil infiltration capacity was mainly caused by the growth of vegetation and the resulting changes in soil structure (Pan et al. 2017, Tian et al. 2017).

Soil properties

The soil properties were determined for vegetation recovered after shifting cultivation in Table 2. These were considered

Table 1. Soil infiltration rate (mean $\pm$ SD) after shifting cultivation.

Parameter	Min	Max	Mean	Standard deviation	Coefficient of variation
Infiltration rate, $\text{mm} \cdot \text{min}^{-1}$	2.41	3.23	2.87	0.22	0.05

Table 2. Descriptive statistics of measured soil properties.

Parameters	Min	Max	Mean	Standard deviation	Coefficient of variation
Bulk density, g·cm ⁻³	1.28	1.48	1.38	0.06	0.00
Soil porosity, %	39.67	47.20	43.58	2.00	4.01
Organic matter, %	1.45	4.65	3.31	0.84	0.70
Soil moisture, %	14.90	25.50	20.08	3.21	10.29
Clay, %	14.43	39.19	24.55	5.54	30.67
Silt, %	16.87	34.06	25.81	5.47	29.90
Sand, %	27.54	68.70	49.64	8.60	74.04

as the independent variables, which were used to establish the correlations between infiltration rate and soil properties and development of the prediction model.

The correlation between infiltration rate and each soil properties

The results in Table 3 showed that *SP*, *OM*, sand have a positive correlation with infiltration rate, which means increase *SP*, *OM* and sand content in the soil will increase the infiltration rate. Whereas *BD*, *SM*, clay and silt have a negative correlation with infiltration rate, which means increasing *BD*, *SM*, clay and silt content in the soil will decrease the infiltration rate. The infiltration rate was significantly affected by *BD*, *SP*, *OM* and *SM* as *R* has varied from 0.77 to 0.86. Whereas clay, silt and sand have a lesser significant

effect on the infiltration rate as *R* is only 0.13–0.22.

Different soil properties are influencing infiltration processes. Several studies have been conducted to assess the impact of shifting cultivation on soil properties and its correlation with infiltration rate. Andriesse and Schelhaas (1987) investigated the changes in soil fertility associated with burning in shifting cultivation. They found that burning can lead to a decrease in organic matter content and nutrient availability in the soil, which can ultimately affect the infiltration rate. Ishizuka et al. (2000) found that abandoned land had lower infiltration rates compared to land that was still under shifting cultivation. In addition to organic matter content and nutrient availability, other soil properties can also influence infiltration rate in shifting cultivation. Nye and Greenland

Table 3. Correlation and regression analysis of infiltration rate with soil properties.

Dependent variable	Independent variables	<i>R</i>	<i>F</i>	<i>p</i>	Coefficients	
					Variable	Constant
<i>IR</i>	<i>BD</i>	0.80	60.99	< 0.001	-2.969	6.972
	<i>SP</i>	0.77	50.61	< 0.001	0.086	-0.876
	<i>OM</i>	0.86	93.41	< 0.001	0.228	2.121
	<i>SM</i>	0.81	63.44	< 0.001	-0.056	3.998
	Clay	0.21	1.62	0.21	-0.009	3.083
	Silt	0.13	0.60	0.44	-0.005	3.012
	Sand	0.22	1.75	0.19	0.006	2.589

Note: *IR* is infiltration rate, *BD* is bulk density, *SP* is soil porosity, *OM* is organic matter, *SM* is soil moisture.

(1960) reviewed studies on the impacts of shifting cultivation on soil properties and found that cultivation can deteriorate physical soil properties, such as soil structure and compaction, which in turn affect the infiltration rate. Osuji et al. (2010) reported that soil bulk density, soil porosity, organic matters, soil moisture, soil particle size distribution influence the infiltration. An increase in soil bulk density decreases soil porosity resulting in a decrease in soil infiltration characteristics. Results from previous studies also have demonstrated the inverse correlation (Rashidi et al. 2014, Patle et al. 2019). The porosity is one of the aspects that best explains soil infiltration. Ren et al. (2016) found that an increase in porosity could significantly increase soil infiltration. The increase in soil infiltration value is due to porosity, which is related to taproots and the activity of soil organisms (Fischer et al. 2014, Huang et al. 2017). Organic matter is also important for infiltration because it also provides an environment for mesofauna and macrofauna to grow. The stability of organic matter represents an important contribution to the maintenance of the soil porosity. The soil moisture was negatively correlated with *IR* in our study. Water infiltration into the soil diminishes when the soil moisture increases. This result was consistent with the results of previous studies (Assouline 2013, Fouli et al. 2013, Liu et al. 2019), which have proposed that higher soil moisture may lead to a reduction of *IR*. The increase in the soil particle dimension and porosity enhanced soil infiltration capacity directly. Our study showed that a higher soil particle size directly and clay content indirectly enhanced soil infiltration capacity. This result is consistent with those of several studies that have shown that finer-textured soil has a higher hydraulic conductivity than coarse-textured

soil due to its well-developed soil structure and a high degree of macropores (Fischer et al. 2014).

Prediction model using multiple linear regression

The effect of soil properties on soil infiltration rate was mentioned not only in a separate factor but also in overall factors (Table 4 and Fig. 2). For prediction of basic infiltration rate, the analysis was categorized into the 5 best models. In the first model, four independent variables were considered: soil porosity, organic matter, soil moisture and sand. The second model included soil porosity, organic matter and soil moisture as independent variables. The third model incorporated soil porosity, organic matter, soil moisture and silt as independent variables. The fourth model featured bulk density, organic matter, soil moisture and sand as independent variables. Lastly, the fifth model encompassed soil porosity, organic matter, soil moisture and clay as independent variables.

Each row corresponds to a variable and each column corresponds to a model; the corresponding rectangle is red if the variable is in the model and yellow otherwise; blue if the variable is a negative correlation with the dependent variable. The width of the column is proportional to the model's posterior probability.

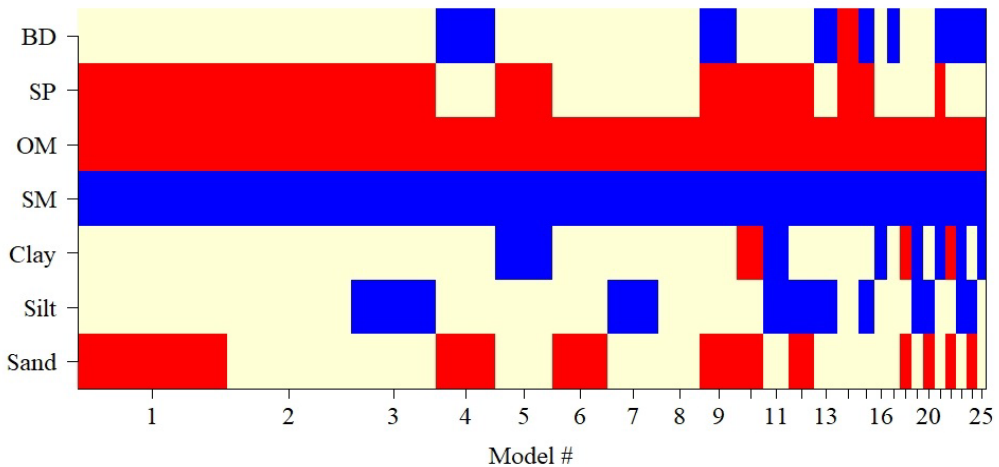
Development of first model

The infiltration rate was estimated using soil porosity, organic matter, soil moisture and sand. The developed prediction equation for the *IR* is given below: $IR = 1.745 + 0.026 (SP) + 0.016 (OM) - 0.026 (SM) + 0.003 (Sand)$ with the coefficient of determination $R^2 = 0.856$,

Table 4. Models selected by BMA for regression analysis of infiltration rate with soil properties.

Factor	Post. prob.	Mean	SD	Model 1	Model 2	Model 3	Model 4	Model 5
Intercept	100.0	2.477	1.037	1.745**	1.807**	2.098***	4.099***	1.875**
<i>BD</i>	24.3	-0.155	0.415	-	-	-	-0.950*	-
<i>SP</i>	63.5	0.017	0.016	0.026*	0.028*	0.024*	-	0.029*
<i>OM</i>	100.0	0.115	0.037	0.016**	0.108**	0.112**	0.010*	0.103**
<i>SM</i>	100.0	-0.026	0.007	-0.026***	-0.026***	-0.027***	-0.024**	-0.025***
Clay	20.5	-0.0005	0.002	-	-	-	-	-0.004
Silt	29.8	-0.0013	0.003	-	-	-0.005	-	-
Sand	43.8	0.0017	0.002	0.003*	-	-	0.005*	-
<i>n</i> variable				4	3	4	4	4
<i>R</i> ²				0.857	0.841	0.853	0.850	0.849
<i>BIC</i>				-55.77	-55.38	-54.63	-53.93	-53.83
Post. Prob.				0.165	0.136	0.093	0.066	0.063

Note: Best 5 models of 25 models were selected (cumulative posterior probability = 0.523); Mean $\pm$ Standard Deviation (SD) of independent variable; *BIC* is Bayesian Information Criterion; *BD* is bulk density; *SP* is soil porosity; *OM* is organic matter; *SM* is soil moisture; Post. prob. is Posterior probability. Significance codes: (***) < 0.001, (**) < 0.01, (*) < 0.05, (') < 0.1, () < 1.

**Fig. 2. Models selected by BMA.**

BIC = - 55.77 and posterior probability = 16.5 %. The *SM* has the lowest *p*-value = 0.0005 (< 0.001), followed by *OM*, *SP* with 0.0018 (< 0.01), 0.0297 (< 0.05), respectively. However, the sand has a *p*-value of 0.0668 (< 0.1). The results showed that *SM*, *OM* and *SP* are statistically signifi-

cant predictors, while Sand is not an important predictor (*p* < 0.05).

Development of second model

The infiltration rate was estimated using soil porosity, organic matter and

soil moisture. The developed prediction equation for the *IR* is given below: $IR = 1.807 + 0.028 (SP) + 0.108 (OM) - 0.026 (SM)$ with the coefficient of determination $R^2 = 0.841$, $BIC = -55.38$ and posterior probability = 13.6 %. The *SM* has the lowest p -value = 0.0009 (< 0.001), followed by *OM*, *SP* with 0.002 (< 0.01), 0.0244 (< 0.05), respectively. The results showed that *SM*, *OM* and *SP* are statistically significant predictors ($p < 0.05$).

Development of third model

The infiltration rate was estimated using soil porosity, organic matter, soil moisture and silt. The developed prediction equation for the *IR* is given below: $IR = 2.098 + 0.024 (SP) + 0.112 (OM) - 0.027 (SM) - 0.005 (Silt)$ with the coefficient of determination $R^2 = 0.853$, $BIC = -54.63$ and posterior probability = 9.3 %. The *SM* has the lowest p -value = 0.0005 (< 0.001), followed by *OM*, *SP* with 0.0013 (< 0.01), 0.0483 (< 0.05), respectively. However, Silt has a p -value of 0.1216 (< 1). The results showed that *SM*, *OM* and *SP* are statistically significant predictors, while silt is not an important predictor ($p < 0.05$).

Development of fourth model

The infiltration rate was estimated using bulk density, organic matter, soil moisture and sand. The developed prediction equation for the *IR* is given below: $IR = 4.099 - 0.950 (BD) + 0.010 (OM) - 0.024 (SM) + 0.005 (Sand)$ with coefficient of determination $R^2 = 0.85$, $BIC = -53.93$ and posterior probability = 6.6 %. The *SM* has the lowest p -value = 0.0022 (< 0.01), followed by *OM*, sand with 0.010 (< 0.05), 0.0164 (< 0.05), respectively. However, the *BD* has a p -value of 0.0749 (< 0.1). The results showed that *SM*, *OM* and sand are

statistically significant predictors, while *BD* is not an important predictor ($p < 0.05$).

Development of fifth model

The infiltration rate was estimated using soil porosity, organic matter, soil moisture and clay. The developed prediction equation for the *IR* is given below: $IR = 1.875 + 0.029 (SP) + 0.103 (OM) - 0.025 (SM) - 0.004 (Clay)$ with coefficient of determination $R^2 = 0.849$, $BIC = -53.83$ and posterior probability = 6.3 %. The *SM* has the lowest p -value = 0.0009 (< 0.001), followed by *OM*, *SP* with 0.0031 (< 0.01), 0.0193 (< 0.05), respectively. However, clay has a p -value of 0.1894 (< 1). The results showed that *SM*, *OM* and *SP* are statistically significant predictors, while clay is not an important predictor ($p < 0.05$).

For the development of predictive models, from all the analysis, it was observed that the increase in the number of the independent variables increases the reliability of the prediction of R^2 . The findings of the present investigation correlate with previous studies. Harisuseno and Cahya (2020) estimated the soil infiltration rate based on soil properties using multiple linear regression. They developed a correlation between soil infiltration rate and soil properties (soil porosity, silt, clay, sand content) with R^2 (0.87). Rashidi et al. (2014) carried out field experiments at the agricultural fields of Karaj (Iran) and developed a correlation between soil infiltration rate and physical properties of soil. They predicted the infiltration rate using silt content and clay content, bulk density, organic matter and moisture content of soil with R^2 (0.9). Pandey and Pandey (2018) conducted a study near the NERIST campus, India, estimating the infiltration rate based on readily available

soil properties (RASPs) in fallow cultivated land. It was found that to predict the soil infiltration rate based on RASPs with seven independent variables (sand, silt, clay, bulk density, particle density, moisture content and organic carbon content) with coefficient of determination R^2 (0.92). Patle et al. (2018) estimated the infiltration rate from soil properties using regression model for cultivated land in India. They predicted the infiltration rate using sand, silt, clay, bulk density, particle density, moisture content and organic carbon content with R^2 (0.80).

The prediction first model had the highest value of posterior probability and lowest value of BIC . This implies that the first model is the best amongst all of the models. The use of infiltration models as an alternative to field-based infiltration measurement (Mirzaee et al. 2014, Parhi 2014, Tuffour and Bonsu 2015). Infiltration rate can successfully be measured using a double-ring infiltrometer. However, field-measured infiltration is difficult, especially in mountainous sites. As an alternative, estimating the infiltration rate from soil properties using the regression model. The previous studies reported that easily measurable soil characteristics could successfully predict the measurement of infiltration in the field (Dabral and Pandey 2016, Rahmati 2017).

Conclusion

In this study, the soil porosity, organic matter content and sand have a positive correlation with infiltration rate, whereas bulk density, soil moisture, clay and silt have a negative correlation with infiltration rate. Soil porosity, organic matter and soil moisture were the main factors influencing soil water infiltration capacity. The

predicted model with four soil properties (soil porosity, organic matter, soil moisture and sand) was the best-fitted model with the highest value of R^2 and posterior probability and the lowest value of Bayesian information criterion and recommended for the research area. The predictive infiltration model from readily observed soil properties, save the resources in the measurement of time-consuming infiltration characteristics and could be applied under limited data conditions.

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***Paulownia tomentosa* (Thunb.) Steud. seed quality from different geographical locations in Ukraine**

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Abstract

Biometric parameters of fruits and seeds of *Paulownia tomentosa* collected from trees growing in soil and climatic conditions of different geographical locations of Odesa, Zakarpattia (Mukachevo) and Lviv regions of Ukraine, as well as technical and absolute germination, germination energy, mean germination time and weight of 1000 seeds, were studied. The effect of different temperatures on seed germination in soil was evaluated under two temperature regimes. The influence of the duration of pre-soaking on seed germination was also determined. Pre-soaking of seeds in water and solutions of five different stimulants on germination in soil was also investigated. It has been found that in the conditions of Odesa region, the species formed larger fruits and the seeds were characterized by significant rate and uniformity of germination. Lowering of germination temperature caused a decrease in germination energy, laboratory and absolute seed germination, and increased the mean germination time of seeds. Pre-soaking of seeds increased significantly germination rate and its duration was associated with the parameters: germination energy, technical and absolute germination. Among the three seed collections, the highest technical germination was recorded for seeds from Lviv region. The seeds from Odesa region had the highest germination energy. The seeds were characterized by high germination rate in soil regardless of the geographical location of seed collection under the conditions of Ukraine. The highest germination in soil was found for seeds, collected in Lviv. Temperature during germination significantly affected the germination of seeds in soil. Under the temperature regime of 21 to 25 °C, soil fertility parameters were significantly higher. Pre-soaking of seeds had the highest stimulating effect on further germination of seeds in soil among the studied treatments. Pre-treatment of seeds with germination stimulants had generally a positive effect, increasing germination in soil.

Key words: biometric parameters, germination, pre-soaking, stimulators, temperature regimes, weight of 1000 seeds.

Introduction

Paulownia (*Paulownia tomentosa* (Thunb.) Steud.) is a fast-growing tree species na-

tive to China and East Asia (Bojnansky and Fargasova 2007, Bonner 2008, Icka et al. 2016). In Ukraine, the species is found in botanical gardens, rarely occurs

in green areas of cities and in landscaping of private estates. Due to its unique characteristics, namely rapid growth, unassumingness to soil fertility and moisture, assimilation of significant amounts of carbon dioxide from the atmosphere, relative frost resistance and, most importantly, the ability to regenerate many times after cutting, the tree has been used in plantations for more than 40 years in different regions of America, Europe, Asia and Australia (Woods 2008, Akyildiz and Kol 2010, Hugo et al. 2013, Yadav et al. 2013, Icka et al. 2016). *Paulownia* is a promising source of plant material for possible development and further production of anti-inflammatory and antibacterial phytopharmaceuticals (Ivaniuk et al. 2023).

In recent years paulownia is under investigation also in Ukraine (Ivaniuk et al. 2023), being the promising tree for plantation cultivation with several short cutting rotation periods, as it is known that the speed of its growth and accumulation of biomass of the second and subsequent rotations of sapling origin is much higher than the first rotation. It can be explained by the ability of plants (of sapling origin) to feed and grow due to the well-developed root system of a felled tree (Zhu et al. 1986, Woods 2008, Akyildiz and Kol 2010, Yadav et al. 2013, Icka et al. 2016).

On the territory of modern Ukraine, *Paulownia tomentosa* appeared for the first time in the Nikitsky Botanical Garden in 1846. Later, the introduced tree has been successfully cultivated and acclimatized in the southern regions of Ukraine. *Paulownia* is currently widespread in various regions of Ukraine. The introduced tree grows successfully in Zakarpattia and Lviv regions (Kolesnikov 1974).

Many researchers have determined the sowing qualities of paulownia seeds or their explants (Kokhno et al. 1991,

Jovanović et al. 2005, Bojnansky and Fargasova 2007, Bonner 2008, Mohamad et al. 2022, Pošta et al. 2022). Most of them note the high value of seed germination of the crop.

The influence of growth regulators on germination of seeds of different woody plant species has been described in several studies. According to Beleya (2014), pre-sowing seed treatment with a number of growth stimulants of various concentrations and for different time duration on European larch seeds can both increase germination energy and capacity and have a negative effect. Serediuk (2011) and Matsiakh et al. (2012) indicated the acceleration of the germination of spruce seeds under the action of growth stimulants. Taranenko (2011) and Hrechanyk et al. (2014) reported an increase in germination of Scots pine seeds under the influence of growth stimulants.

Todorović et al. (2005) revealed that light irradiation of paulownia seeds, which absorbed liquid smoke, cause the highest germination rate. Lazović et al. (2012) demonstrated the significant improvement of germination due to air plasma exposure of *P. tomentosa* seeds in the low pressure CCP reactor. Radu et al. (2015) reported that exposure for 20 min to homogeneous electric field accelerated the germination of paulownia seeds; the germination also depended on humidity and solar radiation intensity. Pošta et al. (2022) recently demonstrated that Nitrozyme, containing extract of sea kelp, had a slight effect on the germination rate of paulownia seeds. During the recent study of Prisa and Guerini (2023), the positive effect of hydrogels on seed germination and seedling growth was shown. Turner et al. (1988) found that the germination of *P. tomentosa* seeds and the growth of its seedlings was affected by soil acidity. At pH 4.0, the seeds

did not germinate. At pH 4.5, germination was very low and seedling growth was inhibited compared to seedlings, growing in soil at pH 5.5 and 6.5. Sabir and Hamad (2022) determined the optimal concentrations of NPK fertilizer and humic acid for paulownia seedling growth.

The purpose of the work was to investigate the sowing qualities of *P. tomentosa* seeds from different geographical locations of Ukraine and the influence of plant growth regulators and pre-soaking (in water) on seed germination. The results of this research could indicate the possibility of using seed zones for growing planting material and establishing plantations with biological resistance inherent in parent plants, in particular to the influence of low temperatures, soil and climatic conditions.

Materials and Methods

Determination of biometric parameters was carried out for paulownia fruits obtained from different geographical regions of Ukraine (Lviv 49.824227° N, 24.002693° E, Zakarpattia 48.620366° N, 22.292871° E and Odesa 46.485039° N, 30.742079° E). Harvesting of capsules was carried out in November 2022 by picking them from growing trees aged 26–35 years. During the measurement of biometric parameters, the research sample comprised the well-developed 200 boxes for each of three homogeneous batches of seeds. The length, diameter and weight of the generative organs (fruits) in the freshly harvested state were measured. Fruits' length and diameter were determined using an electronic callipers (accuracy up to 0.01 mm), and their weight – by electronic scale Axxis with a weighing accuracy of 0.001 g and a weight limit of 50 g. The diameter was determined at the maximum

of the fruit width.

To determine the weight of 1000 seeds, technical and absolute germination, germination energy, mean germination time of *P. tomentosa* from harvested fruits, seeds have been obtained with further formation of three separate samples from the trees, grown in different locations of Ukraine. The seeds were obtained by processing the fruits in December 2022 and were stored in a dry, cool place (3 to 5 °C). All laboratory studies were carried out in January 2023 in the Laboratory of forest seeds at the Department of Forest Planting and Breeding of the Ukrainian National Forestry University.

The experimental part was conducted separately for samples from different geographical locations, in accordance with the current standards: determination of thousand-seed weight (DSTU 5036:2008 2009, ISTA 2011); germination capacity, germination energy, mean germination time (ISTA 2011, DSTU 8558:2015 2017).

To determine the effect of temperature on germination, seed germination was carried out under two temperature regimes: +15...20 °C and +21...25 °C (the minimum temperature at night, maximum – at daytime). Light intensity of 800 lux was applied at maximum temperatures (+20 °C and +25 °C) for 8 h.

Seed germination in soil was determined under indoor conditions (peat moss substrate, pH=6.9), in two temperature regimes: +15 °C at night and +20 °C during the day and +21 °C at night and +25 °C during the day; light intensity – 800 lux for 8 h. The seeds were laid out on the surface of the soil, and to avoid drying out, they were covered by a transparent polyethylene film. The experiment was performed four times for samples of different geographical regions.

In order to determine the influence of

stimulants on germination of seeds in soil, pre-sowing treatments of seeds with the following preparations were carried out:

- Stimovit (soaking in a 10% solution for 24 h);
- Kornevin (soaking in a 0.1% solution for 5 h);
- Succinic acid (soaking in a 0.1%

solution for 24 h);

- Epin (2–3 drops per 100 ml of water and soaking for 4 h);
- Radifarm (soaking in a 0.25% solution for 24 h).

Data concerning the used pre-treatment regimes and the composition of preparations are presented in Table 1.

Table 1. Pre-treatment regimes and the composition of preparations.

Variant number	Commercial product or substance for seeds treatment	Active substance
1	Stimovit	Humic substances (HS) – up to 1.5 %, N – 1.4 %, P – 2 %, K – 1.5 %, Mg – 0.5 %, Mn – 50 mg·L ⁻¹ , Zn – 25 mg·L ⁻¹ , Cu – 50 mg·L ⁻¹ , Co – 5 mg·L ⁻¹
2	Kornevin	4-(indol-3-yl)-butyric acid, 5 g·kg ⁻¹
3	Succinic acid	Succinic acid
4	Epin	Epibrassinolide, 0.025 g·L ⁻¹
5	Radifarm	Polysaccharides – 7 %; organic elements – 14 %; polypeptides – 11 %; steroidal glycosides – 0.2 %; amino acids (arginine, asparagine, betaine, tryptophan) – 1 %; complex of vitamins B1, B2, D, H, PP – 0.04 %; zinc (Zn) – 0.2 %; iron chelate (Fe) – 0.2 %
6 (control)	Without pre-soaking in water	-
7	Soaking in water for 24 h	Water
8	Soaking in water for 48 h	Water

Additionally, to determine the influence of the duration of seed soaking (in water) on germination parameters, the following treatments were tested:

- soaking the seeds with water (+20 °C) for 48 h;
- soaking the seeds with water (+20 °C) for 24 h;
- without pre-soaking (control).

Germination of seeds was recorded on the 3rd, 5th, 7th, 10th, and 14th days of observation. Germination energy was determined on the 7th day, and germination capacity – on the 14th day of the study (DSTU 8558:2015 2017).

Results and Discussion

The study of biometric parameters of fruits and seeds, collected from plants in different geographical regions, helped to reveal variability and to determine the dependence between the sizes of fruits, formed in regions with different soil and climatic conditions, and duration of the vegetative period. After the formation of seed samples, obtained from the harvested fruits of paulownia, the weight of 1000 seeds of different geographical locations was determined. Since the weight of 1000 paulownia seeds is up to 1 g, in order to de-

termine this measure, according to DSTU 5036:2008 (2009), one sample of 500 seeds was counted and weighted with

subsequent multiplication of their weight by 2. The measurements were carried out in quadruplicate (Table 2).

Table 2. Biometric parameters of fruits and seeds from three geographical locations in Ukraine.

Fruit diameter (width)			Fruit length			Weight of freshly harvested fruits			Weight of 1000 seeds		
$X_m \pm m_x$ (Limit), mm	V, %	P, %	$X_m \pm m_x$ (Limit), mm	V, %	P, %	$X_m \pm m_x$ (Limit), g	V, %	P, %	$X_m \pm m_x$ (Limit), g	V, %	P, %
Odesa city											
28.71 ± 0.13 (24–32)	6.31	0.5	38.51 ± 0.13 (34–41)	4.60	0.3	2.33 ± 0.01 (2.1–2.5)	4.53	0.4	0.134 ± 0.001 (0.132–0.138)	2.14	0.7
Mukachevo town											
27.75 ± 0.15 (22–31)	7.76	0.5	37.6 ± 0.11 (33–40)	4.19	0.3	1.76 ± 0.01 (1.5–2.1)	8.22	0.6	0.123 ± 0.001 (0.120–0.125)	1.69	0.8
Lviv city											
23.44 ± 0.3 (15–27)	18.34	1.3	34.15 ± 0.34 (21–38)	14.11	1.0	1.44 ± 0.02 (0.8–1.7)	22.54	1.4	0.107 ± 0.002 (0.110–0.107)	4.21	1.9

Note: X_m – average arithmetic value; m_x – error of the average value; V – coefficient of variation, %; Limit – minimum and maximum values; P – accuracy of the experiment, %.

Analysis of data, presented in Table 2, shows the homogeneity of the samples of the investigated characteristics. It is worth mentioning that the fruits, collected in Odesa and Mukachevo, have a slight variation in all studied parameters. In fruits, harvested in Lviv, we observed an average variation in their size and a significant variation in weight. In our opinion, this is due to the less favourable climatic conditions for the formation and growth of fruits of paulownia, growing in Lviv. It is worth noting that, according to all average indicators, one can observe the increase of the determined values of the fruit samples, obtained from Odesa, compared to the samples, collected in Lviv. Among the three studied locations, the length of the fruits changes the least, and their weight varied the most. The analysis of data on the weight of 1000 seeds indicated a decrease in the weight of seeds in plants, growing in a region with a shorter vegetation period (Lviv). It is advisable to take into account the seed weight parameters, determined by us, when specifying in nurseries the norms for sowing seeds, collected in different geographical locations. There is information in the literature that the weight of 1000 seeds varies from 0.14 to 0.25 g (Milev et al. 2004), on average – 0.17 g (Bonner 1990, Pasiecznik 2008). Our results for three samples are slightly below the lower limit, therefore, the analysed seeds are relatively small.

Under the temperature regime of +20...25 °C, the technical germination of paulownia seeds was determined, which varies from 88 to 99 % and was slightly higher than the value given in literature (Kokhno et al. 1991), regardless of their

geographical locations (Table 3). Moreover, the highest value of the germination index in all variants of the study was found for seeds from Lviv region, which exceeded by 6–7 % appropriate indicators of seeds from Odesa and Mukachevo.

Table 3. Indicators of seed germination under the temperature regime of +21...25 °C.

Germination indicators	Locations where seeds were collected									
	Odesa city			Mukachevo town			Lviv city			
	Duration of soaking in water before sowing seeds for germination, h									
	48	24	0	48	24	0	48	24	0	
Germination energy, %	X_m	85.0	82.8	75.3	34.0	16.0	7.8	50.8	37.8	11.0
	m_x	1.4	0.9	0.9	0.4	0.7	0.3	1.3	0.9	0.4
	V	3.33	2.06	2.27	2.40	8.84	6.45	4.93	4.52	7.42
	P	1.66	1.03	1.13	1.20	4.42	3.23	2.46	2.26	3.71
Technical germination, %	X_m	93.0	90.0	89.0	93.0	90.8	87.8	98.8	96.8	94.8
	m_x	1.5	1.9	0.8	1.5	1.3	1.5	0.6	1.0	0.9
	V	3.17	4.16	1.83	3.17	2.75	3.53	1.27	2.13	1.80
	P	1.58	2.08	0.92	1.58	1.38	1.76	0.64	1.07	0.90
Absolute germination, %	X_m	94.5	90.0	89.8	93.0	91.8	89.3	99.3	97.0	96.0
	m_x	0.9	1.2	1.2	0.4	0.9	1.2	0.3	0.7	0.4
	V	1.83	2.72	2.63	0.88	2.06	2.65	0.50	1.46	0.85
	P	0.92	1.36	1.32	0.44	1.03	1.32	0.25	0.73	0.43
Mean germination time, days		6.4	6.4	7.3	9.1	10.4	10.7	8.3	8.9	10.1

Note: X_m – average arithmetic value; m_x – error of the average value; V – coefficient of variation, %; P – accuracy of the experiment, %.

Pre-soaking, the duration of which correlates with indicators of technical germination, had a significant effect on seed germination. Other authors also indicated in their studies the positive effect of seed soaking on the acceleration of germination. Houšková et al. (2021) investigated the effect of pre-soaking in water on germination energy, mean germination time and germination capacity of Scots pine and Norway spruce seeds and recommended the method of pre-treatment of seeds to increase germination energy. Germination of paulownia seed can reach 75–90 % even after one year of storage;

the germination process can be accelerated by soaking the seeds in warm water for 10 min and then sowing under conditions of intense light and high temperature (Zhu et al. 1986).

During soaking of seeds in water for 48 h, an increase in germination by 4–5 % was observed, in the case of soaking for 24 h – by 1–3 %, compared to the control (without soaking). Pre-soaking had even greater effect on the rate of seed germination. Thus, the energy of seed germination increased by 10–40 % and by 8–27 % (depending on the geographic location) after pre-soaking for 48 h and 24 h, re-

spectively. In general, paulownia seeds, collected in southern region of Ukraine (Odesa), were characterized by the highest germination speed; 84.3–92.3 % of all germinated seeds germinated during seven days of observation. Only the seeds from Odesa developed healthy, normally developed roots already on the third day of observation. To our opinion, there is a correlation between the speed of germination and the weight of the seed, because heavier seeds (in particular, collected in the city of Odesa) have a greater supply of nutrients and are capable for faster growth and development of the embryo.

The mean germination time also characterizes the rate of seed germination. For seeds collected in Odesa, the mean germination time was the lowest, ranging from 6.4 to 7.3 days, which indicated a very high rate of seed germination. Seeds from Mukachevo were characterized by the lowest germination rate (from 9.1 to 10.7 days), which is 1.4 times longer than for those from Odesa. The germination rate of the seeds, collected in Lviv, occupied an intermediate position among the three investigated locations of their harvesting.

Examining ungerminated seeds on the 14th day of observation revealed empty (8.3–20.0 % of the total number of ungerminated seeds), rotten (20.0–36.4 %) and healthy seeds (54.5–100 %), which made possible to determine the absolute germination. Insignificant amount of empty seeds does not have a significant effect on the parameter of absolute germination. In four out of nine variants of the study, the absolute germination did not differ from the technical germination, in the remaining variants it exceeded the technical germination by only 1 %.

Our results of investigation, concerning the effect of temperature on seed germination, confirm the research outcomes

of other scientists. Grubišić and Konjević (1992) pointed out the positive effect of changing the temperature regime and the impact of light on the germination of paulownia seeds. Barton et al. (2007) claimed that storing of paulownia seeds for 4–6 weeks in moist peat or sand at a temperature of about 5 °C had an effective impact on its germination.

In production conditions, it is quite difficult to maintain a temperature regime above +20 °C in the cold season. The study on the influence of temperature reduction on seed germination was carried out at a temperature regime of +15...20 °C, which corresponds to the temperature regime of greenhouses (at the beginning of spring) and production premises, in which preliminary testing of sowing qualities of the seeds is carried out (Table 4).

In general, a decrease in the germination temperature of the seeds of paulownia lead to a reduction in all indicators of germination. Thus, the technical germination of the seeds varies in the range 66–79 %, which was lower than the indicators described in the literature (Kokhno et al. 1991). Compared to germination at a temperature of +20...25 °C, the decrease of the studied indicator is 20–23 %, depending on the variants of the experiment. The highest value of technical germination was found for seeds from Lviv (73–79 %), the lowest one – in seeds from Mukachevo (66–70 %), which corresponds to the results of previous studies.

Pre-soaking of the seeds at lower temperatures also had a positive effect on seed germination. The increase in the technical germination index, depending on the location of collection, was 4–7 % (48 h of soaking) and 2–3 % (24 h), compared to the control.

It has been found that the temperature regime of +15...20 °C significantly

Table 4. Indicators of seed germination under the temperature regime of +15...20 °C.

Germination indicators	Locations where seeds were collected									
	Odesa city			Mukachevo town			Lviv city			
	Duration of soaking in water before planting seeds for germination, h									
	48	24	0	48	24	0	48	24	0	
Germination energy, %	X_m	7.3	5.0	0	0	0	0	0	0	0
	m_x	0.3	0.4	-	-	-	-	-	-	-
	V	6.90	16.33	-	-	-	-	-	-	-
	P	3.45	8.16	-	-	-	-	-	-	-
Technical germination, %	X_m	73.3	69.3	65.8	69.8	67.8	66.0	78.8	74.8	73.0
	m_x	0.9	0.9	0.9	0.9	1.0	0.8	0.9	0.9	0.4
	V	2.33	2.47	2.60	2.45	3.04	2.47	2.17	2.28	1.12
	P	1.17	1.23	1.30	1.22	1.52	1.24	1.08	1.14	0.56
Absolute germination, %	X_m	74.0	70.0	66.3	70.8	68.5	67.5	80.3	76.0	74.3
	m_x	0.7	0.8	0.9	0.9	1.3	1.0	0.9	0.8	0.6
	V	1.91	2.33	2.58	2.68	3.86	3.08	2.13	2.15	1.69
	P	0.96	1.17	1.29	1.34	1.93	1.54	1.06	1.07	0.85
Mean germination time, days		12.6	12.6	13.9	13.9	14.0	14.2	14.3	14.4	14.5

Note: X_m – average arithmetic value; m_x – error of the average value; V – coefficient of variation, %; P – accuracy of the experiment, %.

slows down the process of seed germination. Germination energy was equal to 0 % in seven out of nine variants of the experiment. Only seeds from southern location (Odesa) were characterized by germination energy of 5 % and 7 % after pre-soaking for 24 and 48 h, respectively. The duration of the mean germination time increased significantly (12.6–14.5 days), which is 1.3–2.0 times more than the same variants of the experiment at a temperature of +20...25 °C.

When determining seed germination in soil, the count of germinated seeds was performed on the 14th day of observation. Under the temperature regime of +21...25 °C, the value of the seed germination in soil varied from 83.8 ±1.31 % to 99.8 ±0.25 % (Table 5). Moreover, in the control (seeds without treatment with a stimulator of germination), the lowest germination in soil was characteristic for

seeds, collected in Odesa (83.8 ±1.31 %), the highest one – for seeds from Lviv (92.0 ±0.82 %).

Pre-soaking of seeds resulted in an increase of seed germination in soil compared to the control by 0.6–13.1 %. Moreover, pre-soaking for 24 h was more effective, which led to an increase in germination by 6.0–13.1 %. With pre-soaking for 48 h, the indicators of seed germination in soil were slightly lower and exceed those of the control by 0.6–4.7 %.

The use of the stimulators of seed germination under the temperature regime of +21...25 °C confirms their effectiveness. In general, with their application, an increase of indicators of seed germination in soil was recorded at the level of 3.2–10.1 % compared to the control for seeds from all studied locations. The highest result was found for Stimovit (exceeding by

Table 5. Indicators of seed germination in soil under the temperature regime of +21...25 °C.

Regulators of seed germination	Germination in soil of the seeds, collected from different locations								
	Odesa city			Mukachevo town			Lviv city		
	$X_m \pm m_x, \%$	$V, \%$	$P, \%$	$X_m \pm m_x, \%$	$V, \%$	$P, \%$	$X_m \pm m_x, \%$	$V, \%$	$P, \%$
Stimovit	92.3 $\pm$ 0.63	1.36	0.68	95.8 $\pm$ 0.48	1.00	0.50	99.3 $\pm$ 0.48	0.96	0.48
Kornevin	92.0 $\pm$ 0.41	0.89	0.44	92.0 $\pm$ 1.47	3.20	1.60	99.5 $\pm$ 0.29	0.58	0.29
Succinic acid	88.3 $\pm$ 0.63	1.43	0.71	90.3 $\pm$ 0.85	2.13	1.06	95.8 $\pm$ 0.85	1.78	0.89
Epin	87.8 $\pm$ 0.85	1.95	0.97	95.5 $\pm$ 0.65	1.35	0.68	99.8 $\pm$ 0.25	0.50	0.25
Radifarm	87.8 $\pm$ 0.25	0.57	0.28	96.3 $\pm$ 0.85	1.77	0.89	95.5 $\pm$ 0.65	1.35	0.68
No soaking (control)	83.8 $\pm$ 1.31	3.14	1.57	87.5 $\pm$ 0.65	1.48	0.74	92.0 $\pm$ 0.82	1.77	0.89
Soaking for 24 h	92.3 $\pm$ 0.85	1.85	0.93	99.0 $\pm$ 0.41	0.82	0.41	97.5 $\pm$ 0.65	1.35	0.68
Soaking for 48 h	87.5 $\pm$ 1.04	2.38	1.19	88.0 $\pm$ 0.41	0.97	0.49	96.3 $\pm$ 0.85	1.77	0.89

Note: X_m – average arithmetic value; m_x – error of the average value; V – coefficient of variation, %; P – accuracy of the experiment, %.

7.9–10.1 %), the lowest indicators of seed germination in soil were recorded after pre-treatment of seeds with succinic acid (exceeding by 4.1–5.8 %).

It has been established that at a temperature of +15...20 °C, the process of germination of the paulownia seeds was significantly slowed down; the seed germination in soil is lower, compared to the higher

temperature regime, and the values of its indicators vary from 69.8 $\pm$ 0.48 % to 95.0 $\pm$ 0.41 %, which was less by 1.5–23.0 % than for the same variants of the experiment at temperature of +21...25 °C (Table 6).

A comparative assessment of the germination in soil for paulownia seeds from different geographical locations under the temperature regime +15...20 °C confirms

Table 6. Indicators of seed germination in soil under the temperature regime of +15...20 °C.

Regulators of seed germination	Germination in soil of the seeds, collected in different locations								
	Odesa city			Mukachevo town			Lviv city		
	$X_m \pm m_x, \%$	$V, \%$	$P, \%$	$X_m \pm m_x, \%$	$V, \%$	$P, \%$	$X_m \pm m_x, \%$	$V, \%$	$P, \%$
Stimovit	73.3 $\pm$ 0.85	2.33	1.17	76.5 $\pm$ 0.65	1.69	0.84	95.0 $\pm$ 0.41	0.86	0.43
Kornevin	72.5 $\pm$ 0.65	2.07	1.03	72.7 $\pm$ 0.85	2.62	1.31	94.8 $\pm$ 0.85	1.80	0.90
Succinic acid	82.8 $\pm$ 0.85	2.06	1.03	73.8 $\pm$ 0.85	2.45	1.22	93.5 $\pm$ 1.04	3.28	1.64
Epin	80.5 $\pm$ 1.55	3.86	1.93	79.5 $\pm$ 1.04	2.62	1.31	94.8 $\pm$ 1.25	2.64	1.32
Radifarm	78.0 $\pm$ 1.08	2.77	1.38	74.8 $\pm$ 0.85	2.28	1.14	93.0 $\pm$ 0.71	1.52	0.76
No soaking (control)	69.8 $\pm$ 0.48	1.20	0.60	72.3 $\pm$ 0.63	1.61	0.80	91.8 $\pm$ 0.63	1.37	0.69
Soaking for 24 h	73.0 $\pm$ 0.41	1.12	0.56	76.0 $\pm$ 1.63	4.30	2.15	94.0 $\pm$ 1.08	2.30	1.15
Soaking for 48 h	74.8 $\pm$ 1.55	4.14	2.07	79.8 $\pm$ 1.44	3.60	1.80	94.8 $\pm$ 0.85	1.80	0.90

Note: X_m – average arithmetic value; m_x – error of the average value; V – coefficient of variation, %; P – accuracy of the experiment, %.

the highest germination rate for seeds from Lviv (from 91.8 ± 0.63 % to 95.0 ± 0.41 %). The values of the parameters of germination in soil for seeds of two other origins did not differ significantly from each other, but were significantly lower than the indicators of germination for seeds from Lviv.

Pre-soaking of seeds at a lower temperature regime of germination also had a positive effect on germination in soil, which increased compared to the control by 2.4–5.1 % when soaked for 24 h and by 3.3–10.4 % if soaked for 48 h. Comparing the experiment at a temperature of +21...25 °C, longer pre-soaking of seeds in water with a temperature of 20 °C (48 h versus 24 h) had more effective impact on soil germination. To our opinion, in this case, the determining factor was the temperature, which contributed to the activation of the process of seed germination.

The use of stimulators at temperatures of +15...20 °C increased germination in soil by 3.9–18.6 % compared to the control in seeds originating from Odesa, by 0.6–10.0 % – from Mukachevo and by 1.3–3.5 % for seeds from Lviv.

A generalized assessment for the effect

of stimulators on germination in soil of the seeds made it possible to reveal their effectiveness under both temperature regimes: +15...20 °C and +21...25 °C (Fig. 1).

The temperature of seed germination significantly affected germination in soil (see Fig. 1). Parameters of the seed germination in soil under the temperature regime of +21...25 °C exceeded those at a lower temperature in all variants of the experiment.

In general, under the germination temperature regime of +21...25 °C, the maximum value of the indicator of germination in soil – 95.8 % was recorded in the case of the use of Stimovit, the minimum one (91.5 %) – of Succinic acid.

Under the germination temperature regime of +16...20 °C, the ranking of preparations in order of decreasing their effect on seed germination in soil differs from the previous one and was as follows: Epin, Succinic acid, Radifarm, Stimovit, Kornevin.

Generalized parameters of the germination of paulownia seeds in soil, depending on the geographical origin, are shown in Figure 2.

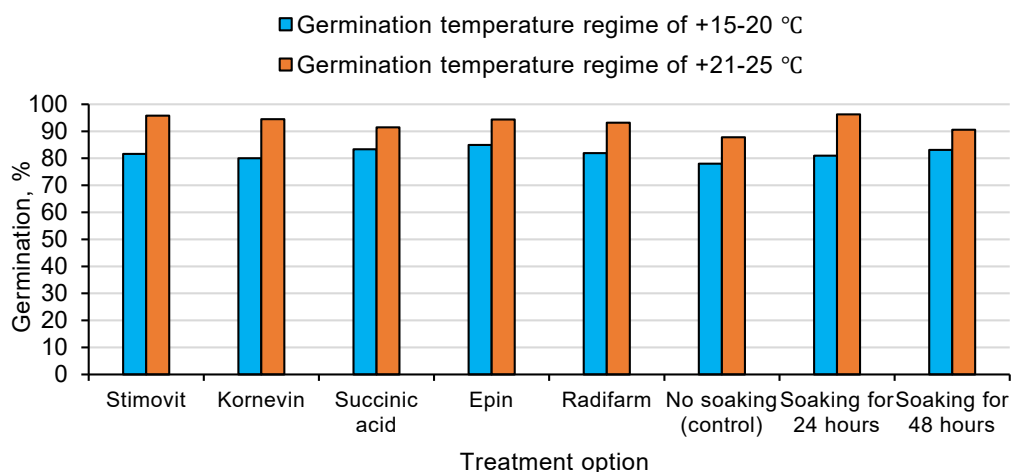


Fig. 1. The effect of germination stimulants on the germination in soil.

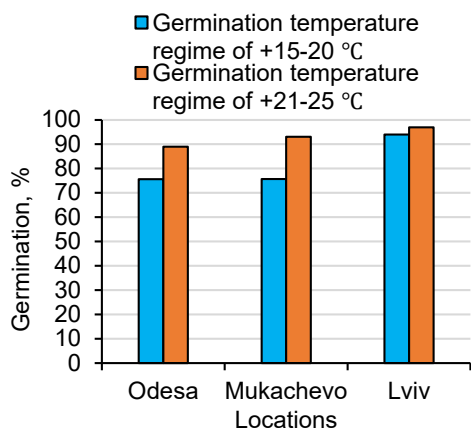


Fig. 2. The influence of the geographical locations, where the seeds collected, on the germination in soil.

According to Figure 2, seeds collected in Lviv were characterized by the highest germination in soil, regardless of the temperature regime of germination. Indicators of germination in soil of seeds from Mukachevo and Odesa were lower, respectively by 3.9–8.3 % and 8.0–8.4 %, depending on the germination temperature. After conducting an additional accounting of germinated seeds on the 28th day after sowing, it was found that the parameters of germination in soil did not change. It demonstrated the ability of seeds to germinate within two weeks after sowing them on the surface of the soil under the two studied temperature regimes.

Conclusions

Under the conditions of the southern regions of Ukraine, paulownia forms larger fruits, the weight of which exceeded the weight of fruits from Zakarpattia and Lviv regions by 24 and 38 %, accordingly. Seeds from Odesa were heavier and characterized by higher germination rate and germination energy.

Paulownia seeds are characterized by high technical germination regardless of geographical location.

To increase the rate of seed germination and germination energy, it is advisable to adhere to a temperature regime +20...25 °C. Decrease in temperature causes decrease in germination. The mean germination time was 1.3–2.0 times higher at temperatures of +15...20 °C.

Pre-soaking of seeds significantly affected germination indicators: both technical and absolute germination, as well as the rate of seed germination increased, and the mean germination time decreased. Increase in the duration of soaking (from 24 to 48 h) correlated with enhancement of technical germination and energy of seed germination.

Seeds of paulownia were characterized by high germination in soil regardless of the geographical location of parent trees under the conditions of Ukraine; the highest germination in soil was characteristic for the seeds from Lviv.

Temperature of germination had a significant effect on seed germination in soil. Under germination temperature regime of +21...25 °C, parameters of germination in soil were significantly higher.

Pre-soaking of seeds has the highest stimulatory effect on further germination of seeds in the soil among the investigated germination stimulants. Pre-treatment of seeds with Stimovit, Kornevin, Succinic acid, Epin, Radifarm generally had a positive effect, increasing germination in soil. The items related to the feasibility of using stimulators of germination and growth of plants, requires further study to investigate the complex effect of a specific preparation on both germination and juvenile development of seedlings.

In general, the studied seeds, collected from three geographical locations

in Ukraine, were characterized by high sowing qualities, can be used for growing planting material with further application in plantation forestry.

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Exploring and assessing *Cinnamomum sintoc* Blume essential oil composition in lowland forests of Mount Ciremai National Park, West Java

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Abstract

Cinnamomum sintoc Blume is native from the lowland region of Indonesia, and is an endemic plant in Mount Ciremai National Park. It is a medicinal plant that can be extracted into essential oil. The purpose of this study was to determine the chemical composition of essential oils contained in the leaves and bark of *C. sintoc* in Mount of Ciremai National Park. The extraction method uses steam distillation. The distillation results are analysed using gas chromatography-mass spectrometry (GC-MS) to determine the chemical composition of the essential oil. The results showed there are differences in the composition of chemical compounds contained in the leaves and bark of *C. sintoc*, the main chemical compound components in the leaves were linalool (8.26–87.12 %), 1,8-cineole (33.20–49.21 %), caryophyllene (1.54–7.78 %), α -terpineol (1.02–17.23 %), β -selinene (1.02–4.16 %), germacrene β (1.02–4.03 %), and (-)-caryophyllene oxide (1.01–2.49 %) and in the bark were 1,8-cineole (11.70–51.88 %), α -terpineol (12.17–25.64 %), linalool (38.11–78.98%), 4-terpineol (3.71–10.11 %), caryophyllene (1.23–4.90 %), β -pinene (1.09–4.02 %), and d-cadinene (1.01–3.28 %). This research shows that the highest yields of essential oils are found on the western slopes of Mount Ciremai National Park.

Key words: bark, GC-MS, leaves, linalool, 1,8-cineole.

Introduction

Cinnamomum sintoc Blume is a plant native to the lowlands of Indonesia, and is an endemic plant in the Mount Ciremai

National Park (TNGC). *C. sintoc* is a plant that belongs to the Lauraceae family. It is a family of woody plants that have around 2700 species and their existence is very important for ecology in the world's trop-

ical and subtropical forests (Ismail et al. 2019, Geethakumary et al. 2021).

Lauraceae family belongs to the order Laurales and includes several well-known genera such as *Cinnamomum*, *Persea*, *Laurus*, and *Litsea*. They generally have distinctive morphological features, such as broad leaves, thick bark, and small but aromatic flowers. Some examples of well-known species are *C. sintoc*, the clove tree (*Syzygium aromaticum* L.) and the laurel tree (*Laurus nobilis* L.), which are known for their leaves used as spices in cooking (Kristiani et al. 2019, Ismail et al. 2021).

C. sintoc trees provide habitat and food sources for various animal species such as birds, mammals, insects, and reptiles. In addition, some members of Lauraceae family have high economic value (Geethakumary et al. 2021). Seeds, fruits, bark, and leaves of some species of Lauraceae can be used as foodstuffs, spices, essential oils, or traditional medicines, one of which is from the genus *Cinnamomum* namely *C. sintoc* (Ismail et al. 2021). It is a type of tree that can grow to a height of about 20 m. The plant has wide, green leaves. The roots, bark, and leaves of *C. sintoc* contain abundant essential oils. It is widespread in several regions in Southeast Asia, including Indonesia, Malaysia, Thailand, and Vietnam. *C. sintoc* grows in the tropical forests of Mount Ciremai National Park, West Java and is currently experiencing a significant decline in numbers to endangered due to overharvesting (Ismail et al. 2022).

Lauraceae plant type species chemical compounds from various parts of plants such as *Cinnamomum* genus contains essential oils with 33 chemical compounds (Handayani 2018, Al-Mira et al. 2021, Sharifi-rad et al. 2021). *C. sintoc* is a type of plant which produces essential oils in its

roots, bark and leaves and contains abundant chemical compounds (Ismail et al. 2019). Based on previous research, there are 11 compounds contained in the skin (Wang et al. 2019, Behbahani et al. 2020, Nuwa et al. 2021), while the leaves contain 21 compounds (Suwandhi et al. 2014, Kumar et al. 2019, Al-Zereini et al. 2022). Compounds from *C. sintoc* essential oil have many benefits and functions such as immunomodulatory, anti-inflammatory, antimicrobial, antioxidant and anti-cancer activities (Kumar et al. 2019, Zhang et al. 2019, Abd El-Hack et al. 2020, Wu et al. 2020, Bottoni et al. 2021).

Mount Ciremai National Park is a conservation area that functions as a protection area for plants and animals (Ismail et al. 2022). *C. sintoc* is an endemic plant in the Park region and is spread throughout the location. The utilisation of *C. sintoc* needs to be maximised in order to increase the economic value of the plant. It has an economic value important in the industrial sector, especially in the essential oil and spice industries (Darlita et al. 2017). The chemical composition of essential oils extracted from *C. sintoc* plants can be influenced by several factors (Dai et al. 2019). Various parts of the plant such as leaves, bark, roots, and flowers can have different chemical compositions in essential oils. For example, essential oils extracted from *C. sintoc* leaves may have different components from essential oils extracted from the bark or other piece (Narayanankutty et al. 2021).

Until now there has been no research that directly compares the chemical content of essential oils from parts of *C. sintoc*. Therefore, it is important to conduct research on the chemical composition of its essential oil in Mount Ciremai National Park, West Java. This research is focused on exploring the chemical compounds

in the essential oils extracted from the leaves and skin. It aims to examine the factors influencing these differences, with the ultimate goal of providing information for the effective management of this plant type. The intention is to optimise production for abundance, quality, and sustainability, making it suitable for various industries.

Methodology

Sample preparation

This research was conducted in Mount Ciremai National Park, West Java. With a location determined deliberately or on purpose. Taking into consideration that the Mount Ciremai national plant area has an altitude that varies between 500–1200 m a.s.l. there are 4 slopes used as sampling areas. Data collection includes field exploration and observation to obtain information about the condition of *C. sintoc* plant population and habitat biophysics followed by laboratory testing. The collection of samples from various slope directions was carried out on points determined on the map (Fig. 1).

Data collection was carried out using the plot/strip method. Plots/strips are placed in each slope direction at each altitude. The starting point is the point where *C. sintoc* was first encountered until the last point the *C. sintoc* plant grows. Plots were created using a nested design, namely plots measuring 20×20 m for inventory of *C. sintoc* trees with a diameter > 20 cm and a height > 2.5 m (Kusmana 2017).

In each plot, samples of leaves and bark were taken from different environmental conditions. In general, the environmental conditions in TNGC have the

following characteristics: there are several types of soils, including Alluvial, Andosol, Red-Yellow Latosol, Podsol, Regosol. The topography in the area is generally dominated by rather steep slopes (16–25 %) and steep (26–40 %), namely an area of 5351.25 ha (36.06 %) for moderately steep slopes and 5295.34 ha (35.68 %) for steep slopes. The area with very steep slopes (> 40 %) is only a small part, namely 387.09 ha (2.61 %). Geologically, Quaternary volcanic rocks are dominant on the eastern slopes. Plio–Pleistocene volcanic rocks are dominantly found on the northern slopes and southern slopes. Neogene Sedimentary Rocks (Mio–Plio) are found dominantly on the western slopes. The climate of the TNGC area is type C with a Q value of 40.5 %. The average rainfall is 2500 to 4500 mm yr⁻¹ with the lowest daily rainfall intensity being 13.6 mm per day and the highest being 34.8 mm per day, and the lowest monthly rainfall intensity being 115.6 mm per month while the highest is 399.5 mm per month. Temperatures range from 18 to 24 °C with an average air pressure of 1010 mb, and humidity of around 63–89 % (BTNGC 2017). Distribution of plots on each slope direction can be seen in Table 1 which shows sampling using plots at each altitude for each slope direction.

C. sintoc population in each direction of the slope has differences in the number of trees. Based on this description, to represent the entire population, it was determined to take samples weighing 2 kg from each plot.

Extraction of essential oils using the steam distillation method

The sample used was 270 g from a total of 2 kg each of *C. sintoc* bark and leaves from each sampling plots. Each sample

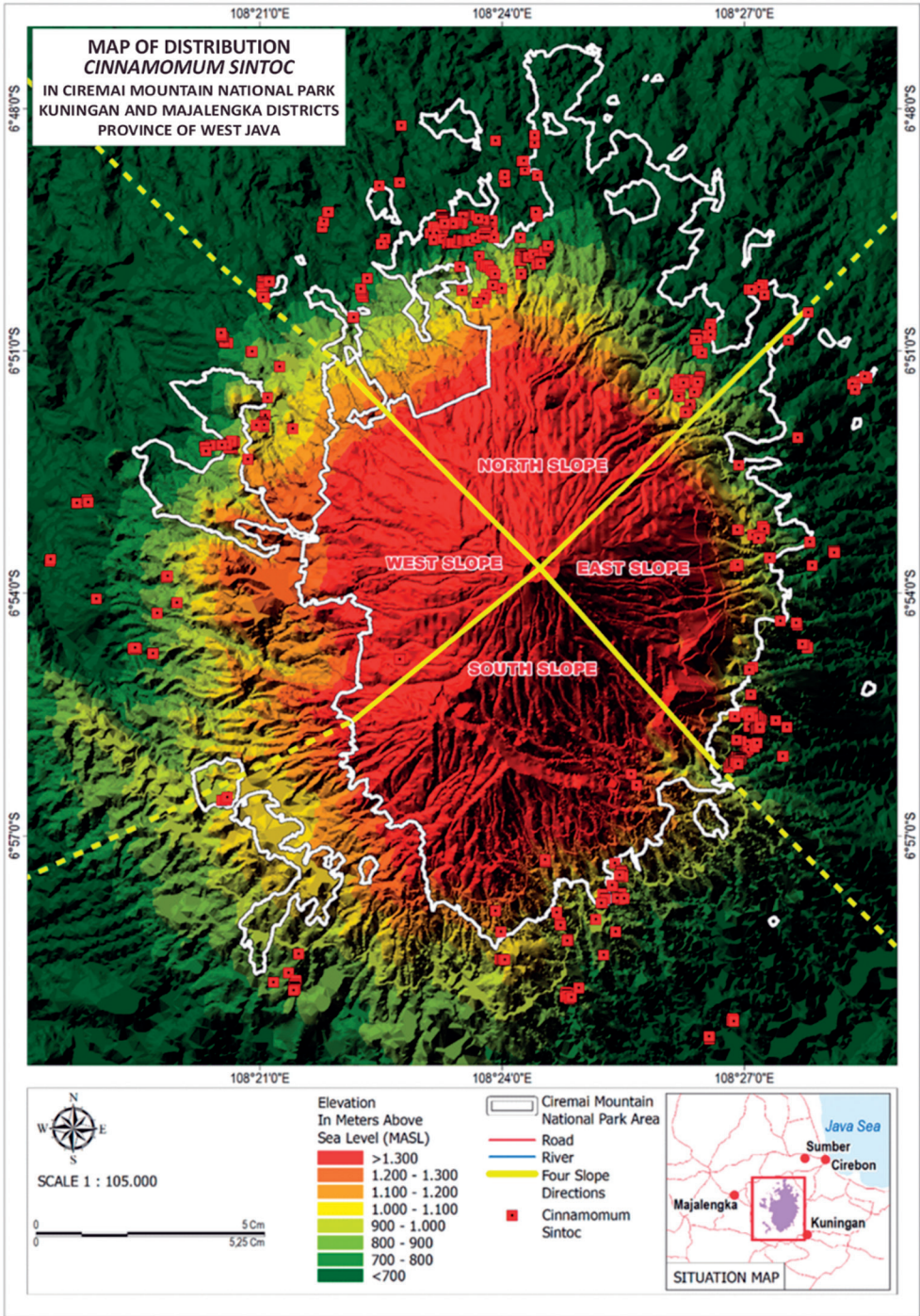


Fig. 1. Map of *C. sintoc* distribution in Ciremai Mountain National Park Area.

Table 1. Distribution of plots sampling based on slope direction and altitude.

Slope direction	Altitude, m a.s.l.	Sampling plots
West	600–1000	5
South	500–1200	5
East	500–1100	7
North	500–1000	6

was taken dry, cut into small pieces and put into a steam distillation tube. Distillation was carried out 6 times, at each stage 45 g of each sample was used. During the distillation process, the oil particles in the raw material were carried along with the steam and flowed to the condenser. In the cooler/condenser the water vapor mixed with the oil condensed and was collected in a medium-sized vial. After that, the mixture of water and oil in the vial was stored in an Erlenmeyer flask, then separated slowly, the resulting oil was stored in a vial.

Analysis and identification of essential oil chemical compounds

Analysis of the essential oil content in *C. sintoc* bark and leaves was carried out using gas chromatography-mass spectrometer analysis. Essential oils that have been pure or distilled were analysed in order to determine the chemical compounds in them (Marzuki and Hariroh 2021). The MS obtained was compared with the known reference compound in the database and has been programmed by the GC-MS tool (Sukmajaya et al. 2012, Nugraheni et al. 2016, Rosmalina et al. 2020).

GC-MS equipment that was used for GC was operated at a temperature of 60 °C for 4 min, then the temperature was increased to 120 °C (2 °C per min). The temperature was maintained at 120 °C for 5 min, then was increased again with

50 °C per min until the final temperature of 290 °C and then maintained for 10 min. The total essential oil flow rate used is 50 mL per min with a slit ratio of 1:30, injector temperature of 300 °C and the amount of sample injected through the injector was 0.1 µL. Meanwhile, for the MS, electron energy of 70 eV was used with an accelerating voltage of 1.30 kV. The detected mass range was between 40–400 µg·mol⁻¹ with a scanning interval of 1 s (Nurhaen et al. 2016).

Results and Discussion

Isolation of essential oil from *C. sintoc* bark and leaves using the steam distillation method

Average results of essential oil distillation from each sample of *C. sintoc* bark and leaves taken from each sampling plot was different and there are also differences in the essential oil content from each direction of the sampling slope. Table 2 shows average yields of essential oil distillation.

Table 2 shows that samples of bark have a higher average yield compared to leaves. The average yield of *C. sintoc* bark was 0.06 % while that of leaves 0.05 %. Based on the data in Table 2, it is known that the volume of essential oil from distilled samples originating from each direction of slope and altitude is different. The highest average yield was obtained from the western slope with an average yield of 0.086 % of the bark and 0.06 % of the leaves, while the lowest average value was obtained from the southern slope with an average yield in the bark of 0.062 % and in the leaves 0.036 %. Based on this, it is the main concern in analysing the distillate using GC-MS to determine the composition of the chemical compounds con-

Table 2. Yield of distillation essential oil from bark and leaves of *C. sintoc* based on environmental conditions.

Slope direction	Altitude, m a.s.l.	Volume of essential oil, mL		Essential oil yield, %	
		Leaves	Bark	Leaves	Bark
West	600	1.25	1.35	0.05	0.07
	700	0.73	1.46	0.04	0.07
	800	1.63	1.88	0.06	0.08
	900	1.70	2.10	0.07	0.09
	1000	1.96	2.31	0.08	0.12
South	500	0.87	1.12	0.03	0.05
	800	0.87	1.13	0.03	0.06
	900	1.08	1.50	0.04	0.08
	1000	0.67	1.33	0.04	0.07
	1200	0.90	1.00	0.04	0.05
East	500	1.37	1.30	0.04	0.08
	600	0.89	1.00	0.04	0.05
	700	0.79	1.03	0.04	0.05
	800	1.20	1.50	0.04	0.06
	900	1.55	2.13	0.06	0.11
	1000	1.27	1.65	0.05	0.09
	1100	0.59	0.10	0.03	0.01
North	500	1.08	1.33	0.05	0.07
	600	1.29	1.65	0.05	0.08
	700	1.33	1.95	0.06	0.1
	800	1.18	1.51	0.05	0.06
	900	2.01	2.11	0.07	0.11
	1000	1.33	1.83	0.05	0.09
Average total		1.20	1.49	0.05	0.06

tained in the essential oil of the *C. sintoc* plants which grow in various directions on the slopes in TNGC.

The composition of chemical compounds of essential oils

C. sintoc essential oil analysed showed 7 main chemical components identified. The major chemical components found in bark are linalool (8.26–87.12 %), 1,8-cineole (33.20–49.21 %), caryophyllene (1.54–7.78 %), α -terpineol (1.02–17.23 %), β -selinene (1.02–4.16 %), germacrene β (1.02–4.03 %), and (-)-caryophyllene

oxide (1.01–2.49 %). *C. sintoc* essential oil has not been researched much compared to other types of *Cinnamomum*. Narayanankutty et al. (2021) said that the main essential oils in the leaves of *C. verum* J. Presl are cinnamaldehyde (35.6 %), linalool (18.92 %), eugenol (18.69 %), and (E)-cinnamyl acetate (12.5 %), in *C. camphora* J. Presl are linalool (41.57 %) and cineole (22.07 %) (Wang et al. 2019) while according to Chang et al. (2021) main chemical compound found in *C. osmophloeum* Kaneh. is linalool (93.30 %). The dominant chemical compound in *C. sintoc* bark in Ciremai National Park is

1,8-cineole. However, there are differences chemical content of essential oils from each direction of the slope where the *C. sintoc* bark samples were taken. The components of *C. sintoc* bark essential oil components are presented in Figure 2.

GC-MS analysis showed that the peak point of abundance of chemical compounds in essential oil samples was detected at 7 min and 78 s (Fig. 3). At the peak point of abundance of the chemical compound analyzed by GC-MS was the compound 1,8-cineole, so it is known that the dominant compound in the essential oil from *C. sintoc* bark is 1,8-cineole. Apart from that, there are other small peak

points which also show that analysis of the chemical compounds of essential oils from bark using GC-MS detected other chemical compounds such as are linalool, caryophyllene, α -terpineol, β -selinene, β germacrene, and (-)-caryophyllene oxide.

Based on previous research 1,8-cineole is also widely found in *C. zeylanicum* (1.02 %) (Abd El-Hack et al. 2020), *C. verum* J. Presl (0.10 %) (Al-Zereini et al. 2022), *C. curvifolium* (Lour.) Nees (10 %) and *C. mairei* H. Lév. (14.6 %) (Dai et al. 2019).

Figure 4 shows the results of chemical compounds analysis of *C. sintoc* leaves. It can be seen that they have differenc-

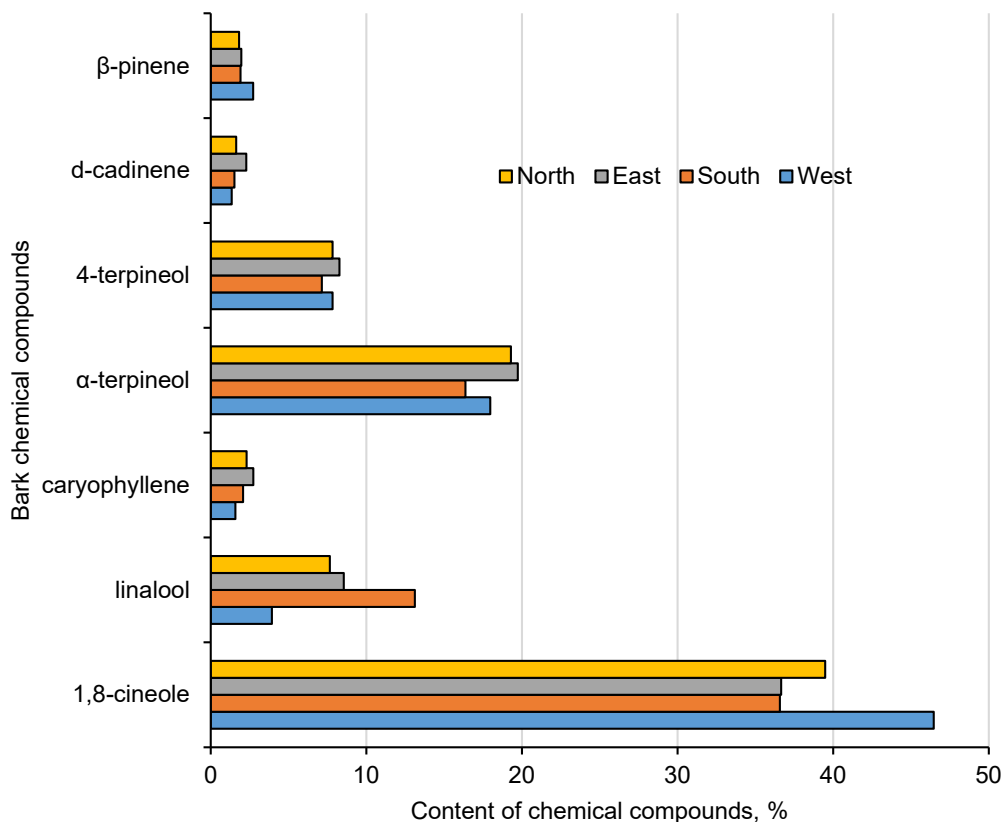


Fig. 2. Components of the main chemical compound of *C. sintoc* bark.

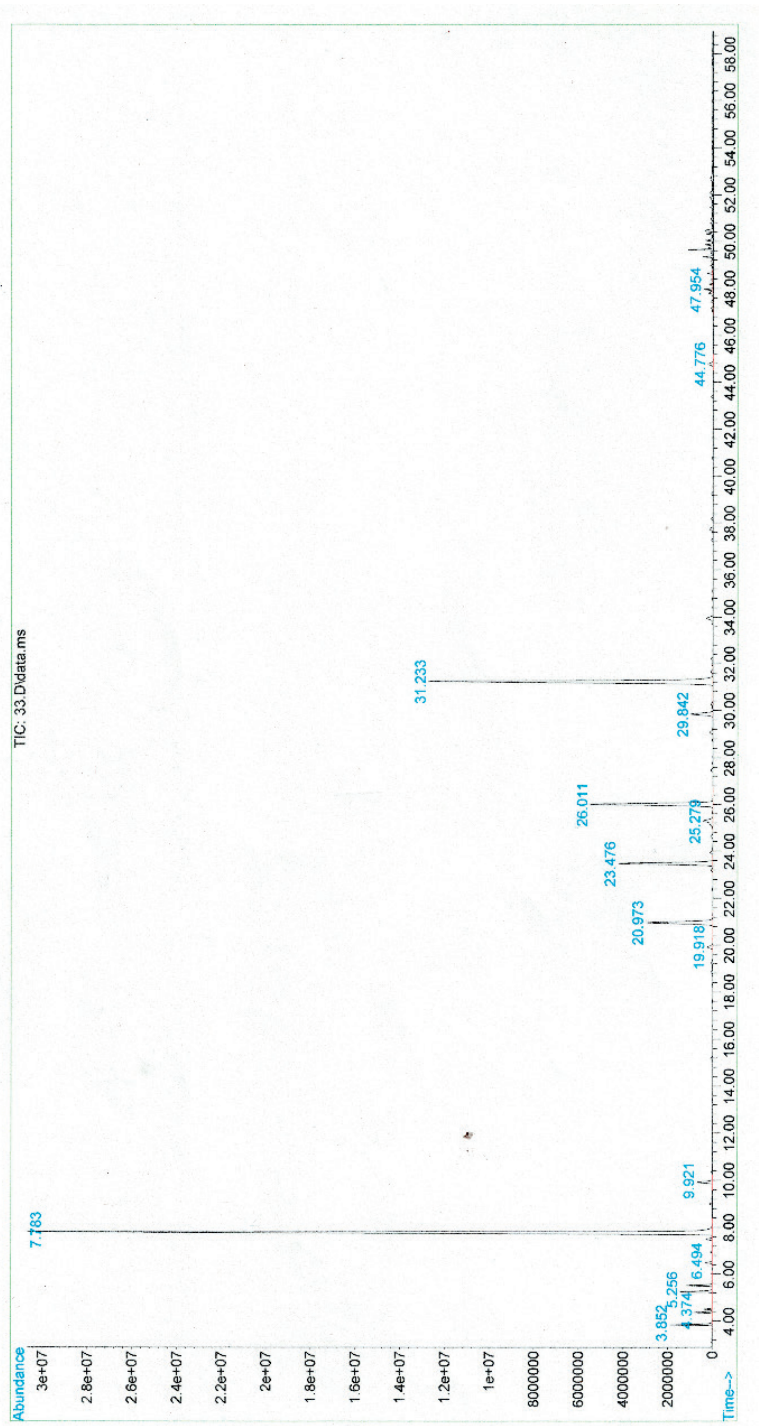


Fig. 3. Chromatogram of *C. sintoc* bark essential oil compound.

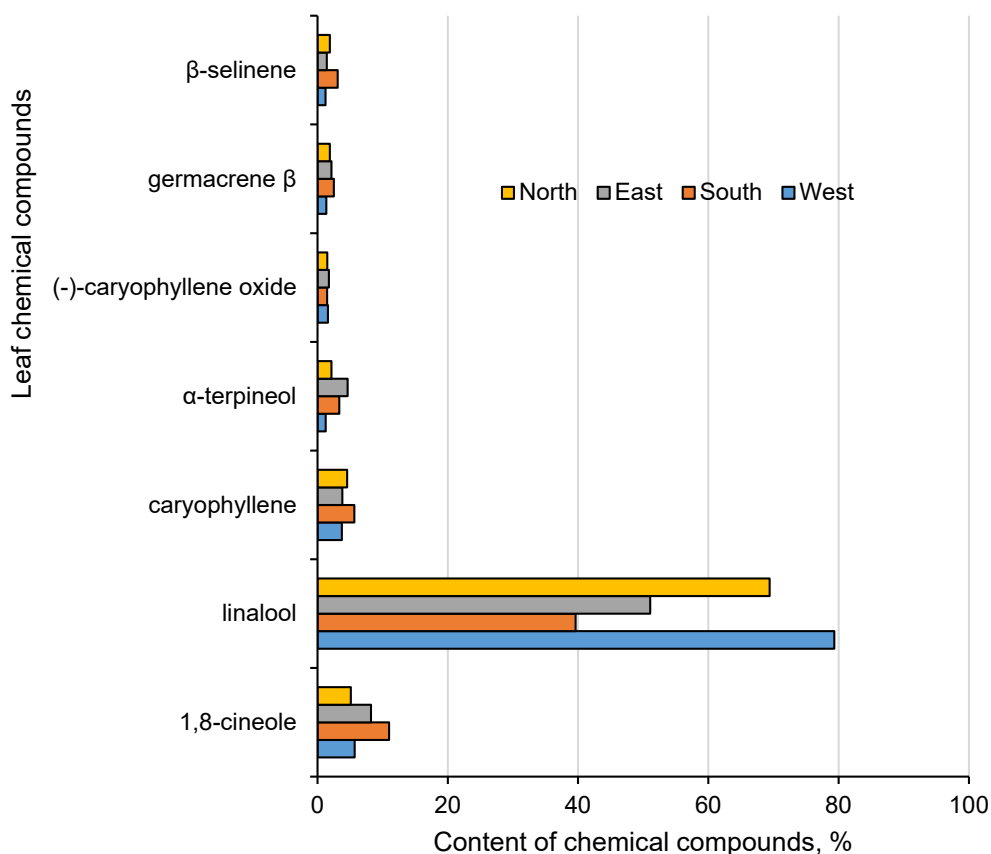


Fig. 4. Components of the main chemical compound of *C. sintoc* leaf.

es from each sampling slope, and significant differences in the concentration and chemical compounds contained in the essential oil. The following are the main components of essential oil extracted from *C. sintoc* leaves. Linalool is the dominant compound with concentrations ranging from 38.11 % to 78.98 %. There are other chemical compounds, namely 1,8-cineole (11.70–51.88 %), α -terpineol (12.17–25.64 %), 4-terpineol (3.71–10.11 %), caryophyllene (1.23–4.90 %), β -pinene (1.09–4.02 %), and d-cadinene (1.01–3.28 %).

From GC-MS chromatogram analysis

time is expressed in minutes and serves as a coordinate on the x-axis (Fig. 5). At 23 min and 56 s there was a peak occurred indicating abundance of linalool in leaf essential oil sample. This peak indicates that linalool is one of the dominant compounds or has the highest concentration in the essential oil at that time. Apart from the highest peak point, there are also other peak points at different times. This shows that there is an abundance of other chemical compounds contained in essential oils such as 1,8-cineole, α -terpineol, 4-terpineol, caryophyllene, β -pinene, and d-cadinene. This is in accordance with

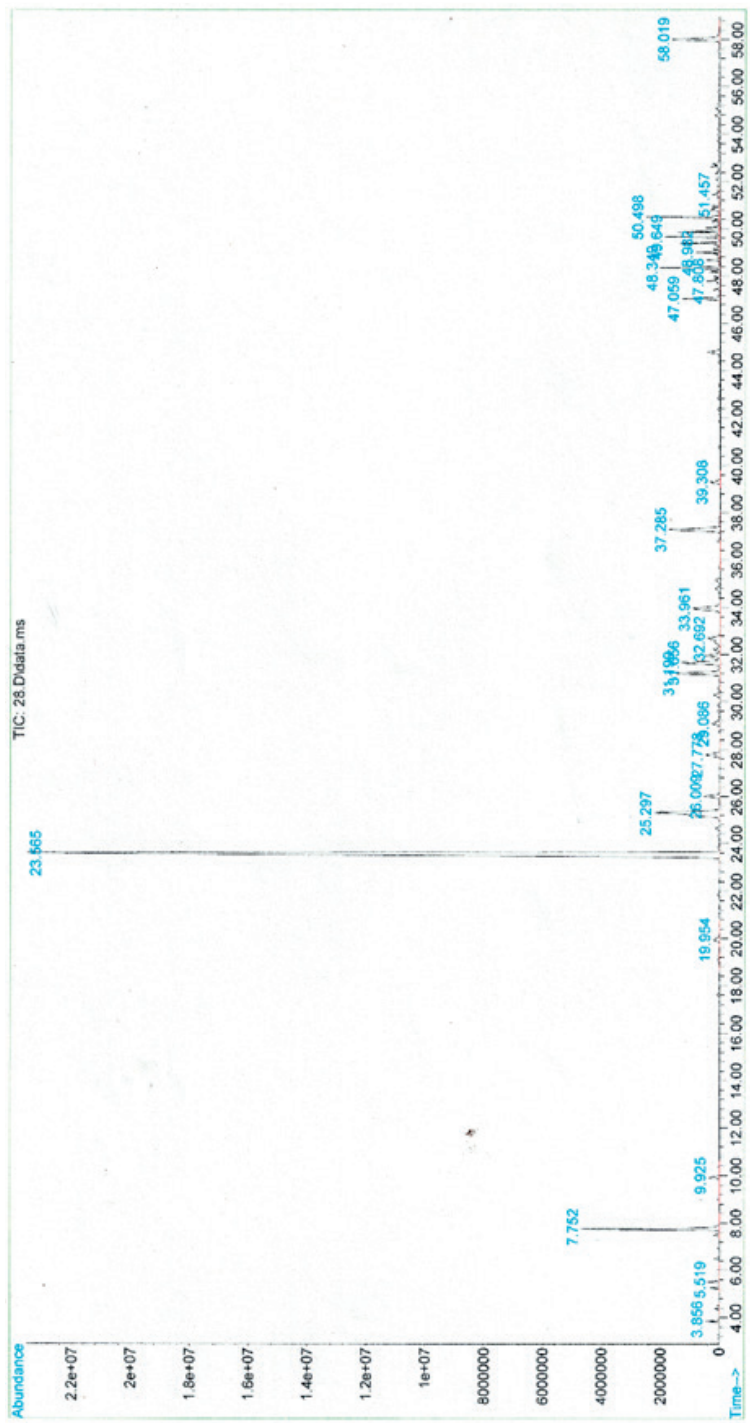


Fig. 5. Chromatogram of *C. sintoc* leaf essential oil compound.

previous research: linalool compounds are found in many *Cinnamomum* species, besides that these compounds are found in many other species such as *Tamarindus indica* L. (Suherman et al. 2020), *Ocimum basilicum* L. (Kristiani et al. 2019), *Pandanus amaryllifolius* and *Citrus limon* L. (Al-Mira et al. 2021).

Conclusions

It was found that there were differences in the volume of essential oils from the distillation of *C. sintoc* samples taken from each direction of the slopes around Mount Ciremai National Park. The western slope is the area with the highest yields of essential oil. According to the part of the plant, this shows that there are differences in the dominant chemical compound content of essential oils extracted from the leaves and bark, including β -selinene, β germacrene, (-)- caryophyllene oxide in leaves and β -pinene, d-cadinene, 4-terpineol in bark.

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Age, growth and condition of the Romanian barbel (*Barbus peteniyi*) in the Vit River, Northern Bulgaria

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Abstract

The article presents a study on the growth patterns of Romanian barbel in the middle reaches of the Vit River, within the Danube River watershed in Bulgaria. The research utilized material collected by anglers along the Vit River, with a total of 209 individuals examined. Fish age was determined through scalimetry, while length and mass were calculated using scale length-radius and mass-length relationships, respectively. The study established four age groups, with the majority of the sample consisting of three and four-year-old fish. The length of the sampled individuals ranged from 88 mm to 192 mm. Growth analysis was conducted by back-calculating the length using the equation $SL = 1.9331 \cdot S + 42.677$ ($r^2 = 0.947$). Furthermore, a relationship between gutted weight (W) and standard length (SL) was established using the equation $W = 0.00003 \cdot L^{2.8233}$ ($r^2 = 0.996$). The obtained results were compared to nine local populations of Romanian barbel in rivers across Bulgaria.

Key words: growth of weight, linear growth, size and age composition.

Introduction

The Romanian barbel (*Barbus peteniyi* Heckel, 1852) is a fish species widespread in the Danube catchment area of Bulgaria and Romania (Mihaylova 1960, 1970; Marinov 1986; Kottelat and Freihof 2007) and in the Kamchia River in the Black Sea watershed in Bulgaria (Drenski 1951, Kottelat and Freihof 2007). This rheophilic fish prefers the middle zones of rivers and typically does not exceed 30 cm in body

length (Marinov 1986, Karapetkova and Zhivkov 1995, Peshev et al. 2003).

The Romanian barbel is commonly targeted for recreational fishing (Karapetkova and Dikov 1986). Previous studies examined various aspects of its biology, (i.e. feeding, reproduction, and fecundity) in northwestern Bulgaria (Mihaylova 1960, 1970). In recent years, information on the growth of the species was published only for the Ogosta River in Northwestern Bulgaria (Kolev 2022), while older publica-

tions (Marinov 1986) contain data on the growth of the species in various Bulgarian rivers within the Danube River watershed.

Several authors investigated its population size and biomass in multitude Bulgarian rivers (Karapetkova and Dikov 1986; Dikov et al. 1988, 1994).

The aim of this study was to calculate the growth parameters of the Romanian barbel in the Vit River, thereby contributing to its biology and ecology.

Study Area

The Vit River (Fig. 1) is one of the largest watercourses in northern Bulgaria. It stretches for a length of 188.6 km, ranking as the 12th largest river in Bulgaria (Hristova 2012). It is formed by the merging of two rivers, considered the main source of the river. Beli Vit originates from an elevation of 1595 m above the sea level in the western part of Yumruka peak in the Balkan Mountains.

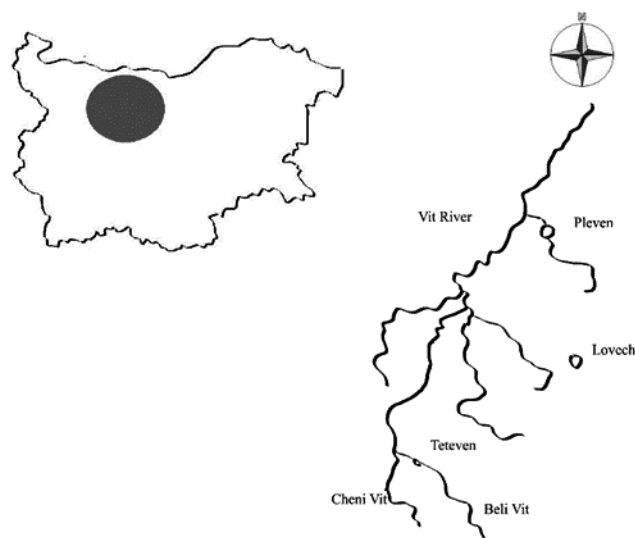


Fig. 1. Schematic map of Vit River, where Romanian barbel was collected.

Flowing through the Lovech and Plevan regions, the Vit River eventually joins the Danube near the Somovit village. The river experiences its highest water levels from April to June, primarily due to the snow melting in the Balkan Mountains, while the lowest levels are during autumn. The nourishment is mixed rain-snow and karst groundwater.

The object of this research is the middle river zone, extending from 200 to 800 m a.s.l. The water here is less turbulent, the bottom of the river is stable, covered with sand, silt or fine gravel. Unlike upper river waters, there is an increase in nutrients and aquatic plants.

Materials and Methods

The research comprised 209 Romanian barbel specimens, collected during the summer and autumn of 2021, from four stations located within the central zone of the Vit River (see Table 1) using sport fishing rods and employing the legering method of fishing. This is a method that results in the bait remaining stationary on the bottom of the river. The bait is anchored with a light weight and the end of the rod is used as a visual way to detect a bite (Purnel et al. 1998). The catch was made with limerick hooks and maggot larvae and earthworms were used as bait.

The linear growth was determined by performing a back-calculation of length data (SL) based on the diagonal oral radius of a scale (S), following the principles related to the relationship between

Table 1. Sampling stations.

No	Location	Geographic coordinates		Altitude, m a.s.l.
		Latitude	Longitude	
1	Near of the town of Teteven	42°53'59.52" N	24°18'43.42" E	480
2	At the point of confluence of Cherni Vit into Beli Vit	42°56'20.18" N	24°12'15.11" E	365
3	A few kilometres west of the town of Teteven	42°54'22.13" N	24°18'15.43" E	450
4	At the confluence of Vasilievka River with Vit River	42°53'12.67" N	24°19'32.57" E	490

scale radius and fish length, described by Lea (1910), Chugunova (1959), Ricker (1979) and Sterlingova (2016). For this purpose, the length to the end of the scaly cover – standard length (SL , mm), the length to the end of the caudal fin – total length (TL , mm) and gutted weight (W , g) were measured. More than ten scales were collected from each Romanian barbel specimen. They were taken from underneath the dorsal fin; equal number of scales were taken from the left and right side of the dorsal fin. Next, the scales were dried up and stored in small paper bags. Each scale was placed between two microscope slides. The age of the fish was determined by counting the number of annuli or year marks of scales Olympus CX 31. The diagonal caudal radius of the scales (S) was also measured. Regression analysis was used to describe the L - S relations (Zhivkov 1981, Prodanov 1982, Raikova-Petrova and Zhivkov 1993). The relation was calculated for all age groups together and can be expressed by the following linear equation (1):

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

where: SL is standard length of fish, mm; S is diagonal oral radius of scale (eyepiece micrometre scales divisions); a , b are coefficients.

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

$$t = SL_n - SL_{n-1}, \quad (2)$$

where: t is absolute annual linear increment, mm; SL_{n-1} is the average SL for two consecutive years, mm.

The determination of gutted weight (W) was performed with the W - L relationship as described in formula (3) by Ricker (1979), which has widely been used various studies (Zhivkov 1981, 1999; Prodanov 1982; Raikova-Petrova and Zhivkov 1993; Kukushkin 1997; Belomacheva et al. 2005).

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

where: W is gutted body weight, g; SL , mm; a and b are coefficients.

To compare the growth in length between populations, a method employed by Zhivkov (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).

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

where: L is weighted average standard body length, cm; W is weighted average gutted body weight, g.

2) by calculating a coefficient K_b , using the Fulton equation, but instead of exponent 3, using b of equation (3).

3) by comparing the weight growth (W) of fish from different populations, which has been performed by many authors (Gold-

spink 1979; Zhivkov 1981, 1999; Basami and Grove 1985; De Silva 1985; Raikova-Petrova 1992). A relation is expressed by the equation (5).

$$W_L = a \cdot SL^b, \quad (5)$$

where: SL is standard length, mm; W_L is gutted weight, g; a and b are coefficients.

In order to obtain comparable values of W in equation (3), pre-selected rounded values of SL (100, 200, 300 and 400 mm) were substituted in place of SL ($SL = 100$, $SL = 200$, $SL = 300$, $SL = 400$). Using equation (5) with the listed values of SL (mm), allows obtaining the corresponding values of mass: $W_{L=100}$, $W_{L=200}$, $W_{L=300}$, $W_{L=400}$. The so-obtained mass values for each of the studied populations were then compared (Zhivkov 1981, 1999; Raikova-Petrova and Zhivkov 1993). The association degree between L and S , as well as between W and L variables, was determined by a correlation coefficient (r^2). All data were calculated by using MS-Excel 2010.

Results

Age and size composition

The age of specimens ranged from one to five years. Most specimens were aged three and four years, comprising 89 % of the overall capture (Fig. 2). A lack of fish one-year-old was noted. Two-year-old fish comprised 5 % of the overall capture. Natural and fishing mortality are more likely to account for the absence of fish aged six years and older than any selectivity of the fishing method.

The largest specimen was a female measuring and weighing 74 g (full weight with entrails) and 192 mm (TL). Mean weight was 30.7 ± 12.9 g, and the mean length was 139.8 ± 21.3 mm. The majority of specimens ranged from 100 to 150 mm,

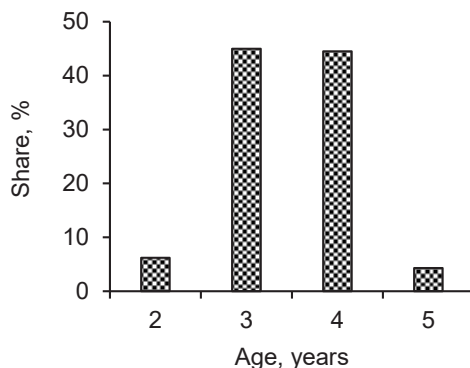


Fig. 2. Age structure of the Romanian barbel population.

comprising 85 % of the total. However, the main group consisted of specimens measuring from 111 to 120 mm, accounting for 26 % (as shown in Fig. 3).

Growth rate

The relationship between SL and scale radius was well expressed based on the equation (6) and shown in Figure 4.

$$SL = 0.19331 \cdot S + 42.677, \quad r^2 = 0.94, \quad n = 209, \quad (6)$$

where: SL is standard length, mm; S is scale radius; r^2 is regression coefficient; n is sample size.

The greatest annual increment in length was shown in yearling fish (Table 2). This is probably related to the need for fish of this age to escape pressure from predators (Nikolsky 1965). In the other age groups, the annual increment in length remains almost constant.

The weight was calculated using the equation (7):

$$W = 0.00003 \cdot SL^{2.823}, \quad r^2 = 0.99, \quad n = 209, \quad (7)$$

where: W is gutted weight, g; SL is standard length, mm; r^2 is regression coefficient; n is sample size.

There is a well-defined and almost

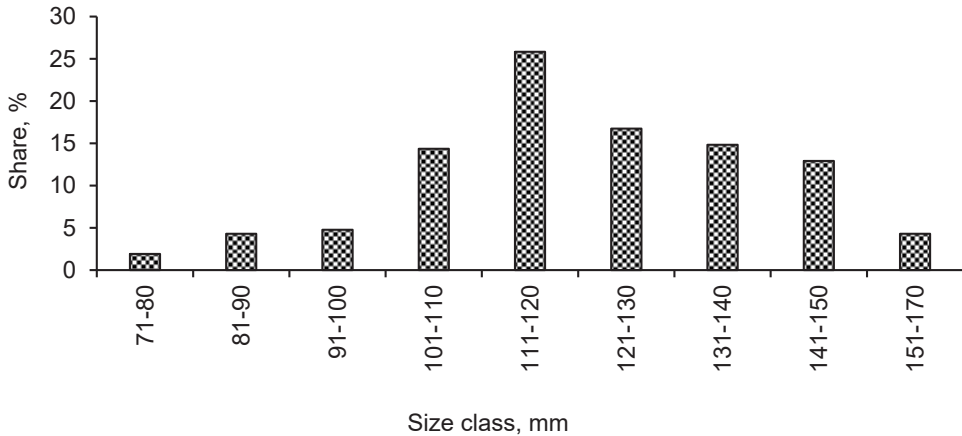


Fig. 3. Size classes of Romanian barbel.

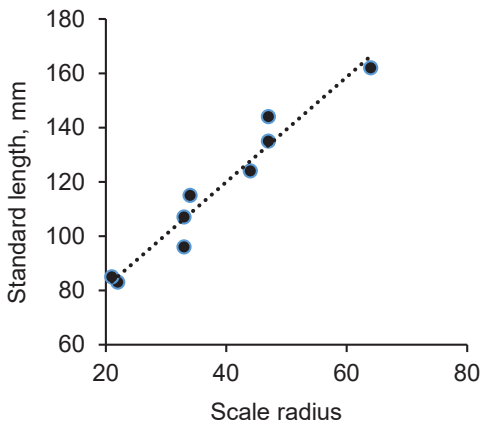


Fig. 4. Growth in length of Romanian barbel.

functional relationship between length and weight of Romanian barbel – equation (7) and Figure 5, which allows the *W-L* relationship to be used to compare the growth of species in different watercourses. There exists a well-defined and nearly functional relationship between the length and weight of Romanian barbel, as indicated by equation (7) and illustrated in Figure 5. This relationship enables the comparison of species growth in various watercourses using the *W-L* relationship

Fish aged over four years weighted over 40 g, and fish over 60 g were considered to be over five years old. The annual

Table 2. Back-calculated *SL* of Romanian barbel.

Age group	<i>n</i>	Mean calculated <i>SL</i> at age, mm				
		<i>SL</i> ₁	<i>SL</i> ₂	<i>SL</i> ₃	<i>SL</i> ₄	<i>SL</i> ₅
II	35	66	87			
III	114	66	85	108		
IV	55	66	89	112	135	
V	5	62	87	112	141	166
Mean calculated length (<i>SL</i>), mm		65	87	111	138	166
Mean observed length, mm		nd	96	118	141	164
Annual increment, mm		65	22	24	26	25

Note: nd – no data.

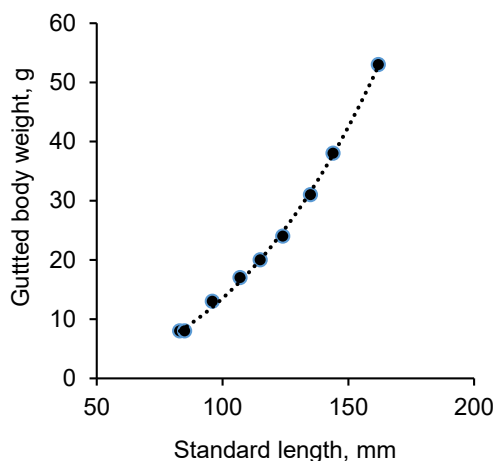


Fig. 5. Growth in weight of Romanian barbel.

weight increment gain increased progressively with age and was highest in the five-year-old group (Table 3).

By comparing the *SL* measurements of Romanian barbel populations from different rivers in Bulgaria we found that Romanian barbel had the highest linear growth in the Rositsa River and the slowest in the Osam River (Table 4). The *TL* data from the Vit River were similar to those reported for the Vedena and Ogosta rivers. However, after a recheck of the results using the calculated *SL* (Zhivkov 1981, 1999; Prodanov 1982; Raikova-Petrova 1992; Raikova-Petrova and Zhivkov 1993; Kukushkin 1997; Belomacheva et al. 2005), differed. Additionally, a comparison was made between the available observed *TL* data from the Vit and Ogosta rivers' populations. It was found that unless the observed *TL* data were similar, the calculated *SL* values (Table 5) differed. Fish from the Vit River showed higher growth in length compared to those from Ogosta River. This finding provides further evidence in favour of the proposition that employing the computed method yields more precise outcomes, as it captures the primary trend in fish growth and mitigates the impact of individual deviations. Furthermore, our data indicate that the calculated length values were generally lower than the observed length values (Table 2).

Condition factor

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 6). Data for both coefficients were available for fish populations of the Ogosta and Vit rivers. Fish from the Vit River had lower K_f but higher K_b values from fish of the

Table 3. Back-calculated gutted body weight (*W*) of the Romanian barbel.

Age group	<i>n</i>	Mean calculated weight <i>W</i> at age, g				
		<i>W</i> ₁	<i>W</i> ₂	<i>W</i> ₃	<i>W</i> ₄	<i>W</i> ₅
II	35	4	9			
III	114	4	8	17		
IV	55	4	10	18	31	
V	5	3	9	18	35	56
Mean calculated weight (<i>W</i>), g		4	9	18	33	56
Mean observed weight, g		nd	13	21	36	58
Annual increment, g		4	5	9	24	30

Note: nd – no data.

Table 4. Observed mean *TL* of Romanian barbel of the same age from different Bulgarian rivers.

River	<i>n</i>	<i>TL</i> , mm					Source
		<i>TL</i> ₁	<i>TL</i> ₂	<i>TL</i> ₃	<i>TL</i> ₄	<i>TL</i> ₅	
Rositsa	20	76	142	163			Marinov (1986)
Nishava	15	77	125				Marinov (1986)
Vedena	168	75	108	158	170	202	Mihaylova (1960)
Ogosta	100	78	108	131	160	202	Kolev (2022)
Vit	209	nd	108	135	177	189	Current study
Dryanovska	20	70	101	133	152		Marinov (1986)
Vit	32	71	120	127			Marinov (1986)
Archar	20	43	100	117			Marinov (1986)
Dryanovska	32	48	86	109	142		Marinov (1986)
Lom	15	42	86				Marinov (1986)
Osam	25	42	86				Marinov (1986)

Note: *TL_n* are total length of fish in *n* age; nd – no data.

Table 5. Mean calculated *SL* of Romanian barbel of the same age from the Vit (this study) and Ogosta rivers (Kolev 2022).

River	<i>n</i>	<i>SL</i> , mm					Source
		<i>SL</i> ₁	<i>SL</i> ₂	<i>SL</i> ₃	<i>SL</i> ₄	<i>SL</i> ₅	
Vit	209	65	87	111	138	166	Current study
Ogosta	100	38	62	90	119	149	Kolev (2022)

Table 6. Condition coefficients.

River	Condition coefficients		Source
	<i>K_f</i>	<i>K_b</i>	
Vit	1.30	1.97	Current study
Ogosta	1.40	1.75	Kolev (2022)

Note: Coefficient of Fulton *K_f* (*n* = 3) and *K_b* (*n* = *b*).

Ogosta River (Table 6). It is worth noting that the exponent in equation (4), which is typically denoted as *n*, is rarely equal to 3. This is why some authors (Zhivkov 1981, 1999; Raikova-Petrova and Zhivkov 1993) suggest replacing the constant *c* with the coefficient *b*. On the basis of our findings, the claim that the condition factor of the fish in the Vit River is greater can be

deemed to be more reliable. This is further supported by the comparison of *W* values at the same length, as shown in Table 7, where fish from the Vit River had higher weight values.

Discussion

The age distribution of the barbel population in the Vit River in Bulgaria spans from 1 to 5 years, with a higher prevalence of individuals aged three and four years. The absence of zero and one-year-old fish suggests selectivity of the catch with a sport fishing rod, while the absence of six-year-old fish and older is likely due to natural and fishing mortality.

The growth rate of Romanian barbel in

Table 7. Weight calculated using Length-Weight relationship at the same length.

River	Equation of the total population	Average weights (W_L) calculated at the same rounded lengths (SL , mm), g				Source
		W_{100}	W_{150}	W_{200}	W_{250}	
Vit	$W = 0.00003 \cdot SL^{2.823}$	13.7	43.2	97.5	183.4	Current study
Ogosta	$W = 0.00002 \cdot SL^{2.839}$	12.3	39.6	91.1	173.7	Kolev (2022)

Note: W_L is weight of the fish, rounded values of length (100 to 250 mm); W is weight, g; SL is standard length, mm.

Vit River was well represented by a linear model between SL and scale radius. The annual increment in length was relatively constant across age, after a highest value in yearling fish. The comparison indicated a notable increase in the SL of Vit River population across all age cohorts compared to other populations (only Ogosta River). The utilization of the calculated approach yields more precise outcomes and effectively represents the primary pattern in growth, but results in generally shorter (lower) calculated values compared to observed lengths.

Our results indicated that Romanian barbel from the Vit River had a faster growth in length, better weight gain, and better overall condition compared to that of Ogosta River. This disparity may be related to certain properties of the Ogosta River's water bed, which may have an impact on the fish species. The Ogosta River's middle section is partitioned by the Ogosta Dam, which is located in close proximity to Montana city. The lack of migration routes, the variable water flow, the cooler temperatures, and the faster waters in the middle section of the Ogosta River (Kolev 2022) likely have a significant impact on the living conditions of the Romanian barbel in that area.

Conclusions

The comparative analysis of the Romanian barbel populations of the Vit and Ogosta rivers revealed that the Romanian barbell of the Vit River exhibited superior overall demographic characteristics. The observed discrepancy could be ascribed to the unique characteristics of the water bed and the presence of obstacles that impede fish migration in the latter river. The results of this study emphasise the importance of simultaneously assessing both habitat parameters and indicators of fish condition in order to comprehensively evaluate the health and well-being of fish populations in various river systems.

Conflict of interest

The author declares no conflict of interest.

Data availability statement

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

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