SILVA BALCANICA

Forest Research Institute

Pre-print – Rositsa Kaneva
Cover design – Krsto Terziev
Kamelia Bisolnakova
Printing house – Marin Drinov
Academic Publishers

ISSN 1311-8706 (Print),
ISSN 2815-2549 (Online)

Silva Balcanica, 24(3)/2023

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Silva Balcanica Journal is included in CABI data base.
This issue is published with the financial support of National Science Fund – Ministry of Education, Youth and Science.

Silva Balcanica is an International Scientific Journal. Original and unpublished results of investigations of all aspects of forest ecosystems and landscapes of Balkan Peninsula, Central and Southern Europe will be published. Silva Balcanica is published by Forest Research Institute – Bulgarian Academy of Sciences (FRI-BAS). Scientific analysis of practical results as well as investigations in the forest sciences, including forest ecology; forest soil science; forest genetics, tree breeding and plantation forestry; biometry and sylviculture; forest economy and management; forest entomology and pathology; ecology and management of game fauna, urban forestry and green infrastructure, are accepted. Critical and constructive articles on scientific publications or events in the field of forestry and forest science are also welcome.

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SILVA BALCANICA

Silva Balcanica 24(3): 5-16 (2023)
doi: 10.3897/silvabalcanica.24.e114699

RESEARCH ARTICLE

Reforestation pipeline: case for quality management of NIR-region grading of Scots pine seeds and FLR-algorithm for information processing

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Academic editor: Georgi Georgiev | Received 24 October 2023 | Accepted 26 November 2023 | Published 28 December

Citation: Novikova T.P., Petrishche E.P., Novikov A.I. 2023. Reforestation pipeline: case for quality management of NIR-region grading of Scots pine seeds and FLR-algorithm for information processing. Silva Balcanica 24(3): 5-16. https://doi.org/10.3897/silvabalcanica.24.e114699

Funding: this study has been supported by the grants of the Russian Science Foundation, RSF 23-26-00228, https://rscf.ru/project/23-26-00228/.

Abstract

When controlling the process of improving the quality of seeds by separating on a spectrometric basis, the primary information about the state of Scots pine seeds is carried by the wavelengths of optical fluxes and their amplitudes. The algorithm for analyzing the required characteristics of small forest seeds in the infrared range is a corresponding sequence of logical terms that provide the ability to determine the specified seed parameters by a combination of spectral frequencies and light flux amplitudes taken from the corresponding photodetectors. At $\Delta C = 0.5$, the efficiency of the algorithm was 77.6 %, and at $\Delta C = 0.9$, respectively, 99.5 %. In this regard, the choice of ΔC is the result of a compromise between the cost of rejection of high-quality seeds and losses when using unrecognized low-quality seeds and it is made according to the results of relevant experiments.

Keywords

Forest landscape restoration; Scots pine, *Pinus sylvestris* L.; seed grading, NIR-region; fuzzy logic

Introduction

Bringing the Scots pine (*Pinus sylvestris* L.) seeds to the sowing condition – improvement of qualitative properties (Ivetic, Novikov, 2019; Afzal et al., 2020) in climatic projects (Andivia et al., 2021) of forest landscapes restoration (Novikova, 2022) – includes the grading task (Drapalyuk, Novikov, 2018; Kaliniewicz, Tylek, 2019), based on the optical features of the seed coat (Novikov et al., 2019; Bernardes et al., 2022). Scots pine (*P. sylvestris* L.) climatic types, as a rule, characterized by different spectrometric properties of seeds, demonstrate different mechanical qualities of wood (Rabko et al., 2021). Optical grading (Sokolov, Novikov, 2019) Scots pine (*P. sylvestris* L.) seeds to varying degrees affects the ontogenesis of juvenile crops on the field (Novikov et al., 2019; Petrishchev, 2021; Novikova et al., 2023a), container nursery (Nosnikau et al., 2020) and seed orchards (Dutkuner et al., 2008) can be the basis for seeds priming (Singh et al., 2020) during sowing (Kazakov et al., 2019) and part of a machine complex (Tsypouk et al., 2021) for reforestation. The optoelectronic (Sokolov et al., 2019) sensing elements that make up the core of the diagnostic system must have a certain accuracy in detecting (Novikov et al., 2021a) absorbed radiation, and must provide a timely signal to the mechatronic (Shafaei et al., 2020; Tylek et al., 2020) elements of the seed grader.

To solve this problem, an optoelectronic device was developed consisting of an optical emitter, photodetectors of reflected and transmission radiation, and an electronic information processing unit containing a microprocessor. To process the information received from photodetectors, fuzzy logic algorithms are implemented in the microprocessor, according to the results of which a control signal is generated, which enters the actuators of the calibration system. The actuators, in turn, form the appropriate trajectory of the seed movement, directing it to a given seed receiver.

Due to the fact that the carriers of the initial information about the quality of seeds are the wavelengths of optical streams and their amplitudes measured with certain errors, it is necessary to use fuzzy logic methods to synthesize an algorithm for processing such information. In this case, the algorithm for analyzing the characteristics of forest seeds will be a corresponding sequence of logical rules and terms described in detail below.

The aim of the study is to develop a fuzzy logic algorithm for grading Scots pine seeds, taking into account the intensity of absorption of optical radiation by the seed surface in the near infrared (NIR) region.

Materials and methods

The construction of the desired algorithm for information processing and quality management of grading Scots pine seeds in the infrared region was carried out by analogy with the VIS-grading algorithm (Novikov et al., 2021b), using the classical fuzzy logic sequence “Mamdani” (Tabakov et al., 2021; Mohammed, Hussain, 2021; Fayaz et al., 2019).

Firstly, the fuzzification of the membership function (MF) $\Xi_{P\alpha\beta}(z_\beta)$ from each (β = 1, 2, ..., ω) detectable variant of z_β (input signal from the photodetector of the grader system) was performed on the basis of (α = 1, 2, .., ψ) fuzzy production rules organized into sets $P_{\alpha\beta}$.

Secondly, aggregation of the set of production rules of the algorithm for information processing and quality management of grading Scots pine seeds in the infrared range was carried out with the setting in each (α = 1, 2, ..., ψ) rule for the statement "variant z_β belongs to the set of grading $P_{\alpha\beta}$" of the truth level of the antecedent pa from the condition of the minimum operation of the MF-conjunction $\Xi_{P\alpha\beta}(z_\beta)$:

$$p_\alpha = \min_{\substack{\alpha = 1,2,\dots,\psi \\ \beta = 1,2,\dots,\omega}} \begin{cases} \Xi_{P_{\alpha 1}}(z_1); \\ \Xi_{P_{\alpha 2}}(z_2); \\ \Xi_{P_{\alpha\beta}}(z_\beta); \\ \dots \\ \Xi_{P_{\alpha\omega}}(z_\omega). \end{cases}$$

Thirdly, the modification of the MF $\Xi_{Q\alpha}(q)$ of the output variant q (the signal of the control action on the elements of the mechatronic grader system) to the $\Xi_{Q'\alpha}(q)$ was made proceeding from the condition of the minimum operation of activating the consequent of (α = 1, 2, .., ψ) fuzzy production rules:

$$\Xi_{Q'_\alpha}(q) = \min_{\alpha = 1,2,\dots,\psi} \left[p_\alpha; \Xi_{Q_\alpha}(q)\right].$$

Fourthly, the accumulation of the activated set , the resulting MF was carried out using the maximum function that implements the operation of fuzzy disjunction for each (α = 1, 2, .., ψ) rule:

$$\Xi_\Sigma(q) = \max_{\alpha = 1,2,\dots,\psi} \begin{cases} \Xi_{Q'_1}(q); \\ \Xi_{Q'_2}(q); \\ \Xi_{Q'_\alpha}(q); \\ \dots \\ \Xi_{Q'_\psi}(q). \end{cases}$$

Fifthly, the defuzzification of the resulting set of to determine the output version of q (the signal of the control action on the elements of the mechatronic grader system) was implemented on the basis of the classical center of gravity method.

Results and discussion

Taking into account the above-mentioned inevitability of recording frequencies and amplitudes of optical flows with certain errors and, in accordance with this, the need to use fuzzy logic methods, we will consider the possibility of seed separation based on the above algorithm of fuzzy logic inference of Mamdani.

Let us consider the case of seed separation in the infrared region. The correspondence of the optical parameters of ordinary pine seeds to the characteristics of the optical beam is given in table 1 (in parentheses in the table are the designations of the output logical variables used in the implementation of the algorithm). For the possibility of implementing a formal logical construction of the algorithm, the tables additionally contain in parentheses the designations of the output logical variables used in the description of the algorithm: (C, C_1), when C is condition seeds, 1-V; C_1 is non condition seeds, 2-NVP and 3-NVE.

Table 1. Correspondence of seed parameters to the optical beam during separation in the NIR-region

Wavelength, nm	Radiation amplitude	Detection options
λ_1	A_0 % and more	Not Condition (C_1)
	less than A_0 %	Condition (C)
λ_2	A_0 % and more	Not Condition (C_1)
	less than A_0 %	Condition (C)
…		
λ_k	A_0 % and more	Not Condition (C_1)
	less than A_0 %	Condition (C)
λ_{k+1}	A_0 % and more	Condition (C)
	less than A_0 %	Not Condition (C_1)
…		
λ_{N+1}	A_0 % and more	Condition (C)
	less than A_0 %	Not Condition (C_1)
λ_N	A_0 % and more	Condition (C)
	less than A_0 %	Not Condition (C_1)

Let us consider the conclusion of the seed separation algorithm based on the qualitative composition. Due to the fact that in real operating conditions, variables λ, A can be determined only with a certain error: $\Delta\lambda = \pm\varepsilon$ nm, $\Delta A = \pm\rho$ %, to describe them, it is necessary to involve the apparatus of fuzzy logic.

In this case, all the logical variables listed in table 1 can be described, based on their physical meaning , by the MF presented in Figs 1–5. Here , in order to avoid complicating calculations, it is advisable to use “triangular” functions (Fig. 1):

$$\mu(\lambda_i) = \begin{cases} 0, if\ \lambda < \mathrm{a}_i, \\ \dfrac{\lambda - \mathrm{a}_i}{\lambda_i - \mathrm{a}_i}, if\ \ \mathrm{a}_i < \lambda \le \lambda_i, \lambda_i = \mathrm{a}_i + \varepsilon = b_i - \varepsilon \\ \dfrac{b_i - \lambda}{b_i - \lambda_{i+1}}, if\ \ \lambda_i < \lambda \le b_i, \\ 0, if \lambda > b_i \end{cases}$$

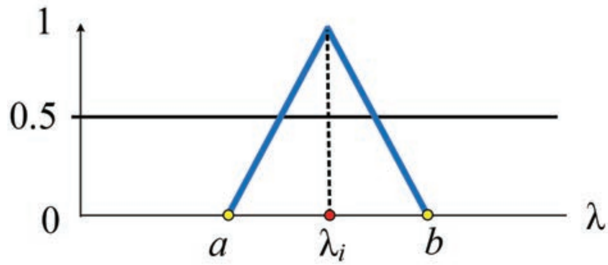

Figure 1. Triangular MF

or "Gaussian" functions with a large spread of parameters of the optoelectronic separating device (Fig. 2):

$$\mu(\lambda_i) = \ \exp\left[-\frac{(x-a)^2}{2b^2}\right];$$
$$3b_i = \varepsilon, a_i = \lambda_i.$$

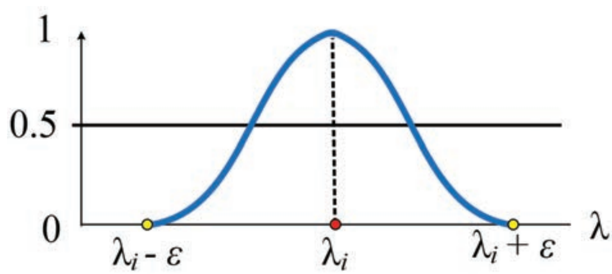

Figure 2. Gaussian MF

To describe the membership functions that characterize the process of seed detection in the infrared range for the 1....k-th wavelength (table 1), based on its physical meaning, you can use the "threshold" functions of the form (Fig. 3):

$$\mu(A, A_0) = \begin{cases} 0, if\ A \leq \mathrm{a}_0 \\ \dfrac{A - \mathrm{a}_0}{A_0 - \mathrm{a}_0}, if\ \ \mathrm{a}_0 < A \leq A_0, A_0 = \mathrm{a}_0 + \rho \\ \\ 1, if A > A_0 \end{cases}$$

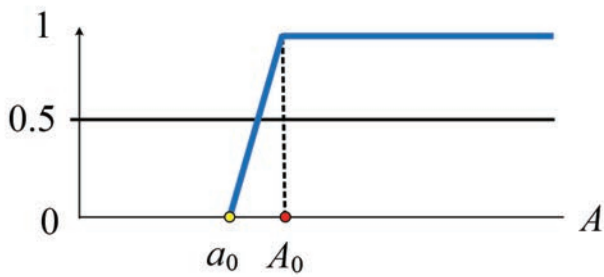

Figure 3. Threshold MF

Otherwise, one may apply those with a large spread of the parameters of the diagnostic system of the separating device, "more blurred" functions of the form (Fig. 4):

$$(A, A_0) = \begin{cases} 0, if\ A \leq A_0 \\ \left(1 + \left(\dfrac{A - A_0}{0.1A_0}\right)^{-2}\right)^{-1}, if\ \ A_0 < A \leq 100 \end{cases}$$

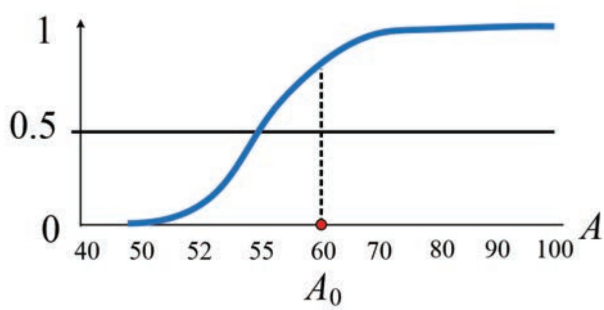

Figure 4. "Blurred" threshold MF (A_0=60)

$$\mu(A, A_0) = \begin{cases} 1, if\ A \leq A_0 \\ \dfrac{\mathrm{a}_0 - A}{\mathrm{a}_0 - A_0}, if\ \ A_0 < A \leq a_0, A_0 = \mathrm{a}_0 - \rho \\ \\ 0, if A > a_0 \end{cases}$$

Accordingly, to describe the membership functions that characterize the detection process for the (k+1) ... N-th wavelength (table 1), you can use "inverse threshold" functions of the form (Fig. 5):

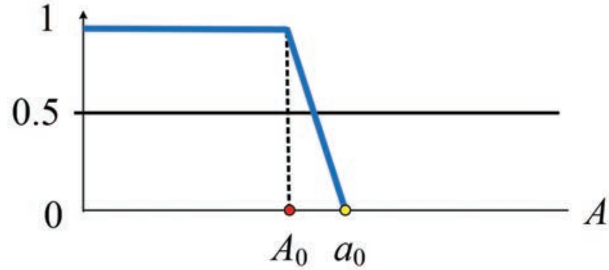

Figure 5. Inverse MF

In a different way, one may use them with a large variation in the parameters of the diagnostic system of the separating device:

$$\mu(A, A_0) = \begin{cases} 1, if\ A \le A_0 \\ \left(1 - \left(1 + \dfrac{A - A_0}{0.1A_0}\right)^{-2}\right)^{-1}, if\ \ A_0 < A \le 100 \end{cases}$$

Setting the MF-functions of all variables allows you to go directly to the construction of the separation algorithm in the infrared wavelength range (according to the qualitative composition). To do this, we use the structure of logical inference further according to the Mamdani scheme (Mamdani, 1974). When executing the Mamdani fuzzy inference algorithm, the base of production rules is generally represented by a multi-in, single-out (MISO) structure, which generally looks like (Mohammed, Hussain, 2021):

Rule *1*: IF x_1 is A_{11} AND x_2 is A_{12} AND..AND x_n is A_{1n}, THEN y is B_1;
Rule *2*: IF x_1 is A_{21} AND x_2 is A_{22} AND..AND x_n is A_{2n}, THEN y is B_2;
…
Rule *i*: IF x_1 is A_{i1} AND x_2 is A_{i2} AND.. AND x_n is A_{in}, THEN y is B_i;
…
Rule *m*: IF x_1 is A_{ml} AND x_2 is A_{m2} AND.. AND x_m is A_{mn}, THEN y is B_m,

when x_1, x_2,.., x_n are n input variables of a Fuzzy Production System (FPS); A_{ij} is the ij-th term of the j-th input variable xj in the i-th rule, represented by a fuzzy set with the corresponding membership function $\mu_{Aij}(x_j)$(i = 1,2, ..,m; j = 1,2,..,n); y is an output variable of FPS; B_i is the term of the output variable y in the i-th rule, represented by a fuzzy set with the corresponding membership function $\mu_{Bi}(y)$ (i = 1,2,..,m).

The first stage of the Mamdani algorithm was implemented above in the synthesis of the FP of logical variables (Figs 1-5). Based on the analysis of the states of the output variable C (C_1) shown in table 1, the implementation of steps 2-4 (see M&M Sections) leads to the construction of the following fuzzy logic analyzing algorithm, the block diagram of which is shown in Fig. 6:4

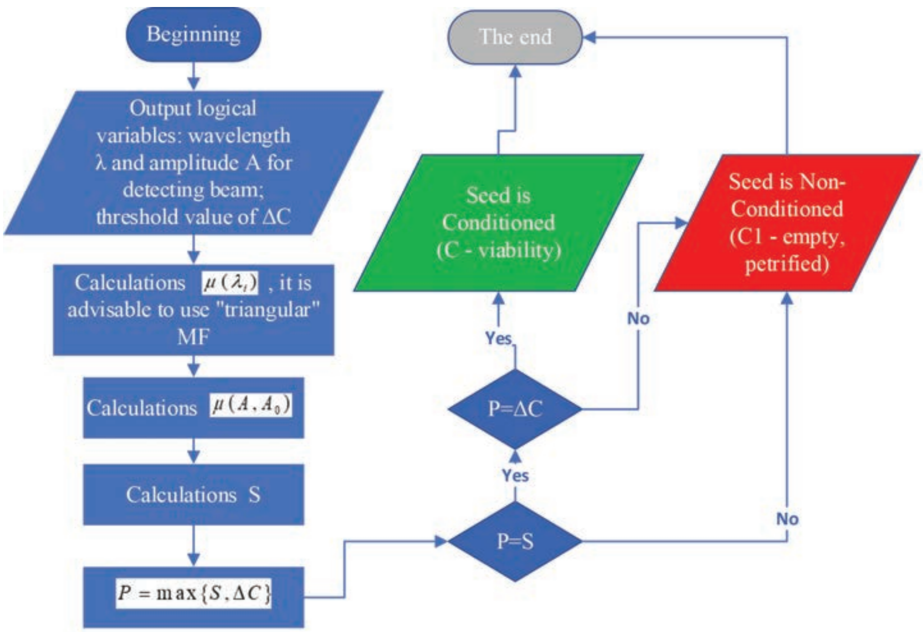

Figure 6. Block diagram of the analyzing algorithm for quality control of the separation of Scots pine seeds in the infrared wavelength region

$$IF\ (\mu(\lambda_1) \cap \mu(A, A_0)) \cap (\mu(\lambda_2) \cap \mu(A, A_0)) \cap \ldots \cap (\mu(\lambda_k) \cap \mu(A, A_0)) \cap (\mu(\lambda_{k+1}) \cap \bar{\mu}(A, A_0)) \cap$$
$$\cap \ldots \cap (\bar{\mu}(\lambda_{N-1}) \cap \mu(A, A_0)) \cap (\mu(\lambda_N) \cap \bar{\mu}(A, A_0)), THEN\ \boldsymbol{S}. \tag{1}$$

Here, when implementing the operation of a fuzzy-logical conjunction, for which there are currently several definitions, the Mamdani (Zade) variant is used:

$$\mu(\lambda_i) \cap \mu(A, A_0) = min\{\mu(\lambda_i) \cap \mu(A, A_0)\}. \tag{2}$$

After calculating the algorithm (1) using the operation (2), the value of the variable *S* is calculated, which is then defuzzified by the right modal value together with the specified threshold value of ΔC:

$$\mu(\lambda_i) \cap \mu(A, A_0) = min\{\mu(\lambda_i) \cap \mu(A, A_0)\}.$$

According to the results of defuzzification, at P = S, a decision is made on the state C_1 – "Not Conditioned", at P = ΔC, respectively, C – "Conditioned". A numerical simulation of the algorithm (1), confirming its computational efficiency, is given below.

The peculiarity of this algorithm, as shown by the results of the numerical experiment, is the dependence of its efficiency on the selected threshold ΔC:

– at low values (about 0.5), the proportion of unrecognized low-quality seeds increases;

– at values close to 1, the efficiency is reduced due to the rejection of high-quality seeds because of errors in determining the wavelength of the received radiation and the amplitude of the light.

The evaluation of the grading algorithm (see Fig. 6) efficiency included in the reforestation algorithm (Novikova, 2022a, 2022b) is considered by the example of the analysis of the Scots pine (*P. sylvestris* L.) seeds, the spectral study results of which are shown in table 2.

Table 2. Detection options for the separation of Scots pine seeds by the spectrometric feature in the infrared wavelength region

Wavelength, nm	Radiation amplitude	Detection options
970	60 % and more	Not Condition (C_1)
	less than 60 %	Condition (C)
1196	60 % and more	Not Condition (C_1)
	less than 60 %	Condition (C)
1390	60 % and more	Condition (C)
	less than 60 %	Not Condition (C_1)
1878	60 % and more	Condition (C)
	less than 60 %	Not Condition (C_1)

The results of the experiments conducted on seed samples (n = 1000) showed that the efficiency of the separation of Scots pine seeds in the infrared range using the developed algorithm significantly depends on the selected threshold value of the ΔC output variable.

Conclusion

A stochastic model for controlling the grading process of Scots pine (*P. sylvestris* L.) seeds in the infrared wavelength range, taking into account the probabilistic deviations of random values of wavelengths and the amplitude of the optical flow, is the basis for the synthesis of the analyzing algorithm.

So, at ΔC = 0.5, the efficiency of the algorithm was 77.6%, and at ΔC = 0.9, respectively, 99.5 %. In this regard, the choice of ΔC is the result of a compromise between the cost of rejection of high-quality seeds and losses when using unrecognized low-quality seeds and it is made according to the results of the appropriate experiments.

Let us note that these results of the algorithm implementation are valid within the boundaries of seeds from this location. The universalization of the NIR classification algorithm for the Scots pine (*P. sylvestris* L.) seeds for any provenance and its practical use will occur as a result of the accumulation of a sufficiently large amount of data (Novikova et al., 2023b) on the seeds spectrometric features.

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SILVA BALCANICA

Silva Balcanica 24(3): 17-26 (2023)
doi: 10.3897/silvabalcanica.24.e116284

RESEARCH ARTICLE

Health status of the field protective forest belts in Dobrudzha – results from the monitoring carried out in 2022

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Academic editor: Alexander Delkov | Received 25 November 2023 | Accepted 30 November 2023 | Published 28 December

Citation: Dodev Y., Georgiev G., Georgieva M., Ivanov V., Belilov S., Madzhov S., Georgieva L. 2023. Health status of the field protective forest belts in Dobrudzha – results from the monitoring carried out in 2022. Silva Balcanica 24(3): 17-26. https://doi.org/10.3897/silvabalcanica.24.e116284

Abstract

In 2022, the health status of the field protective forest belts on the territory of the State Hunting Enterprise Balchik and State Forest Enterprises General Toshevo and Dobrich was monitored. The assessment of tree crown condition covered 7069.3 ha (66% of all field protective belts in Bulgaria). The results showed that 70% of monitored belts were in good condition, 23% - in moderate condition, and 7% - in poor condition. Since 2014 the area of the protective forest belts in poor condition has increased 2.6 times, and 76% of them were situated in Dobrudzha region. Ash belts – *Fraxinus excelsior* (66% of all belts) and *Fraxinus americana* (10%) were in the worst conditon. In ash belts a process of crown dieback, premature falling of leaves and drying of whole trees were observed. In individual ash belts, drying reached up to 80% of tree crowns, regardless of their age and origin. The drying was mostly due to the biotic factors – insect pests and fungal pathogens. The protective forest belts of *Quercus cerris, Q. petraea, Q., rubra and Gleditschia triacanthos* stand out as sustainable tree species. It is necessary to significantly upgrade the methodology by which the monitoring of the health status of trees in the field protective forest belts is currently carried out. In the new methodology a detailed description of the type of data that need to be collected, the methods of assessments, and data reporting formats, have to be included.

Keywords
Protective forest belts, forest management, monitoring of health status, deterioration of ash belts, Dobrudzha

Introduction

In the Dobrudzha region field protective forest belts (FPFBs) were created in the 1950s to protect agricultural areas from wind erosion, to improve the soil moisture storage, and to increase the agricultural crop yields (Marinov et al., 2003; Vassilev et al., 2019). The major goal of the protective forest management is to ensure efficient and effective protective functions of the belts over a long period (Brang et al., 2006). Since their creation, the management practices of forest belts in the Dobrudzha region have been associated with some threats – a lack of experience and expertise, steppe growth conditions, decline of health status of several tree species, security problems, regulatory weaknesses, etc. (Dodev et al., 2023a,b).

The field protective forest belts were created as reclamation facilities (Georgiev, 1960). To fulfil their main purpose, the planted trees in the belts have to be in good physiological and healthy condition, and to have a blown construction (Pamfilov, 1936; Byallovich, 1939; Matyakin, 1948). However, in the last decades, the protective forest belts in Bulgaria have declined due to various reasons. In 2002, a large number of the FPFBs deteriorated in their condition. The application of differentiated approaches for their management according to their condition was proposed (Marinov et al., 2003).

The appropriate health status of the forest belts is the prerequisite for carrying out their protective functions efficiently. Tree deterioration is one of the most important indicators that function as a notification system to maintain forest sustainability (Fuller, Quine, 2016). Since 2020, a serious deterioration of the health status of ash (*Fraxinus* spp.) forest belts has been observed in the Dobrudzha region (Mateva, Kirilova, 2021). The largest affected areas were located on the territory of the State Hunting Enterprise (SHE) Balchik and State Forest Enterprises (SFEs) General Toshevo and Dobrich (Mateva, Kirilova, 2022).

The field protective forest belts planted with *Robinia pseudoacacia* L. gradually degraded due to the repeated clear-cuttings for shoot regeneration (Dodev et al., 2023a). Severe dying of *Ulmus minor* Mill. trees, caused by Dutch elm disease (*Ohiostoma novo-ulmi*) was detected. Dodev et al. (2023a) pointed out some mistakes in the management of the *Gleditschia triacanthos* L. protective forest belts and the need for new afforestations because of the belts' deterioration.

In 2014, the Executive Forest Agency (EFA) at the Ministry of Agriculture, Food and Forests issued executive Guidelines for the management of FPFBs. According to them, the forest belts have to be monitored annually to determine the health condition and suitability for carrying out protecting functions efficiently. The purpose of this study was to analyse the results of the monitoring carried out in 2022 on the health status of the field protective forest belts from different tree species in the SHE Balchik, SFEs General Toshevo and Dobrich.

Objects and methods

This study summarises and analyses the results of the monitoring of health status conducted at the end of May 2022 in the FPFBs on the territory of SHE Balchik, SFEs General Toshevo and Dobrich. The monitored area covered 7069.3 ha (SHE Balchik – 2694.9 ha; SFE General Toshevo – 2783.8 ha; and SFE Dobrich – 1590.6 ha), which was over 66% of all FPFBs in Bulgaria.

The monitoring included a visual assessment by local foresters applying the EFA Guidelines (2014) for management of FPFBs. According to their health status, the belts were differentiated into three categories, as follows:

- good health status – the scheme of forest belts was the same as when they were created; there were no symptoms indicating deterioration (dieback in crowns, frost cracks, cankers on the stems, etc.), the degree of defoliation was up to 25%; the belts fulfilled their purpose.
- moderate health status – crown dieback was up to 30%, the degree of defoliation was up to 60%, occurrence of frost crakes and canker formations; belts had a partially impaired functionality.
- poor health status – as a result of maturity, fires, abiotic, biotic, and other factors, the main species was missing or was up to 50% in tree composition; the degree of defoliation was over 60%, dieback was over 30%; the belt was not fulfilling its functionality.

The monitoring results for the three State Enterprises were kindly provided by the EFA in MS Excel documents. The belts were allocated according to the main tree species' health status, the degree of damage, etc. The comparison of the area of FPFBs in poor health was analysed on the basis of the forest plans in 2014 (SFE General Toshevo and Dobrich) and 2015 (SHE Balchik), and the monitoring implemented in 2022.

Results and discussion

In 2022, the total area of the field protective forest belts in poor health in Bulgaria was 645.2 ha. Over 70% of them were located in the SHE Balchik, and in the SFEs General Toshevo and Dobrich. The largest area of the most deteriorated belts was distributed in SFE Dobrich; 34% of all belts in the country had a poor health status. In the other two monitored enterprises, this area was about 137 ha, or approximately 21% of all belts in the country. The highest percentage (85%) of belts in good health was distributed in the SHE Balchik.

The monitored FPFBs in the SHE Balchik and SFEs General Toshevo and Dobrich were allocated according to the assessment of their health status in 2022 (Table 1). The data showed that the predominant proportion (58-85%) of the belts were in good health, and only 5-14% showed poor health status.

Table 1. Allocation of the field protective forest belts according to their health status (2022)

State Forest/Hunting Enterprise	Good		Moderate		Poor		Total
	ha	(%)	ha	(%)	ha	(%)	ha
Balchik	2291.7	(85)	266.7	(10)	136.5	(5)	2694.9
General Toshevo	1736.2	(62)	910.1	(33)	137.5	(5)	2783.8
Dobrich	929.1	(58)	442.6	(28)	218.9	(14)	1590.6
Total (Average %)	4957.0	(70)	1619.4	(23)	492.9	(7)	7069.3

In recent years, a tendency for deterioration of the health status in the FPFBs in Dobrudzha has been obvious and the degradation processes have proceeded relatively quickly. Since 2014-2015, the area of the belts in poor condition increased from 186.2 to 492.9 ha (Fig. 1). The strongest deterioration was registered in the SFE Dobrich – from 15.2 ha (2014) to 218.9 ha (2022). Decline of trees, dieback in crowns and premature leaf drop prior to autumn were noticed.

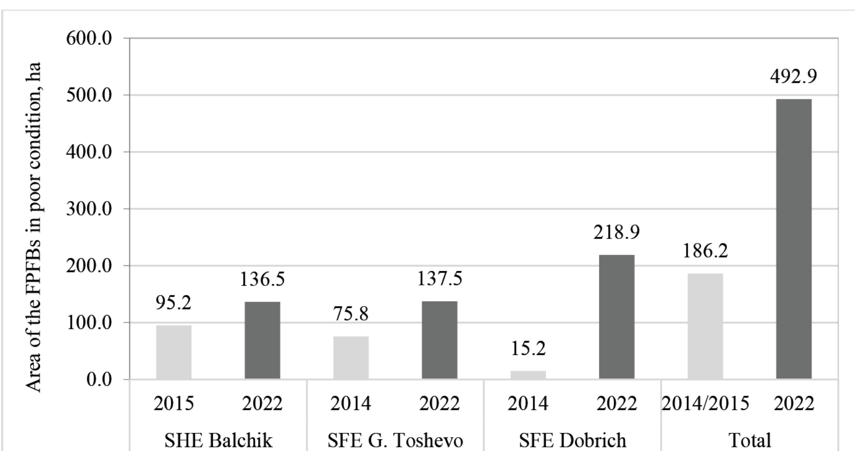

Figure 1. Area (ha) of the field protective forest belts in poor health status for the period 2014-2022

The allocation of the area of the FPFBs in the worst health status according to the main tree species in the three monitored State Enterprises, showed that the degradation processes most strongly affected the ash forest belts (*Fraxinus excelsior* L., *F.*

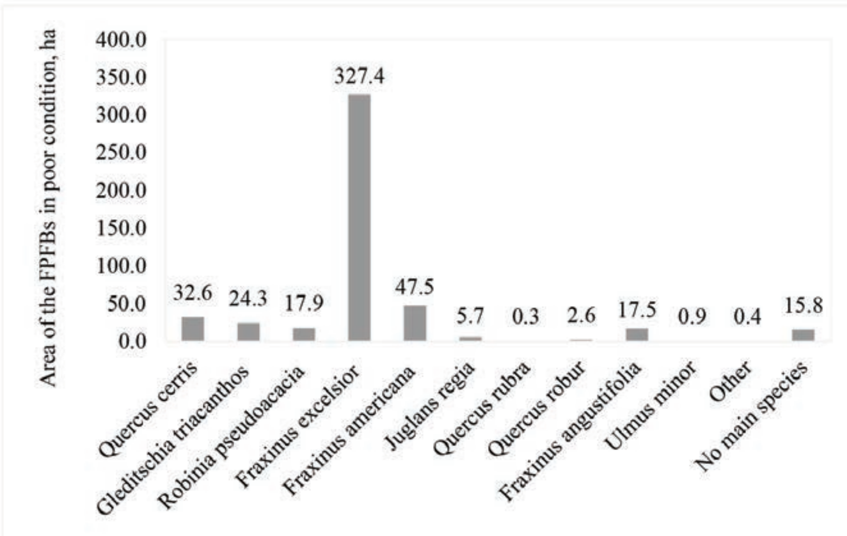

Figure 2. Allocation of the area of the FPFBs in poor condition by main tree species

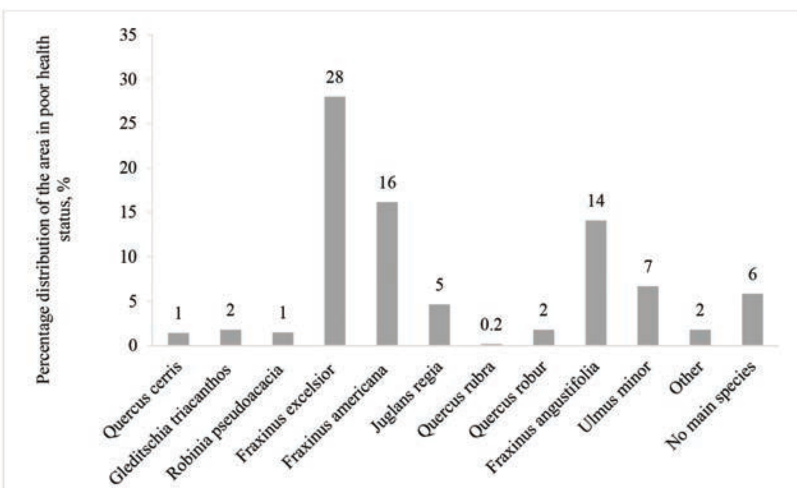

Figure 3. Relative share of FPFB in poor condition for different tree species compared to their total area

americana L., and *F. angustifolia* Vahl.) with an area of 375.8 ha that was more than 76% of all belts in poor condition in the studied region (Fig. 2).

The area of the belts in poor health status was greatest in *F. excelsior* (66.4%), followed by *F. americana* (9.6%). In *F. angustifolia*, this area of declined belts was negligible (less than 0.2%). In *F. excelsior* and *F. americana* the processes of dieback, premature leaf fall and drying of whole trees were found.

The strongest deterioration of the health status was reported for *F. excelsior* (28% of the FPFB were in poor condition), followed by *F. americana* (16%) and *Ulmus minor* Mill. (14%) (Fig. 3). Less affected were the belts of *F. angustifolia* (7%), *Juglans regia* L. (5%), as well as those in which the main tree species were not present or had a reduced participation (6%). The most resistant tree species were *Quercus cerris* L., *Q. robur* L., *Q. rubra* L. and *Gleiditschia triacanthos* L., where the proportion of belts in poor condition was below 2% (Fig. 3).

The results of the monitoring showed that the belts plated with *Robinia pseudoacacia* L. were in good health status. Dodev et al. (2023), however, point out that after the second shoot rotation, the height, vitality and stability of the *R. pseudoacacia* belts greatly decrease, which practically makes them unfit to fulfil their main purpose.

The most damaged were the ash forest belts on the territory of the SFE Dobrich that were more than 60% of all studied ash belts. In SHE Balchik and SFE General Toshevo, their percentage was lower – 15% and 13%, respectively, but there was a tendency for intensive deterioration of their health condition. In 2021, six totally dry ash belts were cut in SHE Balchik. Logging was also expected in many other belts in poor condition.

The distribution of the area of FPFB *F. excelsior* according to their age (for their total number and for those in poor health), showed that the two curves completely overlap, as all age groups were equally affected (Fig. 4). There was no difference in the health status between the belts with seed and shoot origin. This indicated that ash drying was likely due to a combination of predisposing stress factors and opportunistic biotic factors (insect pests or fungal pathogens).

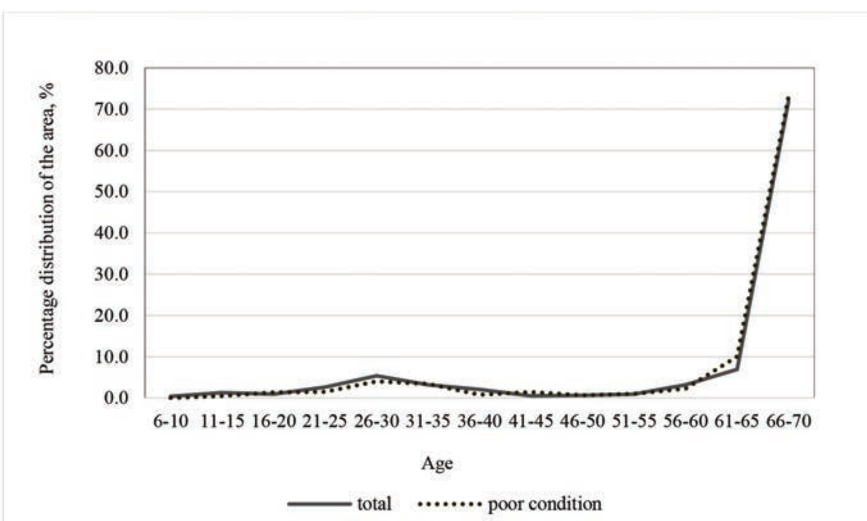

Figure 4. Age distribution of the area of the *Fraxinus excelsior* FPFBs (total number and in poor condition)

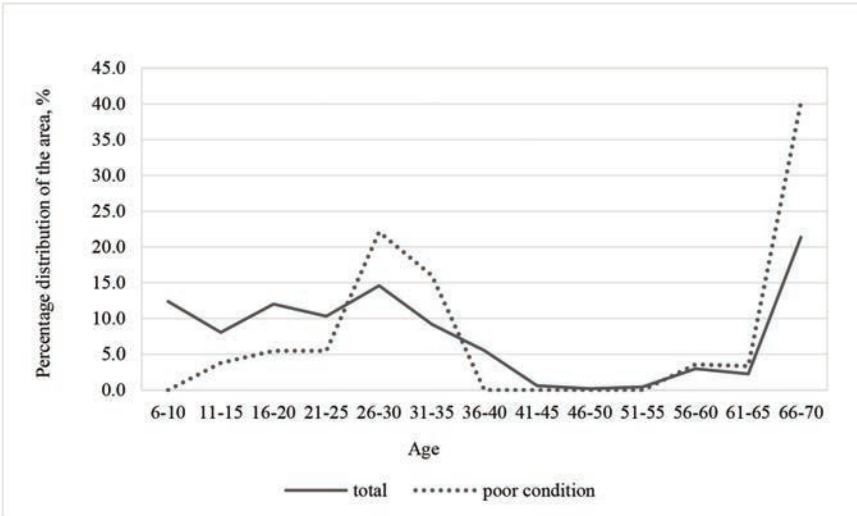

Figure 5. Age distribution of the area of the *Fraxinus americana* FPFBs (total number and in poor condition)

The situation was similar for *F. americana*, where the degree of damage increased with increasing age (Fig. 5). An explanation for this could be the fact that this introduced tree species was not suitable for the ecological conditions in Dobrudzha and with increasing age it weakened physiologically to a greater extent.

Currently, *Fraxinus angustifolia* showed a higher resistance to both environmental conditions and biological factors as pests and diseases. Its health deterioration was much lower than *F. excelsior* and *F. americana*. The results from the monitoring in 2022 revealed that only 0.9 ha of *F. angustifolia* forest belts were in poor health status (Fig. 2).

Deterioration of the health status of ash trees was also observed earlier in northeastern Bulgaria. Rosnev and Petkov (1994) reported that until 1985-1987 the ash forest plantations were in a good health condition, but in 1987-1990 a process of continuous and increasing drying of individual branches and trees began. In the region of the SFEs Novi Pazar and Dobrich, the drying rate in one year (1988-1989) increased from 24% to 37%, which was a critical moment for their forest management. Fungal pathogens *Cytophoma pulchelia* (Sace) Guthn., *Endoxilina astroideae* Fr., *Daldinia* sp. and *Citospora* sp., which causes necrosis on the trees' stems and branches, were established. Currently, a potential threat to ash trees has been the fungal pathogen *Chalara fraxinea* Kowalski, which was established in many European countries, including in Romania (Drenkhan, Hanso, 2010).

Diseases and pests were observed not only on ash trees, but also on other tree species in the FPFB. Masse dying of *Ulmus minor* forest belts due to Dutch elm disease (*Ophiostoma novo-ulmi* Brasier), was observed in the Dobrudzha region. The most dangerous insect pest in oak forests, *Lymantria dispar* (L.) (Lepidoptera: Erebidae), periodically causes complete defoliation of *Quercus cerris* L. forest belts (Zlatanov, 1970). It should be noted, however, that there has been a lack of modern targeted and in depth studies on the health status of FPFBs and the specific abiotic and biotic factors causing the drying of trees in them.

The presence of a system of wind generators for the production of electricity in some regions of northeastern Bulgaria (Balchik, Kavarna, Shabla, etc.) makes it difficult to apply traditional methods of control the main insect pests in the FPFBs by using aviation equipment. In this regard, it is necessary to expand the participation of established biological methods in the future development of integrated control systems. In 2021, the species-specific entomopathogenic fungus *Entomophaga maimaiga* Humber, Shimazu et Soper (Entomophthorales: Entomophthoraceae) was used to control the gypsy moth (*Lymantria dispar*) population in the FPFB in the Balchik region (Georgiev et al., 2021, 2023).

It is also possible to use remote-sensing methods to assess the health status of FPFB through spectral analysis of drone or satellite images, which have been successfully applied to analys es of green settlement systems (Dimitrov et al., 2018), natural forest stands (Dimitrov et al., 2019; Belilov et al., 2022; Georgiev et al., 2022a,b) and forest plantations (Georgieva et al., 2022).

Conclusions

The deterioration of the health status of the field protective forest belts in the Dobrudzha region has developed with high intensity on large areas. The forest protective belts of ash (*Fraxinus* spp.) and *Ulmus minor* were in the worst health status. These belts should be gradually regenerated by planning reforestation activities. In the FPFBs with moderate health status, preventive work should be done to improve and maintain their condition and functions. For this purpose, it is necessary to develop a comprehensive methodology for a complex assessment of the state of the FPFBs.

It is necessary to significantly upgrade the methods by which the monitoring of the health status of trees in the field protective forest belts is currently carried out. In the new methodology a detailed description of the type of data that need to be collected, the methods of assessments, and data reporting formats, have to be included. In addition to the health status of the FPFBs, it is necessary to evaluate in detail their essential structural-functional characteristics that determine the capacity of the belts fulfil their main purpose. The new methodology should be implemented in practice and used to conduct the annual monitoring of the FPFBs and to prepare analytical reports on their condition, and plan the necessary forestry activities in them.

Acknowledgments

The present study was carried out in connection with the implementation of the project 'Deterioration of the health status of field protection forest belts in North-Eastern Bulgaria and opportunities for improvement and reconstruction', financed by the National Fund of Science (Contract No. KP-06-H66/9 of 13.12.2022).

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SILVA BALCANICA

Silva Balcanica 24(3): 27-33 (2023)
doi: 10.3897/silvabalcanica.24.e116223

RESEARCH ARTICLE

Soil erosion rates based on anatomical changes in exposed roots – case study from southwest Bulgaria

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Academic editor: Miglena Zhiyanski | Received 24 November 2023 | Accepted 9 December 2023 | Published 28 December

Citation: Pavlova-Traykova E., Dimitrov D. 2023. Soil erosion rates based on anatomical changes in exposed roots – case study from southwest Bulgaria. Silva Balcanica 24(3): 27-33. https://doi.org/10.3897/silvabalcanica.24.e116223

Abstract

In recent years different methods for soil erosion assessment have been used. Because of its high accuracy in estimations, dendrogeomorphology was selected as one suitable and reliable scientific method to achieve the main goals of this study.

The main goal of the study is to date denudation events using anatomical responses of the tree-rings of the roots. We analyze the histological changes that occur in the roots of two tree species, along the river banks of the Sedelska River, which is a tributary of Struma River.

The significant differences between homogenous groups of measurements in pre-exposed and exposed roots was established, and it shows a remarkable response of roots to sheet erosion.

Keywords

Soil erosion, dendrogeomorphology, Sedelska river

Introduction

Water erosion is a worldwide problem, which depends on many factors, but mainly on rain events and their intensity and frequency (Nicolau et al., 2022). In Bulgaria, with every passing year, in consequence of the tangible climate changes, natural hazards such as soil erosion and floods have become more and more frequent and increasingly damaging. In our country the largest number of floods occurred during the period 2005-2007 (Lubenov et al., 2009) with horrible consequences. In the following years floods affected urban areas again with a dramatic increase in runoff (Marinov et al., 2023). Recent floods affected not only lands close to the rivers but urban territories as well, which were covered with tons of sediment like in Karlovo in 2022 and the sea side in 2023. All these natural hazards caused significant infrastructural damages and also human casualties.

For better understanding, management and in an attempt to control those processes many models for assessment the risk was used. "Methodology for preparing the national long-term programme for protecting from erosion and flooding in the forest lands" (Marinov et. al. 2009) is well applied in Bulgaria for potential and actual risk of soil erosion in forest territories. For the estimation of the amount of solid runoff EPM method (Gavrilovic, 1988), IntEro (Spalevic, 2019) and USLE (Wischmeier, Smith, 1978) are used.

In recent years dendrogeomorphology has been accepted as another suitable method for erosion study. Tree rings are an excellent and frequently overlooked data source for reconstruction of chronologies of geological events (Butler, 1987). Dendrogeomorphology was successfully used for analysis of floods, debris flow and erosion processes (Silhan et al., 2016).

The article presents the results of the studies on soil erosion processes at the territory of Sedelska river by applied dendrogeomorphology in the gully side of the river.

Materials and methods

Exposed tree roots from two tree species (*Pinus nigra* Arn. and *Pinus sylvestris* L.), growing on the gully sides were used as samples during 2022-2023 (Fig. 1). We used the approach for dating of individual erosion events likely caused by some triggering hydrometeorological event. A saw was used to cut two centimeters wide cross-sections (root discs) from the exposed roots. The position of each sample was carefully recorded and the distance from soil measured.

The root discs were dried and the surface was subsequently sanded and polished. Tree-rings were measured using digital equipment for dendrochronological analysis LINTAB 5 (Fig. 2) and TSAP Win software (Rinn, 2005), with measurement accuracy of ± 0,01 mm.

Tree-rings of two radii of each root cross section were dated and measured in direction from the bark to the pit of the discs (Stokes, Smiley 1968). One chronology was built for the normal wood, used as reference chronology (R ref) and one chronology was built for the area with reaction wood (R react), formed after root exposure (Fig. 3). Cross dating technique between measured tree rings chronologies from reference radius (R ref) and reaction radius (R react) from the same root cross section was used to define the exact year of root exposure.

The erosion rate (Er) for the position of each root was calculated as follows: ER = DR /AE, where DR is the perpendicular distance of the root sample from the soil surface, and AE is the number of years since the root exposure.

Figure 1. Morphology of eroded trees

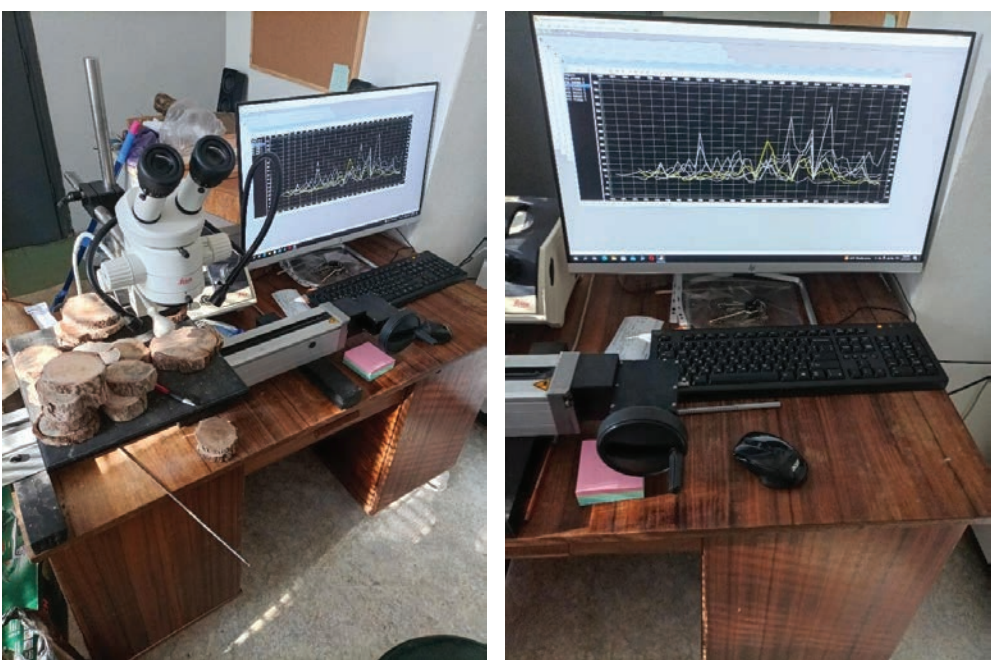

Figure 2. LINTAB 5 tree-ring measurement equipment

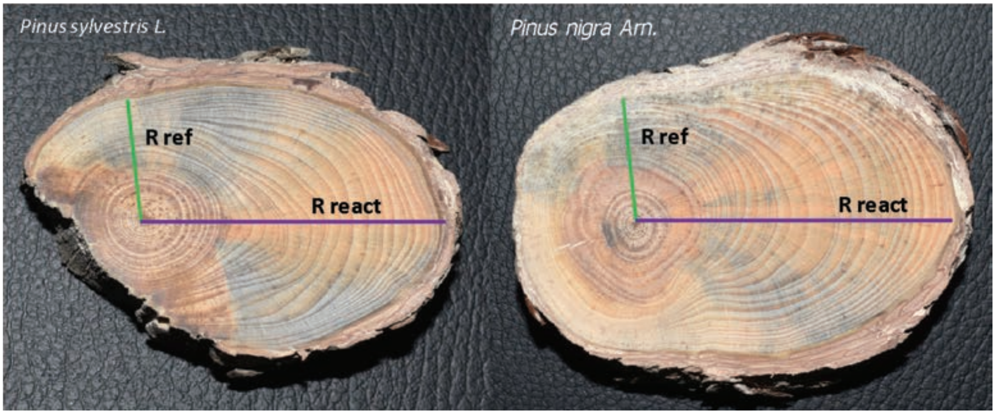

Figure. 3. Cross sections from exposed roots ready to be measured. Explanation notes: in green color (R ref) – reference tree-rings radius; in purple color (R react) – reaction wood tree-rings radius

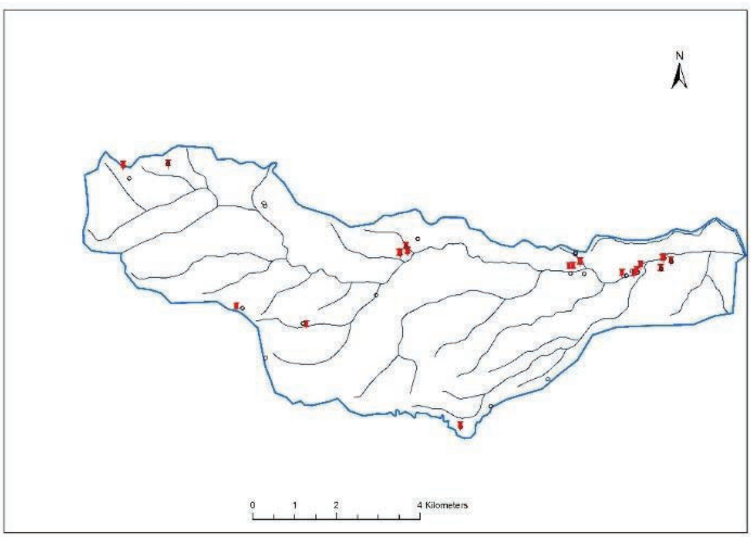

Figure 4. Watershed of Sedelska River with location of experimental trees

Results and discussion

The study area is situated in southwest Bulgaria on the watershed of Sedelska river (Fig. 4). The watershed of the river is situated on the territory of one of the most affected by soil erosion regions in Bulgaria – Regional forestry directorate Blagoevgrad (Marinov,Bardarov, 2005, Blinkov et al., 2013).

The total area of the watershed is 50,2km^2, from this area 42,81km^2 are forest territories (Pavlova-Traykova, 2022). The watershed is characterized by steep slopes, the average slope being 20°. The soils are mainly cinnamon forest soils, but, to a lesser extent, brown forest soils are also found (Petrova et al., 2023).

Dendrogeomorphic studies usually use anatomical analysis of conifers because of a clearly visible reaction to the exposure (Lopes et al., 2011; Silhan et al., 2016). In this research 30 trees were cored for dendrogeomorphological analysis. Coniferous tree species (*Pinus nigra* Arn. and *Pinus sylvestris* L.) and broadleaves tree species (*Platanus orientalis* L. and *Quercus frainetto* Ten.) were observed. For them the results for eight coniferous trees are chosen as representative and are presented in the research.

From the observed results it was established that all representative samples from Black pine were exposed in 1999, and those from Scotch pine – in 1993 (Fig. 5).

The reason for this is probably the weather events that happened in 1993 and 1999. When looking at the data from the climate station Igralishte (Table 1), it was

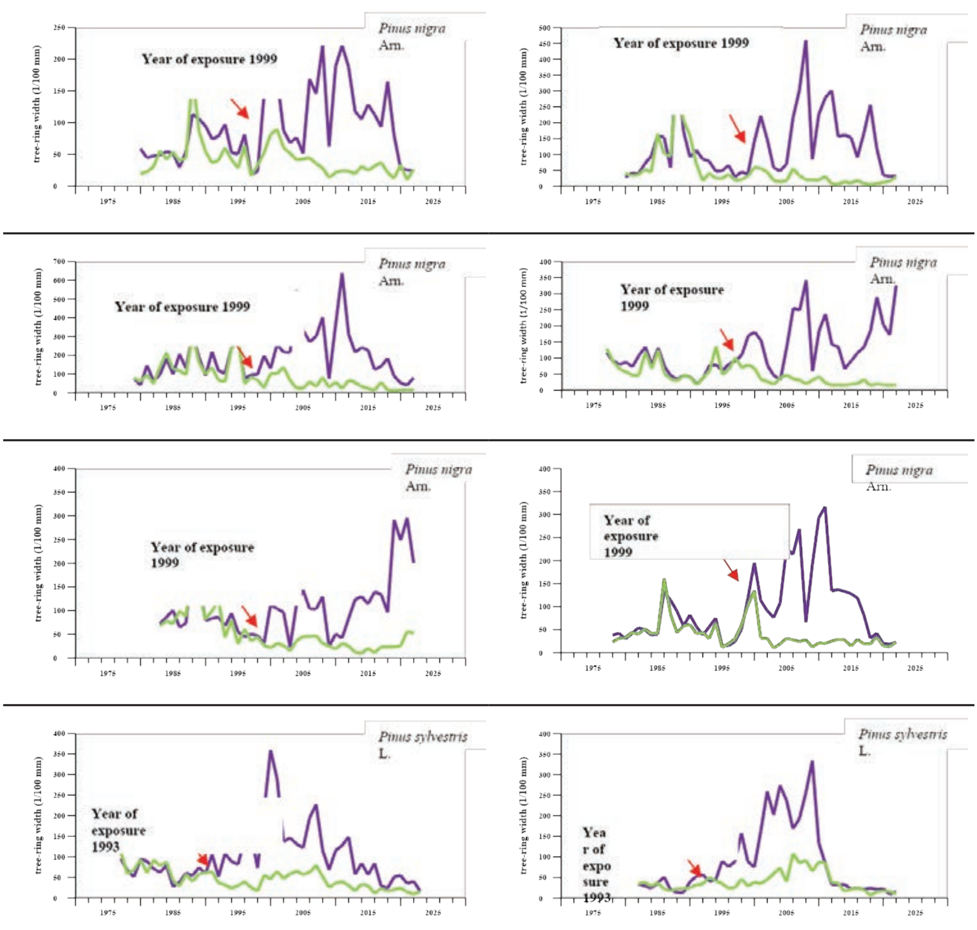

Figure 5. Examples of root exposure dating of *Pinus nigra* Arn. and *Pinus sylvestris* L. based on root tree-ring chronologies. Explanation notes: in green color – reference tree ring chronology; in purple color – reaction wood chronology from the same root

found that precisely in 1999, on the territory of the watershed, there was significant rainfall for three days in July. Which has probably caused the exposure of the roots. No visible cause was noted in the rainfall study for 1993, suggesting that the cause is most likely not in climatic events.

Table 1. Heavy rains in 1999 on the territory of Sedelska river

Month	Year	Date	Characteristic of the rain			Maximum instantaneous intensity, mm/min					
			Quantity – Q, mm	Duration – t, min.	Moderate intensity – Icp, mm/min	I_5	I_{10}	I_{15}	I_{20}	I_{25}	I_{30}
		1	2	3	4	5	6	7	8	9	10
4	1999	24.4.1999	1.8	405	0.004444	1	1	0.93	0.85	0.8	0.77
7	1999	27.7.1999	28	195	0.14359	0.82	0.81	0.67	0.6	0.56	0.52
7	1999	29.7.1999	33.6	335	0.100299	0.5	0.45	0.43	0.39	0.37	0.36
7	1999	30.7.1999	35.9	245	0.146531	1.9	1.3	1.03	0.87	0.78	0.69
10	1999	22.10.1999	29	335	0.086567	0.6	0.55	0.47	0.41	0.36	0.34

The rate of soil erosion was calculated as 0.26cm/year, which corresponded with average levels of erosion in other countries (Bodoque et al., 2011. This erosion rate is considered as low, but they are typical for hilly slope environments (Bahrami et al., 2011).

Conclusion

The method of dendrochronology proves to be a reliable scientific tool in order to identify the exact year of root exposure of the coniferous trees as a consequence of heavy soil erosion process.

Considering the information of heavy rains on the territory of the watershed it could be concluded that individual erosion event in 1999 is the reason for exposures of roots.

The reconstructed erosion rates are 0.26cm/year which is typical for hilly slope environments like in the watershed of Sedelska river.

Additional research on other types of tree species could be conducted for more data and better understanding of the influence of soil erosion on different tree species.

Acknowledgments

The present study was conducted in relation to the implementation of a project approved for financing on the basis of the Fund for Scientific Research Competition for financing fundamental scientific research of young scientists and postdoctoral students – 2021, with number КП-06-М56/5 with topic “Soil erosion assessment and efficiency of applied erosion control activities in Sedelska river, tributary of Struma river”.

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SILVA BALCANICA

Silva Balcanica 24(3): 35-42 (2023)
doi: 10.3897/silvabalcanica.24.e116036

RESEARCH ARTICLE

Monitoring of the health status of *Castanea sativa* in the Belasitsa mountain, southwest Bulgaria

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Academic editor: Ivailo Markoff | Received 20 November 2023 | Accepted 28 November 2023 | Published 28 December

Citation: Georgieva M., Georgiev G., Mirchev P., Filipova E., Matova M., Belilov S., Madzhov S., Hristova M. 2023. Monitoring of the health status of *Castanea sativa* in the Belasitsa mountain, southwest Bulgaria. Silva Balcanica 24(3): 35-42. https://doi.org/https://doi.org/10.3897/silvabalcanica.24.e116036

Abstract

In the period 2017-2023, a survey for the assessment of the phytosanitary condition of sweet chestnut (*Castanea sativa*) was conducted in a permanent sample plot (PSP) Belasitsa, which is part of the European large-scale network for monitoring the health status of forest ecosystems under the International Co-operative Program 'Forests'. The PSP is set in a natural chestnut stand in Belasitsa mountain at an altitude of 643 m. Data collected from the first years of the monitoring determined a slight deterioration in the health status of the chestnut trees caused by an infection with the fungal pathogen *Cryphonectria parasitica*. An improvement in trees' vitality and lack of active necrosis were observed in 2022-2023. On the wounds, initiation of callus along the wounded edges was reported. Currently, the introduction of new and dangerous invasive insect pests *Dryocosmus kuriphilus*, *Corythucha arcuata*, etc., has not been detected. Attacks of both pests could further deteriorate the health status of the sweet chestnut in Belasitsa.

Keywords

Sweet chestnut, monitoring of health status, *Cryphonectria parasitica*, Belasitsa mountain

Introduction

The International Co-operative Program on the Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forests) has been implemented in Bulgaria since 1986. The program operates under the UNECE Convention on Long-range Transboundary Air Pollution (CLRTAP) (Pavlova, Rosnev, 2006). The main objective of the program is to assess the dynamics in the health status of forest ecosystems in Europe. In Bulgaria, the forest monitoring for assessing the state of conifers (*Pinus sylvestris*, *P. nigra*, *Picea abies*, and *Abies alba*) and broad-leaved (*Quercus* spp., *Fagus sylvatica*, *Carpinus betulus*, *Tilia grandifolia* and *Castanea sativa*) tree species, has been implemented in 160 permanent sample plots. These plots are located on a 16×16 km grid to determine the long-time trend of deterioration or improvement of the health status, the structure and functioning of forest ecosystems, etc.

In 2017, a new permanent sample plot (PSP) was established in a natural sweet chestnut (*Castanea sativa*) forest stand in Belasitsa mountain, where the most representative natural chestnut forests are distributed. Since the end of the last century, a deterioration of chestnut trees was observed because of the progressive spread of the invasive fungal pathogen *Cryphonectria parasitica* (Murrill) Barr. (Petkov, Rosnev, 2000; Georgieva et al., 2011; Georgieva et al., 2013). Over time, the process of dieback of chestnut trees has intensified, with the impact of the disease threatening the chestnut forests throughout the Belasitsa mountain. The observed active necrosis on the stems and branches showed a severe spread of the virulent strain of the pathogen *C. parasitica*.

Despite the considerable resources that have been devoted to research of contributing factors in chestnut decline in Belasitsa mountain, an implementation of biological control by the hypovirulent strain of *C. parasitica* has not been applied (Zlatanov et al., 2013). The transmission of the strain started in 1965 in France and proved to be an effective strategy in promoting rehabilitation of chestnut stands (Grente, 1965; Anagnostakis, 1984; MacDonald, Fulbright, 1991; Heiniger, Rigling, 1994; Robin, Heiniger, 2001). Grente (1965) found that lighter colored and less virulent strains of *C. parasitica* existed. When trees were inoculated, atypical strains were found to be of reduced virulence. After re-introduction of whitish strains, necrotic wounds began to heal in most cases. This phenomenon is called hypovirulence. The whitish or hypovirulent phenotype of the fungus is cytoplasmically controlled and associated with high molecular weight dsRNA. H-strains (hypovirulent) can convert V-strains (virulent) to hypovirulent by dsRNA transfer from hyphal anastomosis. This is the basis of biological control, which is applied to control the disease (Heiniger, Rigling, 1994).

In 2021, EU12 hypovirulent strains of the fungus *C. parasitica* were inoculated for the first time in Bulgaria on infected stems in Belasitsa and Pirin mountains, as an opportunity to apply a biological control of the disease (Filipova, 2021). Following observations of inoculated trees showed visibly healthier trees, and isolations made from healed necrotic wounds in nutrient media showed whitish strains.

The aim of this study was to analyse the data from the monitoring of health status of sweet chestnut trees in a permanent sample plot Belasitsa for the period 2017-2023.

Materials and methods

In 2017, a permanent sample plot of sweet chestnut (at an altitude of 643 m) was established on the territory of the State Forest Enterprise Petrich in order to monitor the health status of the species, as a part of the ICP ‘Forests’ large-scale network.

In the period 2017-2023, a complex assessment of the defoliation and leaves discoloration of 40 sample trees was carried out in PSP Belasitsa according to the methodology of the ICP 'Forests' (Eichhorn et al., 2016), which allows an analysis of the changes in the health status that have occurred, as well as to assess the impact of individual factors. Five degrees of damage were used to assess the trends in the tree crown condition: 0 – no damage (0–10%); 1 – slightly damaged (>10-25%); 2 – moderately damaged (>25-60%); 3 – severely damaged (>60–99%) and 4 – dead (100%).

In the annual assessment, damage on the leaves, branches and stems of trees as a result of abiotic, biotic or anthropogenic factors was reported.

Results and discussion

In 2017, active necrotic wounds were found on the trunks and branches of all sample trees. The fungal pathogen *Cryphonectria parasitica* was identified as a causer of the mass dieback and deterioration of the health in the sample plot. The fungus had destroyed the phloem and xylem of the cambial tissue, resulting in necrosis (Fig. 1A). Over the necroses, orange-yellow stroma of the fungus appeared, in which two types of fruiting structures were identified: perithecia (sexual structures producing ascospores) and pycnidia (asexual structures producing pycnidiospores) (Fig. 1B). As a result of this activity, pale-white mycelial fans appeared in the inner bark.

The monitoring carried out in 2017 showed that all sample trees were with deteriorated health status due to the development of the virulent pathogenic fungus *Cryphonectria parasitica*. Out of all trees, 82.5% were moderately damaged with 30-60% defoliation (Fig. 2). The results of the monitoring in 2018 confirmed the process of deterioration of the health of the chestnut trees, as a result of the pathogen development. Compared to 2017, 20% of moderately damaged trees become severely damaged, with defoliation of 70-90%. In the following years, the health status continued to deteriorate, as *C. parasitica* was detected on all surveyed trees, with the proportion of severely damaged trees varying from 20% (2019) to 30% (2020), but no completely dead tree was reported. In the sample plot, single egg masses of *Lymantria dispar* L.) (Lepidoptera: Erebidae) were found on the stems of the trees, but no defoliation by the pest was recorded. The leaves of individual trees were severely damaged by the miner moth *Phyllonorycter messaniella* (Zeller) (Lepidoptera: Gracillariidae).

The tendency for the deterioration of the health status of the sweet chestnut was maintained in 2021. Necrosis on the stems and branches was found in trees. Among them, 82.5% were moderately damaged, and 15.0% - severely damaged. One tree (2.5%) was completely killed by the pathogen. An improvement of tree vitality and lack of active necrosis were observed in 2022-2023. On the wounds, initiation of callus along the wounded edges was noted (Fig. 3). It was reported that 85% of the trees were characterised as moderately damaged, with defoliation of the crowns 30-60%, and 10-15% - severely damaged, with defoliation 70-80%. No completely dead trees were reported.

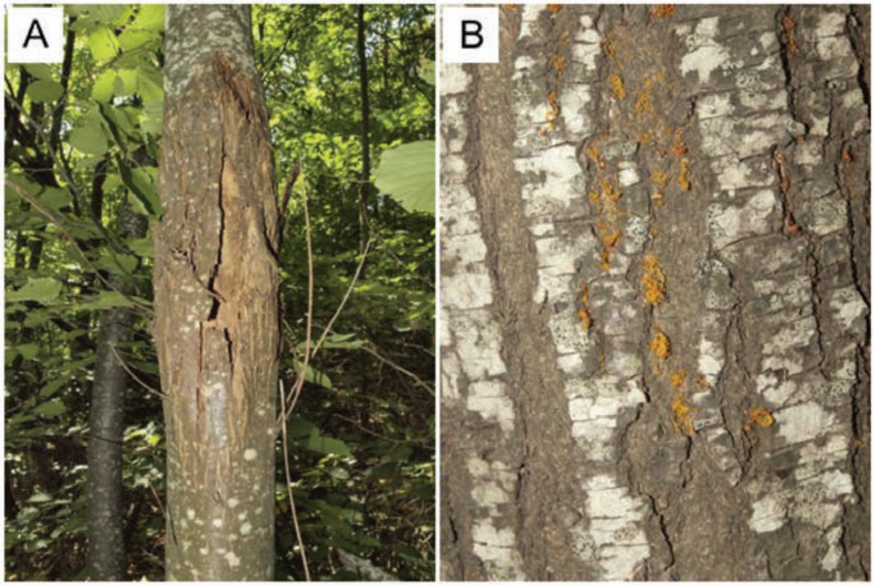

Figure 1. Symptoms of the disease caused by *Cryphonectria parasitica*: A – occurrence of a necrotic wound on the stem; B – development of orange stroma with sporocarps

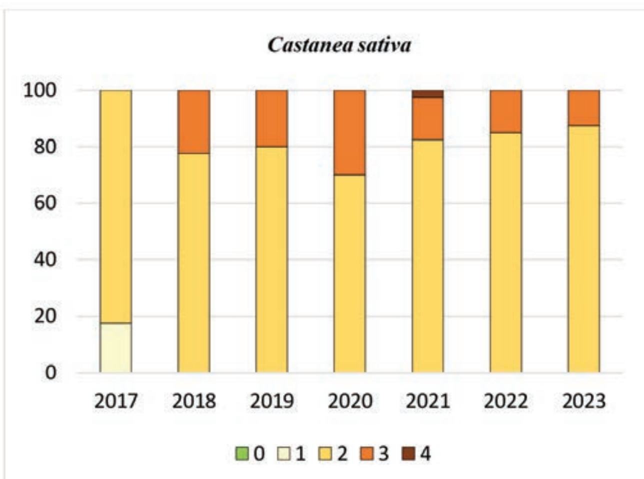

Figure 2. Distribution of chestnut trees in PSP 0153 Belasitsa according to the degree of damage (2017-2023)

In Europe, hypovirulent strains ensure long-term biological control of chestnut trees (Anagnostakis, 1987). The introduction of such strains into chestnut stands has been carried out in Bulgaria's neighbouring countries Greece, Turkey and North Macedonia. Currently, an improvement in the health status of the chestnut forest stands and orchards in these countries is being observed. In Bulgaria, the first attempt

Figure 3. Closed necrosis on chestnut stems in PSP Belasitsa (2023)

for biological control to *C. parasitica* by an artificial inoculation with a hypovirulent strain EU-12 was carried out in 2021 on infected trees in three sample plots in Belasitsa and Pirin mountains (Filipova, 2021).

The presence of an extensive callus layer around the wounds in the sweet chestnut population in Belasitsa mountain indicates that the hypovirulent strain of *C. parasitica* most probably entered in our country through the natural spread from North Macedonia or Greece, where EU-12 hypovirulent strain was inoculated some years ago (Sotirovski et al., 2011; Diamandis et al., 2015).

Undoubtedly, one of the most effective methods for controlling this economically important disease is the biological method based on the spread of the hypovirulent strains of the pathogen *C. parasitica*. This method exploits the low pathogenicity of the hypovirulent strains that are able to associate with virulent ones and suppress their pathogenicity. However, it is successful only if there is vegetative genetic compatibility between the virulent and hypovirulent strains, which will facilitate the establishment of an anastomosis between them, and the exchange of cytoplasmic material. For this reason, the efficacy of hypovirulence as a means of biological control against the disease depends mainly on the number of vegetative compatibility groups existing in the populations of the pathogen. In Belasitsa mountain the most common strain of the pathogen is EU-12, but strains EU-2, EU-10 have also been spread (Filipova, 2021).

Early detection of pest and disease outbreaks and rapid response to prevent the introduction and spread of invasive species are critical to maintaining the health and productivity of European forests (EEA, 2023). The introduction of new invasive pests and pathogens leads to deterioration of the vitality and functioning of forest ecosystems. A real threat for chestnut stands in Belasitsa mountain are two new invasive pests - the widespread oak lace bug (*Corythucha arcuata* Say) and the chestnut gall wasp *Dryocosmus kuriphilus* Yasumatsu, which is expected to be introduced into the country from Greece. The quarantine pest *Dryocosmus kuriphilus* causes severe damage to species of the genus *Castanea*. It is widely distributed in China, Korea and Japan, and in 2002 it appeared for the first time in Italy. The pest has spread rapidly to several European countries, probably due to the trade of chestnut plants. Despite measures taken to prevent the further spread of this pest in other countries, *D. kuriphilus* was detected in Greece in 2014 (Michaelakis et al., 2016). In Bulgaria, the pest has not been detected, yet.

The oak lace bug *Corythucha arcuata* is native to North America, widely distributed in the USA and southern Canada. It is an invasive species recorded for the first time in Europe in Italy (Bernardinelli, Zandigiacomo, 2000) and Switzerland (Forster et al., 2005). *C. arcuata* is distributed in a large part of Turkey (Mutun et al., 2009), from where it most likely entered Bulgaria in 2013 in Simeonovgrad and reached Plovdiv (Dobreva et al., 2013). In the next years, the species spread into many regions of the country, mainly affecting oak forests (Georgiev et al., 2017), but in 2017 it was registered for the first time in Bulgaria on the sweet chestnut (*Castanea sativa*) in the region of Pazardzhik (Simov et al., 2018).

Conclusions

Over a period of seven years, a slight deterioration in the health status of sweet chestnut trees (*Castanea sativa*) has been reported in the PSP Belasitsa. In the first years of monitoring, an increase in the number of trees damaged by the fungal pathogen *Cryphonectria parasitica* was reported. An improvement of trees vitality and lack of active necrosis were observed in 2022-2023. On the old wounds, initiation of callus along the wounded edges was reported.

The most effective method of controlling the economically important chestnut blight disease is the biological method based on the hypovirulence of the pathogen *C. parasitica*. In 2021, for the first time in Bulgaria, a hypovirulent strain of the fungus was inoculated as an opportunity to control the disease. The results show an improvement in the health status of the chestnut forests in Belasitsa mountain.

Currently, the penetration of new and dangerous invasive insect pests (*Dryocosmus kuriphilus*, *Corythucha arcuata*, etc.) which could further deteriorate the health status of the sweet chestnut in Belasitsa mountain, has not been detected.

Acknowledgments

The results in the present study were achieved during the implementation of the project 'Assessment and monitoring of the impact of atmospheric air pollution on forest ecosystems - Level I', financed by the EEA to the Ministry of Environmental and Waters.

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SILVA BALCANICA

Silva Balcanica 24(3): 43-60 (2023)
doi: 10.3897/silvabalcanica.24.e115856

RESEARCH ARTICLE

Integrated mapping of ecosystems and assessment of forest ecosystem services at river basin scale

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Academic editor: Georgi Georgiev | Received 16 November 2023 | Accepted 4 December 2023 | Published 28 December

Citation: Nedkov S., Ananiev I., Prodanova H., Stoycheva V. 2023. Integrated mapping of ecosystems and assessment of forest ecosystem services at river basin scale. Silva Balcanica 24(3): 43-60. https://doi.org/10.3897/silvabalcanica.24.e115856

Abstract

Ecosystems provide various goods and services to society and their valuation is among the main objectives of the concept of ecosystem services (ES). The mapping of ecosystems is the main building block of the whole process of the Mapping and Assessment of Ecosystems and their Services (MAES). The analyses of the ecosystem data produced during the implementation of the national methodology for mapping ecosystems in Bulgaria (MAES BG) reveal some problems that may cause confusion in cases of integrated assessment of all ecosystem types. In this paper, we present an approach that enables formulation of a uniform spatial dataset based on the mapping of the main ecosystem types, that can be used for mapping of ES at a river basin scale. It has been applied to the upper part of the Ogosta River basin and the result is a topologically correct uniform spatial data layer. The approach gives one possible solution to problems related to the different sources of information and the discrepancies between ecosystem types in the national mapping of ecosystems in Bulgaria. It is based on the use of a uniform spatial framework that outlines the ecosystem types and sets the initial database for further mapping. This ensures a topologically correct spatial dataset for the ecosystems and a background for further updates for each ecosystem at the different levels of MAES typology. The most appropriate spatial basis for the territory of Bulgaria is the database for the physical blocks of the Ministry of Interior. Its application to the studied river basin gives encouraging results and can be used as an example for similar areas. Further development of the approach will ensure the mapping of the forest ecosystems at level 3 of the MAES BG typology and more precise delineation of the grassland, heathland, freshwater, and sparsely vegetated ecosystems.

Keywords
CLC, ESA WorldCover, GIS database, MAES typology, physical blocks

Introduction

Ecosystems provide various goods and services to society, which in turn directly contribute to human well-being and various economic activities (Costanza et al., 1997; MA, 2005). Valuing such contributions is among the main objectives of the concept of ecosystem services (ES) which are defined as "the contributions of ecosystem structure and function–in combination with other inputs–to human well-being" (Burkhard et al., 2012). They also have the potential to solve problems related to the conservation of biodiversity and contribute to the achievement of the sustainable development goals (SDG). However, regions whose conservation benefits both biodiversity and ES, cannot be identified unless ES can be quantified and valued and their areas of production mapped (Naidoo et al., 2008). Therefore, the mapping of ecosystems is the necessary basis for further valuation and assessment of ES. This is emphasized also in the European biodiversity strategy with the target mapping of ecosystems and their assessment. This was the driving force for the formation of the Mapping and Assessment of Ecosystems and their Services (MAES) working group that is set to support the implementation of Action 5 by the European Union and its member states.

The MAES working group developed the methodological framework for mapping ecosystems and the services they provide at a European level (Erhard et al. 2016; Maes et al., 2013, 2014, 2020). It has been used as a basis to develop the methodology for Bulgaria under the Methodological assistance for ecosystems assessment and biophysical valuation (MetEcosMap) project. It includes nine separate methodologies, each of which covers a specific ecosystem type according to the MAES typology (Bratanova-Doncheva et al., 2017). In the follow-up mapping, nine separate databases were developed for each ecosystem type. However, applying these data for complex tasks such as water management and regional planning would create at least two serious problems: 1) the fragmentation of spatial units into nine separate Geographical Information System (GIS) layers and the related disparities between them in the form of gaps and overlaps; 2) the absence of mapping for large parts of the country which makes it impossible to cover with data an entire study area. To solve such issues, it is necessary to develop an approach that enables integrated mapping of ecosystems. Forest ecosystems are the most important providers of various services from each of the main ES groups (provisioning, regulating, cultural) as they ensure valuable functions that support their supply (Acharya et al., 2019; García-Nieto et al., 2013). From this point of view, the mapping of forest ecosystems should have special attention in every study that addresses ES assessment at a national or regional scale.

The first attempt to map the ecosystems in Bulgaria based on MAES typology was made by Nedkov et al. (2017). The authors utilized CORINE Land Cover (CLC) data to delineate and map ecosystems in Bulgaria for four periods between 1990 and 2012 and reveal the dynamics of ecosystems for this period. According to this study, agricultural (48%) and forest (38%) ecosystems cover the highest part of the country. This study gives a general overview at the national level but for more precise estimation at regional and especially local level, the CLC data is too raw, and more precise data is needed. Hristova, Stoycheva (2021) explores the relationship between the CLC classification and the MAES typology to develop a basis for mapping ecosystems at a national level for the needs of nature heritage assessment. The relationships between CLC classes and MAES ecosystem types and subtypes established in this study provide valuable information for cross-walking with other data sources and the implementation of integrated approaches for mapping ecosystems. According to the methodological framework (Burkhard et al., 2018), the mapping of ecosystems can be compiled and the underlying spatial data can be analyzed using GIS techniques. The mapping procedures are prone to particular uncertainties during the delineation using spatially explicit units. This is valid, especially in cases when integration of various data sources is necessary. This is an important research gap that needs further studies and a search for appropriate methods of data integration. To solve such problems, it is necessary to develop an approach that enables integrated mapping of ecosystems.

The analyses of the ecosystem data produced during the implementation of the national methodology for mapping ecosystems in Bulgaria reveal two main problems that may cause confusion in cases of integrated assessment of all ecosystem types (Petkova et al., 2022). The first one is related to discrepancies between the typologies of the nine ecosystem types and the hierarchical levels in some of them. This necessitates a revision of the typology, which aligns with the recommendations towards better consistency of the mapping efforts (Maes et al., 2020). The second comes from the topology analyses of the merged data from the eight ecosystem GIS layers (the ninth is about marine ecosystems which are not presented in the study area) which show huge numbers of gaps and overlaps. This determines the development of a new approach for mapping all ecosystem types into a uniform database (Petkova et al., 2022).

The main objective of this study is to present an approach that enables formulation of a uniform spatial dataset based on the mapping of the main ecosystem types, that can be used for mapping of ES at a river basin scale. It has been applied to the upper part of the Ogosta River basin and the result is a topologically correct uniform spatial data layer.

Materials and methods

Case study area

The upper part of the Ogosta River basin (Fig. 1) is chosen as a case study to test the proposed approach. This area has been an object of various studies which ensures data availability and options for validation. The Ogosta River starts from a spring under Vrazha Glava peak (1935 m) in the Chiprovska mountain at about 1760 m. Next to the village of Belimel, it flows in a north-easterly direction in a narrow valley. After the merge with its left tributary, the Prevalska River, it turns to the southeast and forms a wide valley, occupied mainly by arable land. This part receives the biggest tributary—the river Dulgodelska Ogosta. Further downstream it enters the second largest dam in Bulgaria, the Ogosta Dam.

The topography is mainly mountainous with the highest point being Golema Chuka (1967.2 m). From north to south, it goes from low-mountainous in the region of Black Peak (1017.5 m) and the valley of the Ogosta River, to medium and high-mountainous. The climate is temperate continental with distinct mountain features in the southern part of the basin. The average January temperatures are between 0 and 1.5°C, and in the mountains, it reaches -9°C. The average July temperature is between 22 and 24°C, decreasing to 10-11°C in altitude. The average annual precipitation varies between 500 and 650 mm in the low mountain part and increases to 1000 mm in the high mountain part.

The anthropogenic impact in the study area has various aspects. The most pronounced in the spatial aspect are the land use changes but in the environmental quality aspect are the problems form the former mining activities that cause heavy metal pollution in the water and floodplains along the Ogosta River (Kotsev, Stoyanova, 2022; Marcheva et al., 2023).

Spatial data sources

The analyses of the ecosystem data produced during the implementation of the national methodology for mapping ecosystems in Bulgaria reveal that it is impossible to integrate the spatial units from the different ecosystem types into a uniform topologically correct GIS layer (Petkova et al., 2022). This is mainly due to the differences in the data sources used to build the geometry of the spatial units that represent the ecosystem types. Therefore, it is necessary to build the ecosystem dataset starting with a uniform GIS layer that can be used as a spatial framework for further development of the dataset. This spatial data source should fulfill the following criteria: (i) to cover the whole territory of the country; (ii) to have a classification that can be appropriately translated to the MAES typology; (iii) to have a resolution that corresponds to the requirements of the national methodology for mapping of ecosystems in Bulgaria; (iv) to have appropriate precision for mapping of ecosystems at a national scale. Four spatial datasets cover the whole range of ecosystems in Bulgaria: 1) the national dataset produced from the mapping of ecosystems in Bulgaria under MAES methodology (MAES BG); 2) CLC dataset; 3) the European Space Agency (ESA) world cover; 4) the physical blocks (PB) dataset. The spatial extent of the ecosystems derived from these sources is presented in Fig. 2. Furthermore, there are sectoral datasets that have no full coverage of the country and contain data on one or two ecosystem types.

The MAES BG dataset is planned to have full coverage at a national scale following the methodological framework that contains nine separate methodologies. Each of them covers one of the nine main ecosystem types according to the MAES typology. This led to the development of nine separate databases generated within seven

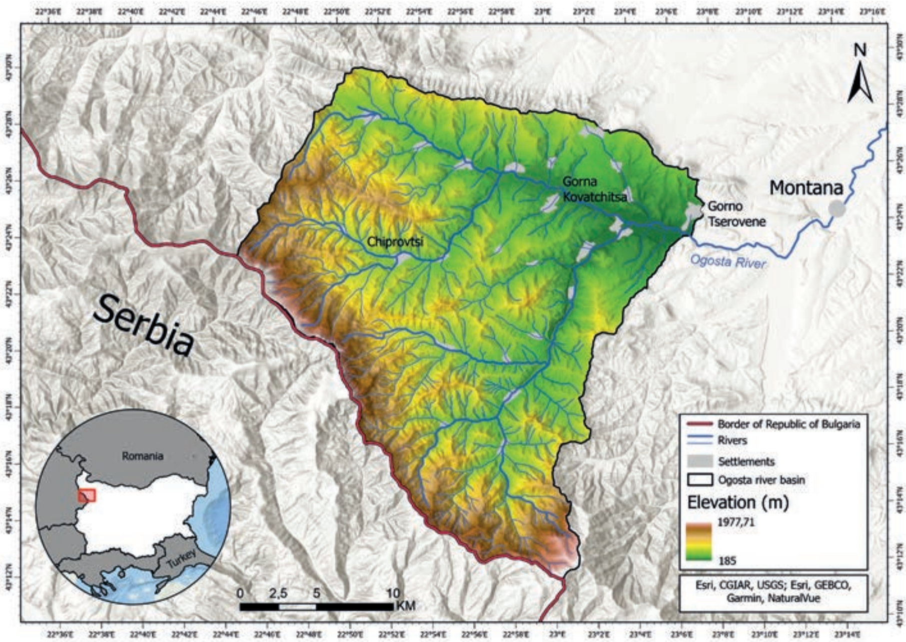

Figure 1. Case study area of the upper part of Ogosta River basin

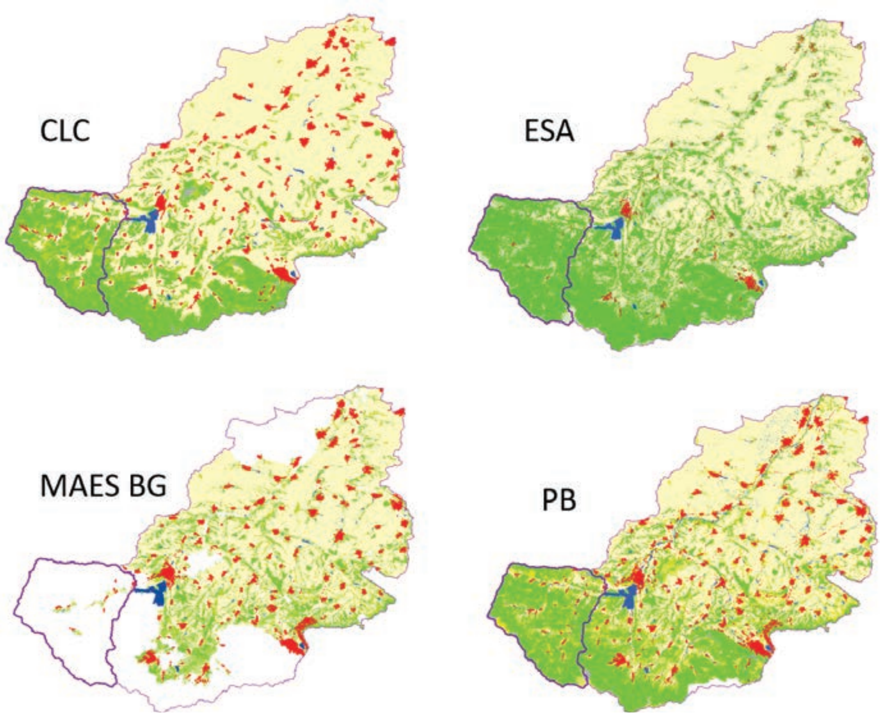

Figure 2. Spatial data sources in the Ogosta River basin

projects funded under the program BG03 "Biological diversity and ecosystem services" of the European Environment Agency grants. However, the mapping results now cover about 65% of the territory of the country. Therefore, this database is not suitable as a basis for integrated mapping as it does not yet have national coverage. The second reason is related to the gaps and overlaps analysis results presented above, which show that they are practically unfit for integration due to topological incompatibility. Nevertheless, this database could be used in the analysis to establish consistency with other sources and to quantify their mapping.

CLC as a spatial data product offers a pan-European land cover and land use inventory with 44 thematic classes, ranging from broad forested areas to individual vineyards. It is updated with new status and changes layers every six years (Bossard et al., 2022). CLC is directed to a multitude of users and has nearly limitless potential and actual applications in fields such as environmental assessment, land use change analyses, climate change assessments, etc. The main objectives of the program are: 1) collection of information about the environment concerning individual aspects that have priority for all member countries; 2) coordination of data collection and organization of information between member countries and/or internationally; 3) ensuring consistency of information and compatibility of data. The scale is 1:100 000 and the minimum mappable unit is 25 ha. The nomenclature is organized into three levels. The first level has 5 classes covering separate categories that are abstract to one degree or another of the land cover. The second level has 15 classes that are scaled from 1:500,000 to 1:1,000,000. The third level has 44 classes which represent the CLC project at a scale of 1:100,000.

The ESA initiated the World Cover project. The ESA World cover product data was developed in response to the need for accurate, timely, high-resolution information on land use/land cover and its changes. The key output of this project was the release in October 2021 of a freely available 10 m resolution global land cover product for 2020, based on both Sentinel-1 and Sentinel-2 data, containing 11 land cover classes and independently validated with a global overall accuracy of 74.4% (Zanaga et al., 2021). Its development further builds on the experience of Glob Cover and CCI Land Cover by the European Space Agency (Arino et al., 2008; ESA, 2017). The algorithm used to generate the ESA World Cover product is based on the 100 m resolution Copernican Global Land Cover (CGLS-LC) dynamic annual land cover algorithm (Buchhorn et al., 2020). The CGLS-LC workflow used 100 m, 5-day, Proba-V data as input, which were reprocessed on the Sentinel-2 UTM grid together with training data obtained at 10 m resolution.

The PB database was developed by the Ministry of Agriculture and Food (of Bulgaria) based on remote sensing data and the creation of an orthophoto map. Land cover is classified into nine types, each of which is differentiated into subtypes depending on land use. The nine types are: arable lands, forest areas, urban areas, water areas and wetlands, disturbed areas, transport infrastructure, bare and eroded areas, other areas, and areas with other uses.

Quality assessment of the spatial data sources and development of a spatial framework for mapping of ecosystems in the case study area

Following the above-mentioned criteria, we assessed the four datasets. The MAES BG dataset failed at the first criterion as it does not have full coverage of the country. The other three datasets passed this criterion as well as the second (about the classification) and the third (about the resolution). The fourth criterion (precision) needs a more comprehensive approach. Thus, we developed an approach for data validation of the spatial data sources to define their precision and furthermore - to choose the most appropriate dataset to be used as a spatial framework. It is based on control points for validation of the mapped data in the individual sources. Validation is done in two ways: visual interpretation by orthophoto map and field validation. Visual interpretation on an orthophoto map is done for all control points. Field validation requires significantly more travel time and funding, so it is done for selected points where the visual interpretation is assessed with low confidence. For this purpose, a two-level confidence scale has been introduced in this type of check—high and low. The first is introduced when the type (or subtype) of the ecosystem is very clearly visible on the orthophoto map and the visual interpretation is considered reliable. The second is introduced when the type of ecosystem cannot be unambiguously determined or there are doubts about the type of vegetation. Validation points were randomly determined by forming a grid of points in GIS using the Fishnet function. The points are arranged in a regular grid with a distance between the points of 250 m.

The results of the assessment show that the PB dataset has the highest precision and it was chosen as a spatial framework for the mapping of ecosystems. The process of building the spatial framework contains two main stages. In the first stage, the PB classification was correlated to the MAES BG classification. In the second stage, the PB classes in the attribute table of the PB GIS layer were transformed into ecosystem types and subtypes following theMAES BG classification. The resulting GIS layer has the geometry of the PB dataset and the classification of MAES BG.

An approach for data integration of forest and urban ecosystems

The spatial framework based on PB data meets the requirements about national coverage, relation to the MAES typology, and resolution of the data. However, the fourth requirement about the appropriate precision is not fully covered as the data for some ecosystems is not detailed enough to represent their spatial distribution at the scale and precision at level 3 of the MAES BG typology. For instance, the forests in PB are presented in a single class which makes it impossible to distinguish the forest ecosystem subtypes (level 3 of MAES BG). PB's urban ecosystems have several classes corresponding to ecosystem subtypes, but the comparison with the MAES BG urban database shows particular differences. The latter is more detailed and precise in the mapping of urban subtypes. Therefore, the ecosystems at level 3 and 4 should be updated. However, such an update should keep the topological quality of the dataset which necessitates the development of precise procedures for the update of the ecosystem subtypes.

The algorithm that contains the spatial procedures for the update of the forest and urban ecosystems in the case study area is presented in Fig. 3. The initial GIS layer developed from the PB dataset (ogosta_eco_mzh) is used as a spatial framework to integrate the forest and urban ecosystem data. The forest inventory dataset is used as a source for forest ecosystem updates. This dataset contains detailed data about various forest parameters developed for the regional and local forestry plans. The first two steps of the procedure (the green part of Fig. 2) are applied to correlate the categories from forest inventory data (Dleso_ogosta and woods_upper_ogosta_basin) with the ecosystems typology and intersect the polygons from the two datasets. The spatial units from the datasets do not fit each other perfectly, causing the formation of many small polygons that should be removed (step 3). The next two steps include procedures to verify the results of the intersections and prepare separate layers with the updated forest ecosystems at level 3 of the MAES BG typology. Then the data from this layer is integrated into the spatial framework differently due to the specifics of the datasets.

Mapping of ecosystems and the services they provide

ES maps quantify and visualize where and to what extent ecosystems contribute to human well-being (Burkhard, Maes, 2017). To test the applicability of the developed ecosystems database, we applied the matrix approach (Burkhard et al., 2012) for ES mapping to four water-related ES (flood regulation, erosion control, water quality regulation, and local climate regulation). To represent ES in a spatial context, it is necessary to define where ES are generated i.e., to map ES supply. In the context of the

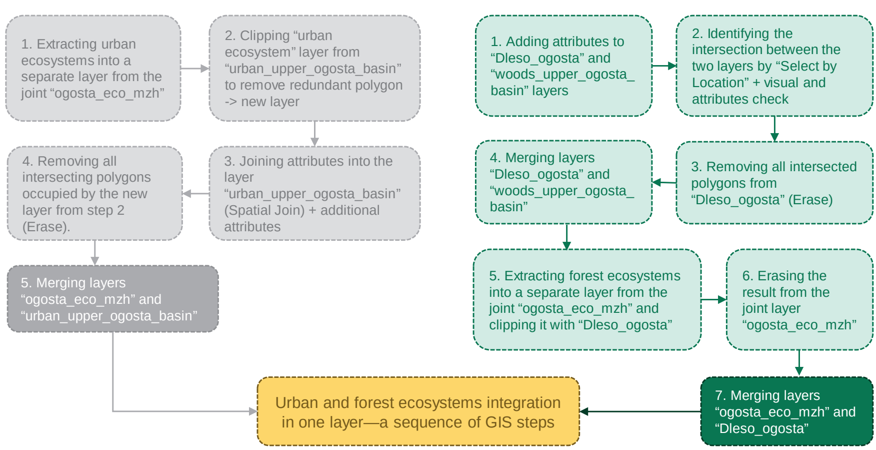

Figure 3. An algorithm of spatial procedures for data integration of the forest and urban ecosystems

mapping and assessment framework, it is important to clarify the place of the spatial units outlined during the phase of ecosystem mapping. In our case, we use the ecosystems as the spatial units that provide the ES. The capacities of the identified spatial units were assessed on a relative scale ranging from 0 to 5 (after Burkhard et al., 2009, 2012). A 0-value indicates that there is no relevant capacity to supply flood regulating services and a 5-value indicates the highest relevant capacity for the supply of these services in the case study region. Values of 2, 3, and 4 represent respective intermediate supply capacities.

Results

Ecosystems in the Ogosta River basin

The mapping of ecosystems is a process that involves various activities in spatial data gathering, data processing, and data storage. The main result of these processes is the generation of a GIS database for the ecosystems. The application of the proposed approach enabled us to develop a GIS database for the ecosystems in the upper part of the Ogosta River basin. It contains spatial data for seven ecosystem types presented in the study area. Only marine and wetland ecosystems are not presented in the study area. The dataset contains 16598 polygons with an average size of 4.25 ha. The map of ecosystem types (Fig. 4) represents their spatial distribution in the study area. The Woodland and forest ecosystems cover by far the largest part of the area with about

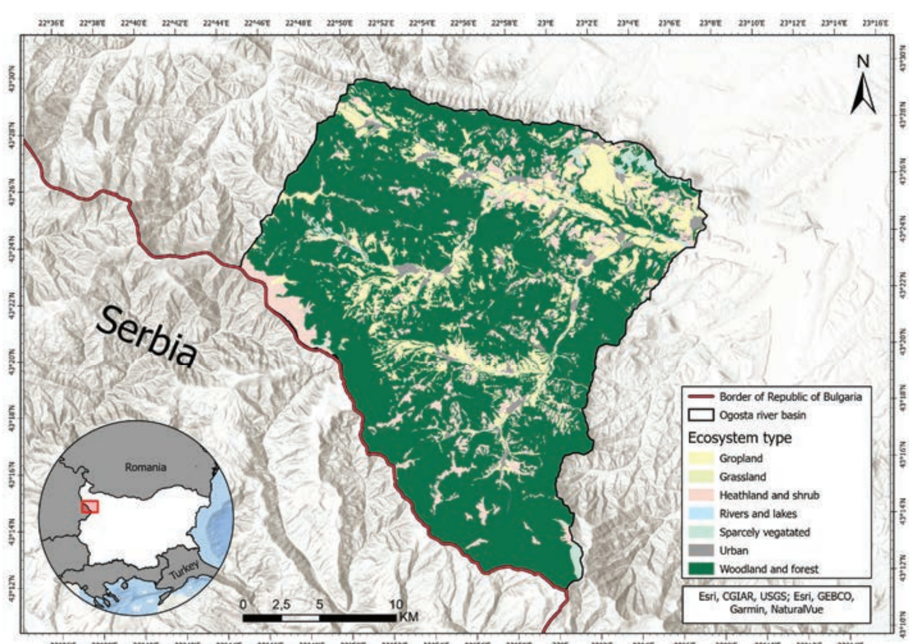

Figure 4. Ecosystems in Ogosta River basin

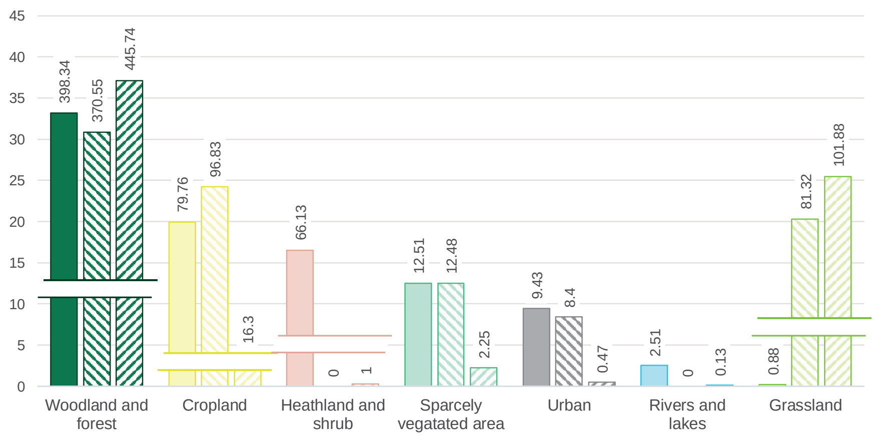

Figure 5. Spatial distribution of the ecosystems in Ogosta River basin

70% share of the whole basin. Cropland (13.5%) and Heathland and shrub (11.6%) are also well represented and with the forests, they comprise almost 96% of the study area. The croplands are presented mainly in the northeastern part of the area, while the shrubs are distributed evenly around the basin. The Urban ecosystems cover about 2.1% located mainly along the river valleys throughout the basin. The Rivers and lakes (0.4%), Sparsely vegetated (1.6%) and Grasslands ecosystems (0.2%) have limited extent in the basin.

The comparison of the results about the ecosystem distribution from the application of the proposed approach, and two of the other sources of spatial data show some similarities but also pronounced differences (Fig. 5). The area of the Woodland and forest ecosystems vary from 370.55 km^2 (according to CLC data) to 445.74 km^2 (ESA) with the results from our mapping placed in between them with 398.34 km^2. The most pronounced are the differences in the Heathland and shrub ecosystems with 66.13 km^2 from our mapping quite limited from the other two sources. The results for Cropland ecosystems are similar between our mapping (mainly based on the PB dataset) and CLC data. In contrast, the area from ESA data is almost four times lower. The results for Grasslands ecosystems show a similar pattern but, in this case, CLC and ESA data show close results, while the ecosystem types based on PB data are almost absent in the study area.

Forest ecosystems in the Ogosta River basin

The distribution of forest ecosystems as the most important type in the study area should be analyzed in more detail (Fig. 6). According to the MAES BG typology at level 3, there are four ecosystem classes that correspond to the ecosystem subtype. These are Coppice forests, High deciduous forests, Coniferous forests, and Mixed forests. The application of the proposed approach enables the combination of PB and

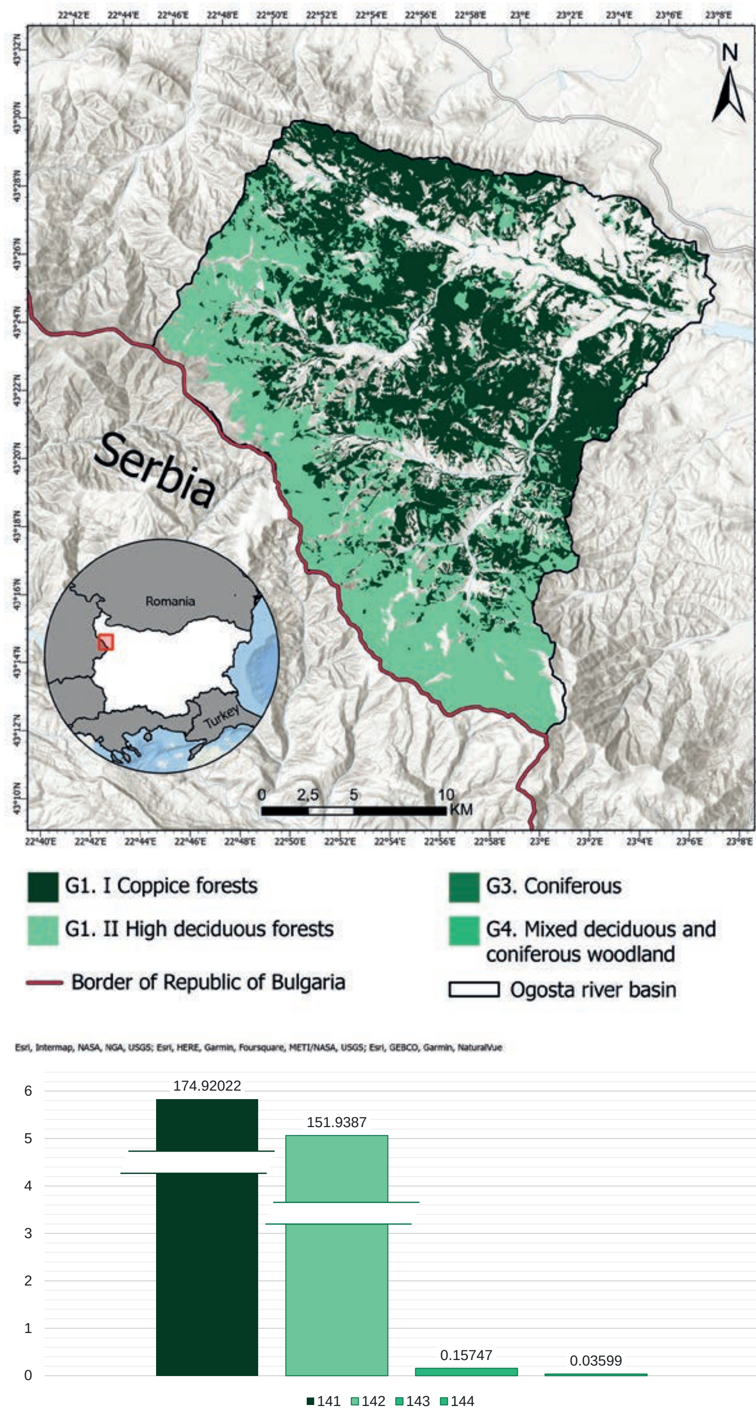

Figure 6. Forest ecosystem subtypes in Ogosta River basin. 141–Coppice forests; 142–High deciduous forests; 143–Coniferous forests; 144–Mixed forests

forest inventory datasets which in this way complement each other. The results show a pronounced predominance of the deciduous forest covering 99.9% of the study area. The coppice forest has a slightly higher extent with 174.9 km^2 (53.5%). They are located in the northern part of the basin at a lower altitude. The high deciduous forests cover 151.9 km^2 (46.4%) of the basin, located mainly in the southern more mountainous part. The coniferous and mixed forests have a limited extent as small patches in the southern part of the basin.

Selected ecosystem services in Ogosta River basin and the role of the forest ecosystems

The main objective of ecosystem mapping is to define the spatial pattern of the ecosystem types which is a basis for further mapping and assessment of the ES. To test the applicability of the ecosystems database for mapping ES, we choose four water-related ES: flood regulation, erosion control, water quality regulation, and local climate regulation. The supply capacity of the ecosystems was estimated using the scores for respective services from the MAES BG database. As the mapping of ecosystems in the upper part of the Ogosta River basin has a limited extent, we extracted the scores from the mapping of the whole basin (Fig. 2). The scores of the four ES per ecosystem type for the whole basin were transferred to the ecosystems in the case study area. The resulting maps are presented in Fig. 7. The maps show that the ecosystem in the upper Ogosta River basin has a relatively high capacity for all four selected ES. The forest ecosystems have the main role for such a high score. Specifically, the High deciduous forests subtype has the most important contribution to these results. The areas with very high capacity (score 5) for flood regulation and erosion regulation almost entirely overlap with the distribution of high deciduous forests. For water quality regulation they have high capacity (score 4) but again these are the areas with higher scores than the rest of the area of the basin. The map of capacity for local climate regulation shows a slightly different pattern as both High deciduous forests and Coppice forests have very high capacity.

Discussion

The proposed approach for integrated mapping of ecosystems enables the combination of information from different spatial data sources in a topologically correct vector layer using an algorithm of consecutive GIS techniques. The main advantage of the approach is the opportunity to integrate all nine ecosystem types into a single dataset that can be used for ecosystem services modeling and assessment designed for specific practical activities such as water management at the river basin scale, flood risk assessment, spatial planning, etc. The results for the upper part of the Ogosta River basin confirm its applicability and demonstrate that this is a significant upgrade to the mapping of ecosystems based on the CLC data (Nedkov et al., 2017). The main limitation is that it uses one particular spatial data source as a spatial framework

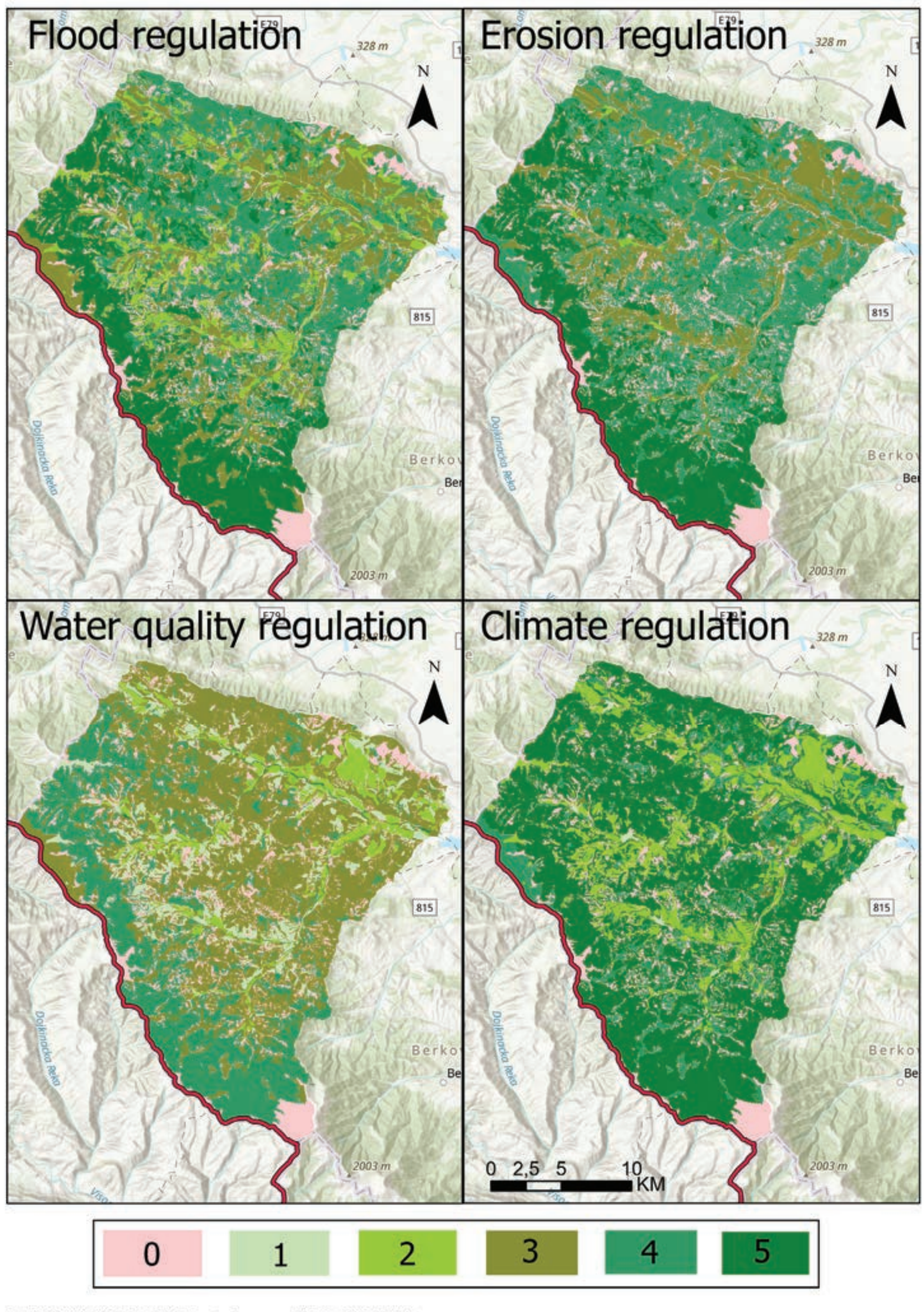

Figure 7. Selected ecosystem services in Ogosta river basin, ES capacity classes: 0–no capacity; 1–very low capacity; 2–low capacity; 3–moderate capacity; 4–high capacity; 5–very high capacity

which means that the limitations of this dataset would be transferred to the resulting ecosystem mapping. Thus, the main challenge for the development of the approach is to find appropriate methods for the comparison of different spatial data sources and update the ecosystems delineation which can increase the precision of the results. In the current stage, the approach has well-developed algorithms for the integration of forest and urban ecosystems. The agricultural ecosystems are well represented in the initial PB dataset but the delineation and the spatial representation of the other ecosystems should be evaluated and the most appropriate data sources for update need to be found.

The differences in the spatial coverage of the ecosystems between the results from our test mapping in the case study area and the other spatial data sources (specifically ESA and CLC) are indicators for uncertainty that need further research. The variations in the spatial extent of the forests are caused mainly by the different initial data sources and the methods for their interpretation. The ESA world cover uses Sentinel data and automated classification of the satellite images. It also has no minimum mapped units (in contrast to CLC) and could not distinguish between forest and shrub vegetation. All these factors led to higher forest cover than any other sources. The forest inventory data also has lower values for the forest cover which is due to the limitation of the inventory within the administratively defined forest lands. Therefore, some forest areas outside these borders are not counted. For instance, there are abandoned agricultural lands that were recovered to forests during the last 20-30 years but they are still not included in the lands that are managed by the forestry agency. The PB dataset appears as the most precise source to outline the forested areas as it is developed from high resolution aerial photographs and visual interpretation. The problem with this dataset is the lack of differentiation of the forest types.

The differences in the Heathland and shrub ecosystems are mainly due to classification discrepancies. The results for Cropland ecosystems show similar results between our mapping (mainly based on the PB dataset) and CLC data. In contrast, the area from ESA data is almost four times lower. The results for Grasslands ecosystems show a similar pattern but, in this case, CLC and ESA data show close results, while the ecosystem types based on PB show that these ecosystems are almost absent in the study area. Further validation and update of the shrubland and grasslands data is much needed and the other studies on grassland vegetation such as Grigorov et al. (2021) could be helpful.

Applying the proposed approach enables the improvement of information about the forest ecosystem by combining the PB and forest inventory data as they complement each other. The outline of the PB better reflects the current state as it incorporates all forested areas. The differentiation of the forest types is ensured by the forest inventory data. The results about the limited extent of the coniferous and mixed forests have different explanations. The coniferous forests are not typical for Stara Planina Mountain in general and the study area is no exception. However, the results for mixed forests need further checks and potential updates because the CLC data show a higher extent of such forests. The reason for such a difference is the variety of methods used in CLC and forest inventory. Further development of the approach towards the delineation of the forest's ecosystems at the fourth level of the MAES BG typology is much needed. The data from forest inventory contains such information but its format does not allow direct link with the columns in the attribute table. Solving this problem will also contribute to the above-mentioned case with the mixed forests.

The results of the test mapping with four water-related ES (flood regulation, erosion control, water quality regulation, and local climate regulation) are encouraging as they show a good correlation with other studies on these ES (Boyanova et al., 2014, 2016; Nikolov et al., 2022;). The ecosystems database is an appropriate source for mapping ES at tier 1 (Grêt-Regamey et al., 2015) but also as an input for ES models that can generate more comprehensive and precise results for the spatial distribution of these services.

Conclusion

The approach for integrated mapping of ecosystems, presented in this paper, gives one possible solution to problems related to the different sources of information and the discrepancies between ecosystem types in the national mapping of ecosystems in Bulgaria. It is based on the use of a uniform spatial framework that outlines the ecosystem types and sets the initial database for further mapping. This ensures a topologically correct spatial dataset for the ecosystems and a background for further updates for each ecosystem at the different levels of MAES typology. Research shows that the most appropriate spatial basis for the territory of Bulgaria is the database for the physical blocks of the Ministry of Interior (Nedkov et al., 2023). Its application to the studied river basin gives encouraging results and can be used as an example for similar areas. Further development of the approach will ensure mapping of the forest ecosystems at level 3 of the MAES BG typology and more precise delineation of the grassland, heathland, freshwater, and sparsely vegetated ecosystems.

Acknowledgments

This work has been carried out within the INES project (Integrated assessment and mapping of water-related ecosystem services supporting nature-based decisions in river basin management), funded by the National Science Fund of the Bulgarian Ministry of Education and Science, Contract No. KP-06-N-54/4. and in the framework of the National Science Program "Environmental Protection and Reduction of Risks of Adverse Events and Natural Disasters", approved by the Resolution of the Council of Ministers № 577/17.08.2018 and supported by the Ministry of Education and Science (MES) of Bulgaria (Agreement № Д01-271/09.12.2022) and the Bulgarian Ministry of Education and Science under the National Research Programme "Young scientists and postdoctoral students-2" approved by DCM 206/07.04.2022.

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SILVA BALCANICA

Silva Balcanica 24(3): 61-76 (2023)
doi: 10.3897/silvabalcanica.24.e116522

RESEARCH ARTICLE

Egg parasitoids of *Thaumetopoea pityocampa* in the region of Gyumyurdzhinski Snezhnik in Eastern Rhodopes, Bulgaria

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Academic editor: Margarita Georgieva | Received 16 November 2023 | Accepted 23 November 2023 | Published 28 December

Citation: Mirchev P., Georgiev G., Georgieva M., Zaemdzhikova G., Bocheva L., Boyadzhiev P., Dobreva M., Matova M. 2023. Egg parasitoids of *Thaumetopoea pityocampa* in the region of Gyumyurdzhinski Snezhnik in Eastern Rhodopes, Bulgaria. Silva Balcanica 24(3): 61-76. https://doi.org/10.3897/silvabalcanica.24.e116522

Abstract

The region of Gyumyurdzhinski Snezhnik in the Eastern Rhodopes is the closest in Bulgaria to the Aegean Sea. However, the climate is characterized by specific parameters that are determined by its relief. It is poorly protected from the invasion of cold air masses from the north. From the south, the Gyumyurdzhinski Snezhnik hill restrains the Mediterranean influence. The orography of the area favors the retention of cold air masses and a further drop in temperatures. The experimental material for the study includes 5 generations of *Thaumetopoea pityocampa* (2016, 2017, 2018, 2019, and 2022), collected in 31 locations of four State Forestry Enterprises: Kirkovo, Ardino, Momchilgrad, and Zlatograd. The sample for analysis included 693 egg batches with 148420 eggs in them. Seven primary egg parasitoids were established in this region: *Ooencyrtus pityocampae*, *Baryscapus servadeii*, *Pediobius bruchicida*, *Anastatus bifasciatus*, *Eupelmus vesicularis*, *E. vladimiri*, *Trichogramma* sp. and one hyperparasitoid (*B. transversalis*). Dominant parasitoids were *B. servadeii* and *O. pityocampae*, and *E. vladimiri* and *P. bruchicida* – occasional parasitoids. The hyperparasitoid *B. transversalis* participated in the complex with a relatively low share. The survival of the egg parasitoids in the laboratory conditions, in which the samples were kept, was low. The total mortality of the parasitoids in larval and adult stages was 47.8%. After collecting the samples, in laboratory conditions, a total of 442 individuals of the hyperparasitoid *B. transversalis* emerged, of which 56.3% were females and 43.7% were males. The average number of pine processionary moth eggs in a batch was 214.2. 70.8% of all the eggs in the samples hatched successfully. The egg parasitoids are a very serious natural factor, regulating the density of the pine processionary moth, but their impact varied from 2.1% to 30.3%. The natural characteristics of the area, the air temperature during the stages of eggs and young larvae, are favorable for the development of the pine processionary moth. Unhatched larvae without the influence of entomophages were 7.2%.

Keywords
Thaumetopoea pityocampa, ecology, parasitoids, Eastern Rhodopes, Bulgaria

Introduction

The pine processionary moth, *Thaumetopoea pityocampa* (Denis & Schiffermuller, 1775) (Lepidoptera: Notodontidae) is the most dangerous defoliator in pine forests in the Mediterranean region (Demolin, 1969b; Schmidt et al., 1990), including Bulgaria (Mirchev et al., 2003). The larvae attack the needles of different pine species (Devkota, Schmidt, 1990). Their hairs contain urticarial substances, causing dermatitis (Lamy, 1990).

The egg parasitoids are the most significant biological factor, regulating the numbers of the pine processionary moth (Mirchev, 2005; Schmidt et al., 1999; Tsankov, 1990).

The diversity of egg parasitoids of *T. pityocampa* in different areas is explained by the influence of ecological factors: temperature (Masutti, 1964), altitude (Tiberi, 1990), the floristic richness of the habitats is a prerequisite for the high parasitoid numbers, due to the favorable conditions for the development of alternative hosts (Mirchev, 2005).

Environmental factors influence the survival and other stages of the ontogenetic development of *T. pityocampa*. High summer temperatures are critical for the survival of eggs and young larvae (Huchon, Demolin, 1970; Santos et al., 2011; Robinet et al., 2013). Cold temperatures could be lethal for overwintering larvae (Radchenko, 1927; Russkoff, 1930; Zankov, 1960; Demolin, 1969a; Roques et al., 2015).

The Eastern Rhodope study area is the closest in Bulgaria to the Aegean Sea. However, the climate is characterized by specific parameters that are determined by its relief. It is poorly protected from the invasion of cold air masses from the north. From the south, the Gyumyurdzhinski Snezhnik hill restrains the Mediterranean influence. The orography of the area favors the retention of cold air masses and a further drop in temperatures. Under such conditions, minimum temperatures in the low parts of the region are sometimes from -10 to -12°C and in some cases -24 to -26°C (Georgieva et al., 2018).

The aim of the present study is: (i) to give a geographical and climatic characterization of the Gyumurdzhinsky Snezhnik region in the Eastern Rhodopes, important for the survival of the species as an egg and early-instar larva; (ii) to make a detailed characterization of the complex of egg parasitoids of *T. pityocampa* and their impact on host numbers; (iii) to provide information on the fecundity of *T. pityocampa* and the proportion of unhatched larvae without entomophagous influence.

Material and methods

Study area

The study area is located in the Eastern Rhodopes, surrounded by the following hills: Zhalti dyal in the west, Stramni rid in the east, Arda River in the north and in the south – Gyumyurdzhinski Snezhnik, with the highest peaks Veikata (1463 m a.s.l.) on Bulgarian territory, and Orlitsa (1510 m a.s.l.) in Greece.

Climate analysis

The climate analysis of the temperature regime for the period 2000-2022 is based on climate data from the National Institute of Meteorology and Hydrology. For the same period, the number of days with minimum air temperature ≤-15°C as well as days with maximum air temperature ≥32°C (critical for PPM eggs and larval evolution) was calculated for summer months.

Collection of biological material and laboratory studies

The experimental material includes five generations of *Thaumetopoea pityocampa* collected from 31 villages in the area of four State Forestry Enterprises (SFE) (Fig. 1), as follows:

- SFE Kirkovo – Yanino (2016), Dyulitsa (2016), Medevtsi (2016), Kayaloba (2016), Drangovo (2016), Dzherovo (2016), Domishte (2016), Dobromirtsi (2017, 2022), Gorno Kapinovo (2017), Yakovitsa (2017), Kolarovo (2017), Fotinovo (2018, 2019), Preseka (2019, 2022), Kitna (2022);
- SFE Ardino – Yabalkovets (2018, 2022), Svetulka (2018), Sransko (2018), Ardino (2022), Brezen (2022), Stoyanovo (2022), Yabalkovets (2022);
- SFE Momchilgrad – Mrezhichko (2018, 2019), Ridino (2018), Iliysko (2018), Rogozche (2018), Ustren (2019), Yamino (2019);
- SFE Zlatograd – Startsevo (2018), Kundevo (2018), Nedelino (2018, 2022), Izgrev (2022), Sredets (2022).

The sample for analysis included 693 egg batches with 148420 eggs in them. Part of the egg batches were collected by the Forest Protection Station – Plovdiv. Egg batches were collected after the larvae hatched. After collection, the egg batches were transported to the Forest Research Institute in Sofia. In laboratory conditions, each batch was put in a single test tube, covered with a cotton stopper, and kept at room temperature (20-22 °C). The scales of egg-masses were removed and the samples were analyzed according to the protocol, described by Tsankov et al. (1996). The fi-

Figure 1. Geographical location of the study area

nal laboratory analysis of each sample was performed after the end of the parasitoid flight. Every egg without a hole in its shell was opened carefully and the meconia and remains of the emerged or dead insects were determined using a stereomicroscope (40× magnification). Parasitoids that emerged before collection were determined by their meconia and remains according to Schmidt, Kit (1994), Tanzen, Schmidt (1995), Schmidt et al. (1997) and Tsankov et al. (1996, 1998a), Zaemdzhikova et al. (2021).

Results

Climatic characterization of the studied area

Climate region of East Rhodope river valleys (Kirkovo, Dzhebel, Krumovgrad, Ivailovgrad)

The region covers the East Rhodope river valleys and the relatively low hills separating them from the east of the Maritsa valley to the south of the Harmanliyska River. Compared to the valleys of Struma and Mesta, it is considerably less protected from the influence of cold air masses. The area has an altitude of 50 to 400 m and is relatively close to the Aegean Sea.

With the activation of the Mediterranean cyclones during fall and the beginning of winter, the region of the Eastern Rhodope River valleys gets one of the largest rainfall for the lower part of the country – about 200 mm. Because of the southern position of the area, much of this precipitation is from rain or rain and snow and often leads to a dangerous rise of river levels and local floods.

Winter is relatively mild, with average January temperatures above 0 °C (+0.5 °C to +2.5 °C). But after the invasion of a cold front from the north followed by an anticyclonic synoptic situation, the air temperatures in the area fall down rapidly. The orography of the area favors the retention of cold air masses and further fall of temperatures. Under such conditions, the minimum temperatures in the lower parts of the area are sometimes from -12 °C to -15 °C (Dzhebel and Krumovgrad), and in some cases, -20 °C to -22 °C. During the period 2000-2022, the mean annual number of days with minimum air temperature equal to or below -15 °C was about 1.5 days.

The average January soil temperature in the 2-20 cm layer is between 1.5 °C to 2 °C and between 2.5 °C to 3 °C respectively. Nevertheless, at these relatively high temperatures, the soil almost freezes every year to a depth of 10 cm. In extreme cases with prolonged cold weather without snow cover the soil freezes to a greater depth (up to 32 cm).

The summer is sunny, hot and dry. The average July temperatures are 23-25 °C, and during only a few days the average daily temperature is lower than 20 °C. The maximum temperatures in July and August reach values of 41-44 °C. The mean annual number of days with maximum air temperature ≥32°C for this region was above 40 days during the period 2000-2022 and the mean number of consecutive hot days was about 12-13 days/year. The highest number of consecutive days with maximum air temperature ≥32 °C was 25-30 days in 2020, followed by 21 days in 2016.

Eastern Rhodope low-mountain climatic region (south of Kirkovo, Zlatograd, Gyumyurdzhiiski Snezhnik)

The Eastern Rhodope low-mountain climate region is distinguished from the region of the Eastern Rhodope river valleys both by its higher altitude (400-1000 m) and by the quantitative and structural characteristics of the regime of individual meteorological elements.

Due to its higher altitude, the winter in the Eastern Rhodope low mountain region is slightly colder than that in its adjacent valley region. The average January temperature is about 1 °C lower than those in the valley region (-1.5 °C to 1 °C). But in return for its predominance of sloping and salient terrain, this region does not experience such appreciable drops of temperature as the ones possible in the valley region in cases of anticyclonic weather following a more severe cold intrusion. During the period 2000-2022 the mean annual number of days with minimum air temperature ≤-15 °C was below 1 day, and even in the region of Zlatograd, since 2012, there have been no recorded minimum temperatures equal to or lower than -15 °C.

The summer is moderately warm with average July temperatures between 20 °C and 22 °C. The maximum temperatures in July and August reached values of 36-38 °C during the period 2000-2022. The mean annual number of days with maximum air temperature ≥32°C for the same period was 20, while the number of consecutive days with such temperature was about 7 days/year. The highest number of consecutive hot days was 15 in 2007, followed by 14 in 2008 and 2012.

It can be summarized that in lower parts of the region of interest, the climatic conditions in both winter and summer are less favourable for the PPM eggs and larval survival. Unfavourable temperature conditions are almost twice more frequent both in winter and in summer in the East Rhodope river valleys region compared to the Eastern Rhodope low-mountain climatic region.

Spectrum of egg parasitoids

The results obtained by the analysis of the parasitoids that emerged or died in their developing stages in the eggs, are presented in Table 1. Seven primary egg parasitoids were established in this habitat: *Ooencyrtus pityocampae* Mercet, 1921 (Hymenoptera: Encyrtidae); *Baryscapus servadeii* Domenichini, 1965; *Pediobius bruchicida* Rondani, 1872 (Hymenoptera: Eulophidae); *Anastatus bifasciatus* Fonscolombe, 1832; *Eupelmus* (*Macroneura*) *vesicularis* Retzius, 1783; *Eupelmus* (*Macroneura*) *vladimiri* Fusu, 2017 (Hymenoptera: Eupelmidae) and *Trichogramma* sp. (Hymenoptera: Trichogrammatidae), and one hyperparasitoid, *Baryscapus transversalis* Graham, 1991.

Table 1. Egg parasitoids found in egg batches

	State Forest Enterprise										
	Kirkovo					Momchilgrad		Zlatograd		Ardino	
Parasitoids Year	2016	2017	2018	2019	2022	2018	2019	2018	2022	2019	2022
Total number of parasitoids, of them	4791	6675	382	536	1413	162	1115	615	336	112	2089
Ooencyrtus pityocampae, %	29.1	35.2	35.6	53.5	28.5	0.6	55.2	15.6	37.8	2.7	16.3
Baryscapus servadeii, %	62.4	59.6	44.2	44.8	69.3	93.8	42.6	60.8	48.8	81.2	72.3
Baryscapus transversalis, %	2.5	5.0	17.8	0.6	1.6	1.9	0.1	0.8	4.2	2.7	7.7
Anastatus bifasciatus, %	5.9	-	-	0.9	0.6	3.7	0.5	0.3	1.2	0.9	2.6
Trichogramma sp., %	0.1	0.1	1.6	0.2	-	-	1.6	22.5	8.0	12.5	1.1
Eupelmus vladimiri, %	-	0.1	0.5	-	-	-	-	-	-	-	-
Pediobius bruchicida, %	-	-	0.3	-	-	-	-	-	-	-	-

Dominant parasitoids were *B. servadeii* and *O. pityocampae*. The first species was the most numerous in 9 out of 11 analyzed samples (81.8%) and *O. pityocampa* only in the 2019 samples from Kirkovo and Momchilgrad.

The polyphages *A. bifasciatus* and *Trichogramma* sp. were found in 81.8% of the samples. In the case of the polyembryonic *Trichogramma* sp., the abundance was counted according to the number of eggs of the host, in which it was found. The relative share of *Trichogramma* sp., decreased from 22.5% (Momchilgrad, 2018) to around and below 1% in six of the samples. The participation of *A. bifasciatus* with a maximum value of 5.6% in the 2016 sample from Kirkovo was also in this order.

E. vladimiri and *P. bruchicida* were occasional parasitoids on *T. pityocampa* eggs. Of *P. bruchicida*, only one male individual was imagined from Kirkovo – 2018, and of *E. vladimiri* – 6 and 2 male individuals from the same location in the 2017 and 2018 samples, respectively. The hyperparasitoid *B. transversalis* participated in a complex with relatively low share (0.1-17.8%).

Egg parasitoids and their development rates in egg-batches

Parasitoids have clearly defined differences in imagination time (Table 2). The main part – 72.5 % in *O. pityocampae* were imagined before collecting the sample, i.e. parasitizing happens at an early stage after the appearance of the egg batches. For the other egg parasitoids, these values are: *A. bifasciatus* – 68.1%; *B. servadeii* – 56.4%; *Trichogramma* sp. – 23.8 % and for the hyperparasitoid *B. transversalis* – 1.0 %.

The survival of egg parasitoids in laboratory conditions, in which the samples were kept, was low. In the larval stage, 43.3% died. Following percentage of the parasitoids were found dead as a developed imago in the egg of the host: *Trichogramma* sp., – 70.0 %; the hyperparasitoid *B. transversalis* – 34.0%; *O. pityocampae* – 18.8%, *A. bifasciatus* – 9.8% and the lowest percentage for the specific parasitoid *B. servadeii* – 4.3%.

The total mortality of all parasitoids in larval and imago stages is nearly half of their number – 47.8% (Table 2).

Sexual ratio of the hyperparasitoid *B. transversalis*

After collecting the samples, in laboratory conditions, a total of 442 individuals of the hyperparasitoid *B. transversalis* were imagined, of which 56.3% were females and 43.7% were males.

In the three samples with a significant number of emerged individuals, the following ratios were obtained: Kirkovo (2017): imagined 177 adults, with a female: male ratio of 52.5:47.5; respectively, Kirkovo (2018): 80.3:19.7 out of 61 individuals and Ardino (2022): 145 individuals with 61.4:38.6 ratio (Table 2).

Structure of egg clusters and rate of larval hatching

A total number of 148414 eggs of *T. pityocampa* was analyzed (Table 3). The average number of eggs laid in a batch varied from 176.9 (Kirkovo, 2019) to 226.2 (Momchilgrad, 2019), with an average of 214.2 for the study area.

70.8%. of all the eggs in the samples hatched successfully. In individual samples, these values vary within very wide limits from 57.8% (Kirkovo, 2017) to 94.8% (Ardino, 2019).

The results show that egg parasitoids are a very serious natural factor, regulating the density of the pine processionary moth. However, their impact varied widely from 30.3% 2.1% (Ardino, 2019) to (Kirkovo, 2017), i.e. a difference of 14.4 times. The role of predators was negligibly low, between 0.1 and 1.7%.

Table 2. The egg parasitoids of *T. pityocampa* and their development rates in egg-batches

	State Forest Enterprise										
	Kirkovo					Momchilgrad		Zlatograd		Ardino	
Parasitoids Year	2016	2017	2018	2019	2022	2018	2019	2018	2022	2019	2022
Ooencyrtus pityocampae	1393	2349	136	287	403	1	615	96	127	3	341
Emerged before collection	1098	1620	45	226	328	1	449	33	86	1	285
Emerged after collection	80	201	38	28	10	-	88	39	10	1	5
Adults died in eggs	215	528	53	33	65	-	78	24	31	1	51
Baryscapus servadeii	2992	3980	169	240	979	152	475	374	164	91	1510
Emerged before collection	1483	2326	41	237	541	130	443	171	53	86	760
Emerged after collection	1366	1465	126	-	401	22	7	198	102	1	693
Adults died in eggs	143	189	2	3	37	-	25	5	9	4	57
Baryscapus transversalis	122	331	68	3	23	3	1	5	14	3	160
Emerged before collection	4	3	-	-	-	-	-	-	-	-	-
Emerged after collection, ♀♀	38	93	49	-	3	1	-	1	1	-	89
Emerged after collection, ♂♂	23	84	12	1	9			1	4	3	56
Adults died in eggs	57	151	7	2	11	2	1	3	-	-	15
Anastatus bifasciatus	281	-	-	5	8	6	6	2	4	1	54
Emerged before collection	232	-	-	5	-	3	-	-	-	-	10
Emerged after collection	33	-	-	-	2	3	3	-	1	-	36
Adults died in eggs	16	-	-	-	6			2	3	1	8
***Trichogramma* sp.**	**3**	**9**	**6**	**1**	-	-	18	138	27	14	24
Emerged before collection	3	-	-	1	-	-	5	31	10	3	4
Emerged after collection	-	9	6	-	-	-	-	-		-	-
Adults died in eggs	-	-	-	-	-	-	13	107	17	11	20
Eupelmus vladimiri	**-**	**6**	**2**	-	-	-	-	-	-	-	-
Emerged after collection	-	6♂	2♂	-	-	-	-	-	-	-	-
Pediobius bruchicida	-	-	**1**	-	-	-	-	-	-	-	-
Emerged after collection	-	-	1♂	-	-	-	-	-	-	-	-
Undetermined larvae of parasitoids	2189	6342	736	379	913	64	697	186	172	15	1154
Eggs destroyed by predators	504	667	10	2	17	47	81	139	24	19	144

Table 3. Structure of egg clusters and rate of hatching of larvae of *Thaumetopoea pityocampa*

	State Forest Enterprise										
	Kirkovo					Momchilgrad		Zlatograd		Ardino	
Parameters Year	2016	2017	2018	2019	2022	2018	2019	2018	2022	2019	2022
Total number of egg batches	137	199	30	27	41	17	51	50	30	28	83
Total number of eggs	30426	42952	6367	4775	8116	3639	11536	10225	6939	6058	17381
Number of egg per batch	222.1	215.8	212.3	176.9	198.0	214.1	226.2	204.5	231.3	216.4	209.4
Larvae hatched, %	68.1	57.8	72.6	75.3	63.7	82.9	79.5	84.2	90.3	94.8	76.4
Impact of egg parasitoids, %	22.9	30.3	17.6	19.2	28.7	6.2	15.7	7.8	7.3	2.1	18.7
Impact of predators, %	1.7	1.6	0.2	0.1	0.2	1.3	0.7	1.4	0.3	0.3	0.8

Unhatched larvae without the influence of entomophages

The natural characteristics of the area, the air temperature during the stages of eggs and young larvae, are favourable for the development of the pine processionary moth. The unsuccessfully hatched larvae were less than a tenth of the eggs – 7.2%, from 2.8% (Ardino, 2019) to 10.4% (Kirkovo, 2017).

Eggs with unhatched larvae were categorized into four groups: dead larvae without opening, the death of the larvae occurred in the egg at various stages of their development; larvae died, with an opening in the egg; undeveloped eggs with dried-up yolk; eggs totally empty, without any remains.

Of the unhatched eggs, on average for the region, the share of the first group is the highest – 35.4% and the difference between individual samples is 41.2 points. On average, undeveloped eggs with dried-up yolk were 29.5%, with a more homogeneous group: max – 42.1%, min – 18.2%. Close to this average value was that of empty eggs, without any remains – 27.4% (max – 42.7%, min – 1.2%). The share of fully developed larvae that died during the hatching process was the lowest – 7.7% (Table 4).

Table 4. Structure of unhatched larvae without the influence of entomophages

	State Forest Enterprise										
	Kirkovo					Momchilgrad		Zlatograd		Ardino	
Parameters Year	2016	2017	2018	2019	2022	2018	2019	2018	2022	2019	2022
Unhatched caterpillars, %	7.3	10.4	9.7	5.5	7.4	6.6	2.0	9.6	4.1	2.8	4.1
Total number of larvae died, of them	2225	4453	615	262	600	675	140	348	472	166	709
Larvae died, without opening, %	27.3	25.2	54.8	66.4	25.8	55.2	47.2	58.1	61.3	64.5	48.5
Larvae died, with opening, %	6.1	5.8	17.1	6.9	5.8	15.3	7.1	13.2	5.9	3.6	11.0
Undeveloped eggs with dried-up yolk, %	23.9	35.6	18.2	24.4	20.2	28.9	42.1	26.7	28.8	30.7	28.2
Eggs totally empty, without any remains, %	42.7	33.4	9.9	2.3	48.2	0.6	3.6	2.0	4.0	1.2	12.3

Discussion

The studied area belongs to the South-Bulgarian subarea of the Continental-Mediterranean climate area, but in it 2 different climatic regions can be distinguished (Sabev, Stanev, 1959) – East Rhodope river valleys and Eastern Rhodope low-mountain regions. Each of them has specific climatic characteristics. The main features of the climate subarea are the mild and very humid winter and sunny, hot and dry summer. During the second half of the autumn (in November) or at the beginning of winter (in December) maximum precipitation sums are observed – about 2.5-3 times more than in August or September. The summer is characterized by dry, hot weather – most pronounced in the lower parts of the considered area (up to 400 m a.s.l.), along the river valleys, with average July temperatures 22-25 °C. The driest month of the year for this area is August or September.

The comparison of the ecological conditions with the habitats in the lower reaches of the Struma River, based on the research and assessments for the period 1991-2017, according to data from the meteorological database of NIMH, it can be concluded that the summer in Sandanski and Kirkovo is dry and hot, but in the first region, it is significantly warmer and drier, especially in June.

For both regions, the warmest month is August, while the absolute summer maximum air temperature is recorded in July. The average number of days with maximum air temperature ≥ 32 °C (critical for the development of PPM larvae) for the Kirkovo region is 4 days in June, 12 in July, and 14 in August. For the Sandanski region, they are as follows: 11 days in June, 21 days in July, and 22 days in August. In addition to the significantly higher average number of days with air temperature ≥32 °C, significantly longer periods of retention of these temperatures were also recorded in Sandanski: 43 days in 2012 (from June 29 to August 10); 41 days in 2015, and 38 days in 1998 and 2013. For the Petrichko-Sandanski climate region, the typical retention period of maximum temperatures above the specified limit is 15-20 days during the summer months. At the same time, this number for the Kirkovo region was only 10-12 days. The longest periods of retention of maximum air temperatures ≥32 °C for the region of the Eastern Rhodope river valleys were observed in 2016 – 21 days (from July 22 to August 11) and in 1998 – 20 days (Mirchev et al., 2018).

In the easternmost part of the Rhodopes, in the region of Ivaylovgrad, five parasitoids were found: *B. servadeii*, *O. pityocampae*, *A. bifasciatus*, *B. transversalis* and *P. bruchicida*. The most numerous is *Baryscapus servadei,* with relative participation of 45.9–85.6%, followed by *O. pityocampae* (7.2–38.4%). The relative participation of *A. bifasciatus* and the hyperparasitoid *B. transversalis* is about 10%. *P. bruchicida* has sporadic participation (Mirchev et al., 2012; 2014; Zaemdzhikova et al., 2019).

In the westernmost part of southern Bulgaria, in habitats along the Struma River, *Trichogramma embryophagum* and *E. vesicularis* (in Marikostinovo) were also found in addition to the parasitoids mentioned above. In all localities (Ploski, Sandanski, and Marikostinovo), *O. pityocampae* is the most numerous. The abundance of *A. bifasciatus* and *B. servadeii* is much lower. The hyperparasitoid *B. transversalis* was found at a low density (Tsankov et al., 1996; 1998b; 1998c; Mirchev, Tsankov, 2003).

Halfway between the above two geographical points in the Western Rhodope region (Satovcha, Valkosel, and Slashten) 6 parasitoids have been reported, without the one mentioned in Marikostinovo – *E. vesicularis*. The most frequent parasitoids were *O. pityocampae* and *B. servadeii* (85% of total parasitoids counted). A clear trend in these two parasitoids over the years is an increase in the proportion of *O. pityocampae*, while *B. servadeii* is in sharp decline (Tsankov et al., 1998c; Mirchev et al., 2010).

There are several hypotheses in the literature that seek to explain why a given parasitoid is more numerous in a certain area.

Massuti (1964) pointed out that temperature is the limiting factor, the representatives of Eulophidae are more plastic and develop successfully in areas with temperatures above 30 °C, conditions that hinder the development of *O. pityocampae*. Therefore, in Italy, *B. servadeii* has the highest abundance in the warmer areas of the central and southern part of the country but was not found in Sicily and in the pine forests of Abruzzo at low altitude (Tiberi, 1990).

B. servadeii can successfully parasitize the pine processionary moth eggs from their laying until the caterpillar's hatch, while for *O. pityocampae* this period is shorter. When encyrtid parasitizes eggs after 32 days of the host incubation period, the parasitoid cannot develop (Halperin, 1990a).

The successful development of *O. pityocampae* requires a richer species diversity in the floristic aspect of the given habitat, which would create a favourable environment for the development of these hosts. Eighteen alternative hosts have been reported for this parasitoid (Thompson, 1954; Battisti et al., 1988; Tiberi et al., 1993; Masuti et al., 1993; Halperin, 1963, 1990b; El-Yousfi, 1989; Schmidt and Kitt, 1993, 1994, 1995; Kitt, Schmidt, 1993; Trjapitzin, 1978, 1989).

In summary, the essential factors for the development of *O. pityocampae* are (i) certain temperature conditions – below 30 °C (ii) a particular stage of embryonic development of the host; (iii) availability of alternative hosts. Knowledge of the biology and ecology of *B. servadeii* and *O. pityocampae* does not explain the obtained data on the number and ratio between them in the southern limit of the distribution of the pine processionary moth in Bulgaria. For example, the low number of *B. servadeii* in Marikostinovo is striking, and radically different from the results and conclusions indicated by Tiberi (1990).

Of the two parasitoids that have sporadic involvement, *E. vladimiri* was recorded for the first time in trophic association with *T. pityocampa* in the region of Kirkovo (Boyadzhiev et al., 2020), and *P. bruchicida* has been reported for Marikostinovo, Central Bulgaria (Mirchev et al., 2021) Western Rhodopes (Mirchev et al., 2010) and Ivaylovgrad (Mirchev et al., 2012).

In the study area for the imago of *B. transversalis* the female: male individuals ratio is 56.3:43.7, i.e. the proportion of females is lower than the established average values for the hyperparasitoid population in Bulgaria, which are 63.1:36.9 (Mirchev et al., 2022).

There is no data in the literature on the influence of environmental factors on the formation of the sex ratio in this parasitoid. In other parasitoids, such an influence has been demonstrated. The sex of *O. pityocampae* depends on the temperature at which they develop. At a constant temperature of 32 °C, only females imagine (theliotoky), at 32.5–33.0 °C males are also found (deuterotoky, amphitoky), while at 34 °C or more, all offspring are male (arenotoky) (Halperin, 1990b). The influence of temperature on the formation of the sex in another member of this genus, *O. submetallicus* (Howard, 1897), was reported by Wilson, Woolcock (1960). Schmidt, Tanzen (1998) reported that the offspring of fertilized females were of both sexes.

Stahl et al. (2018) found that in *A. bifasciatus*, sex depends on host egg size.

In the present study, only male individuals of *E. vladimiri* emerged. For another representative of this genus – *Eupelmus vuilleti* (Crawford, 1913) it was established that, in larger hosts, fertilized eggs are laid, from which female adults appear, and in smaller hosts – unfertilized eggs and male generation (Terrasse et al., 1996).

In this study, *T. pityocampa* fecundity averaged 214.2, ranging from 176.9 to 226.2. In the neighbouring areas of the southern border of the pine processionary moth in Bulgaria, these values are: Ivaylovgrad 250-279 (Mirchev et al., 2012); Western Rhodopes 207-225 (Mirchev et al., 2010); Marikostinovo 203-253 (Tsankov et al., 1998b); Ploski 198-241 (Tsankov et al., 1998a) and Sandanski 193-253 (Mirchev, Tsankov, 2003). The data show that fecundity is neither a constant value for the species nor for a given region. In the present study, the deviations around the mean value were 17.5%, similar to the reported data for the neighboring districts. It is determined both by several environmental factors and by the phase of the population size in the given year. Masutti, Battisti (1990) considered that the fecundity of the pine processionary moth depends on the climatic conditions, the host plant, and the population cycle. Özkazans (1987) noted that the egg productivity of the pine processionary moth increases with increasing altitude of the species' habitats.

With all the conventions, it can be concluded that the fertility of *T. pityocampa* in the studied area is comparable to that of the neighbouring areas.

70.8% (57.8–94.8%) of all the eggs in the samples hatched successfully. Parasitoids are the most serious regulator – 20.9% parasitized eggs, with a large variation in samples from 2.1 to 30.3%. The role of predators is in the range of 1.1% (0.1–1.7%). Unhatched larvae were 7.2% (2.8–10.4%). The values of hatched larvae, the impact of parasitoids, predators and the relatively low relative proportion of unhatched larvae are indicators of favourable ecological conditions of the environment for the development of *T. pityocampa* and entomophages.

In conclusion, it could be noted, that the region of Gyumurdzhinsky Snezhnik in Eastern Rhodopes is a very specific habitat for the pine processionary moth in the southernmost part of Bulgaria in which summer air temperatures are quite favourable for its survival in egg and early-instar larval stage. On the other hand, the rich complex of egg parasitoids in the study area is a very serious natural factor, regulating the density of the pest by up to 30%.

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SILVA BALCANICA

Silva Balcanica 24(3): 77-94 (2023)
doi: 10.3897/silvabalcanica.24.e114644

RESEARCH ARTICLE

Identifying key quality characteristics of woody biomass for bioenergy application: an international review

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Academic editor: Ivailo Markoff | Received 24 October 2023 | Accepted 18 November 2023 | Published 28 December

Citation: Ghaffariyan M.R. 2023. Identifying key quality characteristics of woody biomass for bioenergy application: an international review. Silva Balcanica 24(3): 77-94. https://doi.org/10.3897/silvabalcanica.24.e114644

Abstract

Biomass characteristics play an important role in product classification, economic values, and types of usage. This research was initiated by the IEA Bioenergy Technology Collaboration Programme, which aimed to review and identify the top biomass characteristics as they relate to commercially viable biomaterial and bioenergy processes. An online search (in English) was conducted using the following keywords: biomass, chips, quality, characteristics, moisture content, calorific values, contamination and ash content. The search was restricted to woody biomass and raw feedstock materials. Review results were classified based on regions including Africa, America, Asia, Europe and Oceania. Each case study was described based on the study background, type of biomass and biomass attributes that were measured. The key biomass characteristic was moisture content that was consistently measured in almost all reports. Ash content and calorific value were classified as second place in terms of frequency in the biomass studies. Lower frequency belonged to the attributes such as bulk density, contamination, particle shape and nutrient (elemental) content. Detailed information of different case studies is provided in this report. It is anticipated that this literature review will assist IEA Bioenergy and its industrial and scientific network to better understand the current knowledge gaps regarding woody biomass characterisation.

Keywords

Woody biomass, Quality characteristics, Moisture content, Calorific value, Contamination, Ash content

Introduction

Globally there is increased demand for sustainable energy solutions as well as an increasing range of bioproducts that are driving increased demand for biomass. As these markets grow and mature biomass producers will shift from primarily seeking out economically viable market options to seeking to access the highest value market their biomass resource is suitable for. The ability to match biomass quality and characteristics to market value and opportunities will require a shift from simple trading values based on volume, mass and moisture content to being able to identify and measure characteristics of the biomass that dictate its value in different energy and biomaterial production processes like calorific value, cellulosic content, ash content, fiber length/strength, etc. In addition to better positioning in high demand, multiple end-user markets, this basic knowledge of biomass quality will enable effective and economic access to areas with emerging biomass opportunities (Brown, 2022).

Biomass characteristics play an important role in product classification, economic values, and types of usage. One of the key characteristics is particle size distribution of wood chips. Handling and combustion of solid biofuel, ventilation properties and storage types can be impacted by particle size (Kristensen and Kofman, 2000). According to Kuptz et al. (2019) wood chip quality is a key factor to achieve low-emissions combustion of small boilers with capacity less than 100 kW.

There are two types of biomass lab analysis including proximate and ultimate analysis. Proximate analysis is a laboratory technique used to determine the major components or constituents of a sample. It provides information about the approximate composition of a substance based on its physical and chemical properties. The main components typically analysed in proximate analysis include moisture content, volatile matter, fixed carbon, and ash content. Ultimate analysis is a more comprehensive analytical technique that determines the elemental composition of a substance. It involves measuring the percentage of Carbon (C), Hydrogen (H), Nitrogen (N), Sulfur (S), and other elements present in the sample (Turn et al. 2005). Key quality characteristics of the woody biomass depend on the biomass conversion process and the related product. Kenney et al. (1992) mentioned that qualitative, physical, and chemical characteristics of biomass feedstocks are important when defining their suitability for different conversion systems. Different types of sugar such as hemicellylose and guaiacyl/syringyl ratio in the lignin are main qualitative traits. Moisture content and density are key factors for converting woody biomass into energy. According to Kenney et al. (1992) there are three main types of biomass process including direct combustion (heat process), thermochemical and biochemical. For the heat process the biomass feedstock requires low moisture content, high density, low cellulose/lignin ratio, high guaiacyl/syringyl ratio, high extractive content and low ash content. The thermochemical process would benefit from low moisture content, high density, low cellulose/lignin ratio, high guaiacyl/syringyl ratio and high extractive content. When the biomass feedstock has high cellulose/lignin ratio, low proportion of pentose sugars, low guaiacyl/syringyl ratio and minimum content of potentially toxic extractives or heavy metals then it may be ideal for biochemical processes.

This research was initiated by the International Energy Agency of Bioenergy Technology Collaboration Programme (IEA Bioenergy TCP) which aimed to review and identify the top 3 to 5 biomass characteristics as they relate to commercially viable biomaterial and bioenergy processes. The intention is to assist IEA Bioenergy and its industrial and scientific network to better understand the current knowledge gaps regarding woody biomass characterisation.

Methods

An online search (in English) was conducted using the following keywords: biomass, chips, quality, characteristics, moisture content, calorific value, contamination, ash content. Search engines such as Google Scholar, Scopus, Web of Science and Research Gate were used to find relevant articles via Google online search. The online search yielded 219,000 cases in total. The first 10 pages of online search were found to be relevant to the topic of the article. Out of 110 cases, 42 articles/reports published after 2000 and primarily over the last decade were chosen for this literature review which focused on woody biomass and its raw feedstock materials. The rest (68 cases) were excluded after checking their title and content as they were related to other types of biomass and feedstock. Review results were classified based on regions including America, Asia, Europe and Oceania. Each case study was described based on the study background, type of biomass and biomass attributes that were measured. Through a literature and technology review, current and near commercial technologies for the production of energy and materials from biomass were identified as well as what characteristic(s) of biomass was the key driver of the efficiency and effectiveness of the process. A list of the key characteristics was developed for each case study, and priorities based on how many bioenergy and bio material processes it has an important influence on (Brown, 2022).

AMERICA

Brazil

Generating energy from biomass is known as an opportunity in Brazil. Brazil has large Eucalypt plantations which cover about 6.9 million ha. Caraschi et al. (2019) reported that Eucalypt barks were one of the waste materials (including industrial waste and sweepings) that had low quality due to high ash content (up to 10%) and low calorific value. A combustion process was difficult due to the high moisture content of the barks. Rebeiro et al. (2021) evaluated the Eucalypt woodchip utilisation as a source of fuel in a thermal power plant. They sampled wood chips from 7 year old *Eucalyptus* hybrids *E. urophylla* x *E. grandis* that was harvested. Biomass characterisation was conducted by measuring attributes such as moisture content, bulk density, calorific value and ash content which are key factors to help reduce the costs and improve combustion performance to create sustainable thermal power generation.

Canada

Thiffault et al. (2019) investigated the properties of four types of residue feedstock including green wood chips, dry shavings, solid and engineered wood sawdust to optimize the quality of wood pellets. Tested properties included particle size distribution, moisture content, bulk density, ash content, calorific value, hemicelluloses, lignin, cellulose, extractives, ash major and minor elements, and carbon, nitrogen, and sulphur. Moisture content and biomass composition were the most impactful properties in terms of determining pellet quality. According to Canadian biomass producers moisture content is a key factor to predict the net calorific value of biomass materials (https://www.ontario.ca/page/biomass-burn-characteristics) while biomass composition, ash content, carbon, hydrogen, nitrogen, sulphur, chloride and soil contamination remain important factors to consider.

Mann (2012) compared yield and biomass characteristics of woody and herbaceous biomass in Southern Ontario including *Miscanthus*, switchgrass, willow, and poplar during the first and second years of growth. The characteristics tested included gross calorific value, ash level (%) and ash elemental analysis. The combustion characteristics of woody biomass were different to the grass biomass. A report published by FPInnovations provided a list of critical biomass attributes for various applications including direct combustion, gasification, pyrolysis, torrefaction, fermentation, and densification. Biomass format was one of the attributes including short and long logs, chunks, firewood, hog fuel, wood chips, construction and demolition waste, processing residue and sawdust. Other attributes included moisture content, calorific value, bulk density, foliage/bark content, ash, lignin, carbohydrate, extractive contents (Marinescu, 2013), extraneous material (stones, sand, and dirt) and contamination (such as glass, metal, plastics) (Natural Resources Canada https://www.nrcan.gc.ca). For the pyrolysis process, pre-treatment of the biomass feedstock can play a major role. Rezaei et al (2018) mentioned that these pre-treatments can change the biomass feedstock's size, shape, mineral content, composition, hygroscopic properties, homogeneity, grindability, stability and transportability.

USA

There have been several research projects conducted in the USA dealing with various types of biomass and species. In 2008 a study was carried out by CNH Industrial Group involving harvesting short rotation crops in Auburn using a Holland single pass harvester-chipper. The willow, poplar and Eucalypt stands were cut and chipped using the Holland harvester-chipper (Figure 1). The main biomass characteristics of willow stands were assessed which included moisture/energy content, size classification and ash content as selected elements (N, P, K, Ca, Cu, Mg, Na, S, and Zn) (Eisenbies et al. 2008).

Figure 1. Willow biomass chips for temporary storage in Upstate NY, USA (Eisenbies et al. 2008)

Eisenbies et al. (2016) studied the storage of willow stand chips collected by an unmodified New Holland FR9080 harvester, equipped with a New Holland 130FB coppice header near Groveland, New York. Changes on moisture content, ash content and calorific value were assessed during several months of storage. Chip quality change during the first two months of storage was minimal while it did not vary highly over a longer period. In a study by Turn et al. (2005) in plantations on the islands of Kauai and Hawaii wood chip samples (Figure 2) were collected from slab wood produced from sawmill operations. Several species including *Eucalyptus grandis,* ironwood, waiwi, tropical ash, and Moluccan albizia trees were chosen to sample randomly from the plantations.

Bulk density (dry and wet), particle size distribution, ash content, volatile matter content of bole wood samples and calorific value were assessed. The ultimate analysis evaluated the elements as Nitrogen, Carbon, Sulphur, and Chlorine.

Figure 2. Measuring wood chips bulk density in Hawaii, USA (Turn et al. 2005)

Ciolkosz (2010) indicated that calorific value, moisture content, chemical composition and size classification and density can impact the performance of biomass fuel (https://www.engineering.iastate.edu). A study in loblolly pine stands in central Georgia by Cutshall (2012) examined the impact of natural drying on the cost of whole tree chipping and transportation operations. Biomass characteristics such as calorific value, ash content, bark content and nutrient content of the produced wood chips were assessed. Drying reduced moisture content but did not significantly change the ash content. Transportation costs decreased due to reduced moisture content and increased payload (Cutshall, 2012).

Pradhan (2015) tested several physical treatments to reduce ash content and its impacts on pyrolysis products in Alabama based on sweetgum, residual pinewood, whole pinewood and dirty pinewood. To reduce soil contaminants from the wood chips (which could then reduce ash content) the following tools were tested: vibratory sieve shaker, hammer mill, and mixer. The vibratory force created by the vibratory sieve shaker, the rotary motion created by the mixer and the beating action by the hammer resulted in the separation of soil from wood chips.

Sharma et al. (2017) reported that ash content, calorific value, moisture content and density of the feedstock are the most critical attributes of biomass feedstocks. The research on pine and hardwood pellets in Louisiana suggested that these resources are suitable for gasification due to their high density and low moisture/ash content. Scholars in Georgia studied the biomass characteristics of two main species including Loblolly pine (*Pinus taeda*) and slash pine (*Pinus elliottii*) trees as main biomass resources in the Southeastern United States. Calorific value was claimed to be the most important variable for bioenergy production. The stands were thinned using feller-bunchers and grapple skidders. The whole trees were then chipped using a Morbark 30/36 drum-style chipper. Wood chips samples were collected which contained bark, needle, branch and wood. The samples were dried and screened by a 1 mm screener, then used for laboratory analysis. The research team applied near infrared reflectance (NIR) spectroscopy to measure gross/net calorific value, ash/moisture content, total carbon, total nitrogen/carbon/sulphur. The application of NIR provided accurate results with standard error less than twice of the laboratory method (Saha et al. 2017).

ASIA

India

Lenka (2016) published his thesis on "characterization of the properties of some biomass species and estimation of their power generation potentials" in India. He indicated that India has several energy resources and the energy demands of the country are high. Among the available energy resources, renewable energies sound attractive due to their low emissions. Power generation using biomass could be more environmentally friendly due to the large resource availability, low ash content and low pollutants element such as Cox, SOx and NOx. Two species including *Vachellia nilotica* and *Azadirachta indica* were tested. Their biomass samples contained leaf, branches, bark and root. Calorific value, fixed carbon content, moisture/ash content and bulk densities were measured. In the other trial Chakradhari and Patel (2016) sampled 53 trees in Chhattisgarh state. Various tree parts were sampled, and oven dried at 50°C for a period of one day. Then all samples were crushed and passed through a sieve of 0.25 mm. The characteristics such as bulk density, moisture/ash content and calorific value were assessed. Statistical results confirmed the larger bulk density increased calorific value based on a linear model function. Moisture content did not significantly change net calorific value. Following a linear model function higher ash content resulted in lower calorific value (Figure 3).

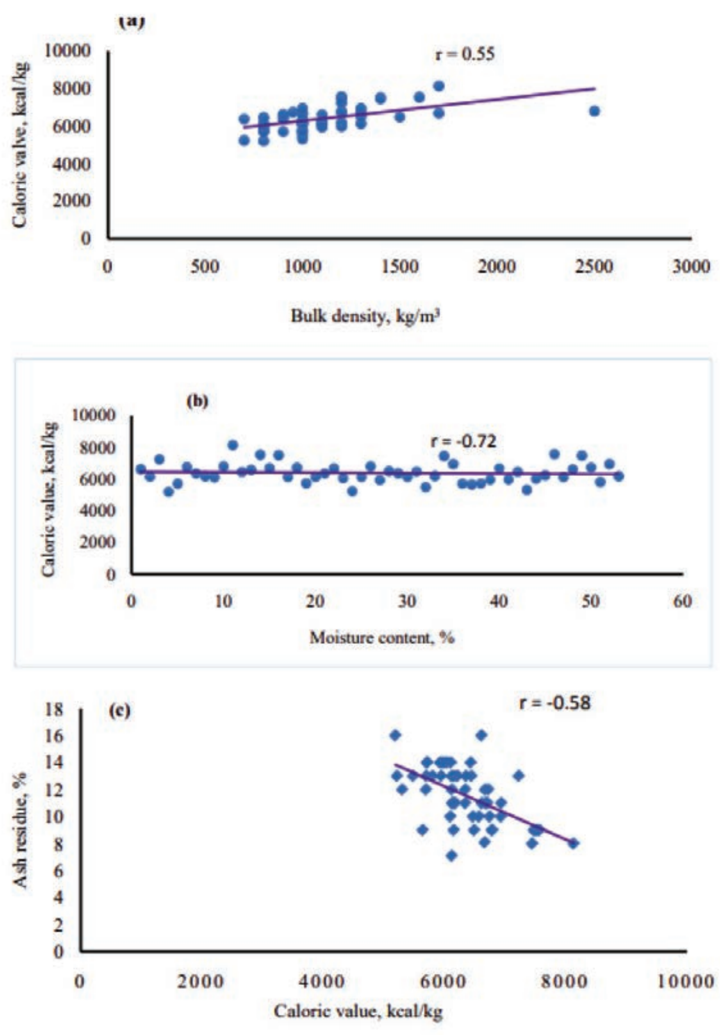

Figure 3. Correlation between bulk density, moisture content and calorific value (Chakradhari and Patel 2016)

Indonesia

One of the main forestry areas in Indonesia that can provide woody biomass for electric power generation purposes is the East Kalimantan Province. Yuliansyah et al. (2022) assessed the physical properties of fast-growing native species (medium tree with DBH of 6-8 cm) as bioelectricity feedstocks. The species in the trial included *Elaeocarpus ferrugineus (Jacq.) Steud., Ficus aurata (Miq.) Miq., Fordia splendidissima (Blume ex Miq.) Buijsen, Lindera lucida (Blume) Boerl., Mallotus paniculatus (Lam.) Mull. Arg. and Schima wallichii (DC)*. The research showed that processing solid wood into wood chips reduced the moisture content to achieve higher energy content. The wood chips from *F. splendidissima* provided the highest energy content (3.61 MWh/t) which indicated this species might be suitable to plant in large scale for bioenergy production in East Kalimantan.

EUROPE

Krajnc (2015) published a wood fuel handbook by the Food and Agriculture Organisation (FAO). She indicated that moisture content, gross and net calorific value, ash content and bulk density are the main characteristics for coniferous and broad-leaf woody species. Carbon (C), Oxygen (O) and Hydrogen (H) make up the main woody biomass chemical composition. After the combustion of woody biomass, harmful emissions elements include Sulphur (S), Nitrogen (N), Chlorine (C) and ash contents (Krajnc, 2015). Moskalik and Gendek (2019) conducted a review of European literatures on wood chip production and its quality from logging residues. They indicated that chipping logging residues in terrain or roadside are popular methods. Storage period from 5 to 7 months can be recommended to reduce moisture content by natural air drying in European climate conditions. Reducing moisture content improved calorific value and ash content. Moskalik and Gendek (2019) mentioned that there have been some cases that wood chips from logging residues did meet the required ISO standards due to technological problems occurring during combustion in small to medium energy plants.The Irish Department of Agriculture conducted a comprehensive review of standards of solid biofuels in 2016. Four wood fuels were considered including wood briquettes, wood pellets, wood chips/hogs and firewood. The physical and chemical properties included origin of wood, trade form, wood species, dimensions, moisture content, ash content, mechanical durability, bulk density, additives, net calorific value, Nitrogen/Sulphur/Chlorine content, Arsenic, Cadmium, Chromium, Copper, Lead, Mercury, Nickel, Zinc, ash melting behaviour and surface area (for briquettes) (Kofman, 2016). Vosic et al. (2021) considered moisture and ash contents, calorific value and particle size as main attributes in a Croatian case study on assessing the quality of wood chips of fir/spruce and beech energy roundwood under bark and debark treatments. Researcher from University of Strathclyde in UK developed a biomass installation feasibility tool that considered same biomass attributes (moisture/ash content, calorific value and particle size) (www.esru.strath.ac.uk; https://woodyfuel.co.uk/why-biomass-fuel-quality-is-important/).

Debarking reduced moisture and ash content. Wood species also made a significant impact on the gross calorific value and particle size distribution. Researchers in Lithuania measured moisture content, ash content and size distribution from wood chips of logging residues collected from a period of 3-years (Pedišius et al. 2021). Polish scholars considered quality attributes such as calorific value, moisture content, ash and Sulphur content to study various types of biomass resources including logging residues (Smaga et al. 2018; Smołka-Danielowska and Jabłońska 2021). Their research showed that the carbon content, H, O, N, S depends on wood species and length of drying period. Gavrilescu (2008) in Romania reported that solid woody waste generated in pulp and paper mills could be utilized as a source of energy. He considered calorific value, moisture/ash content and elemental analysis (C, H, S, N, O) as main biomass quality characteristics.

According to Slovakian researchers, bark has higher ash content compared with the branches and trunks. Large shares of bark during combustion may create further clinker in the furnace which will increase maintenance costs and cause more emissions. Nosek et al. (2016) collected bark samples from Norway spruce, birch, and European Beech. The main study finding pointed out that a 1% increase in bark content could increase the ash content from 0.033 to 0.044%. Another comprehensive research was reported by Dimitorva et al. (2017) in Bulgaria. These scholars studied important biomass characteristics such as bulk density, calorific value, cellulose, lignin, ash contents, carbon, hydrogen, nitrogen of stem wood of juvenile black locust trees and clones. The study sites were in Northern and Southeastern Bulgaria. The stands were young (2-6 years old) consisting of species such as hybrid black poplar (*Populus deltoides×P.nigra*) and *Paulownia sp.* The study confirmed that the age class of 2-6 years significantly impacted the bulk density. The wood density of poplar clones averaged at 300-400 kg/m^3 in this study. Black locusts reached the highest density of 450-650 kg/m^3. *Paulownia* trees had higher contents of cellulose, lignin and ash compared to other species. The highest calorific value was found in poplar stem wood. These findings confirmed that the studied species and clones could be considered as suitable biomass sources of generating energy (Dimitorva et al. 2017)

Pruning residues from five orchard species were collected and chipped using a prototype chipper model PC50 in Spain and Germany (Suardi et al. 2021). Parameters such as moisture content, apparent bulk density and particle size distribution were considered to assess the quality of the wood chips in this case study. Chipping knife type had an impact on the chip size. Continuous knife type yielded 97% higher material capacity than hoe shaped knives.

Germany

According to Kuptz and Hartmann (2014) parameters play a key role to determine physical and chemical characteristics of wood chips: moisture content, ash quality and content, calorific value, particle size and shape. When wood chips are used for small to medium size combustion units, they are transported from a bunker to the furnace using a hopper equipped with a horizontal agitator. Bulk density and moisture content of wood chips can impact this process. Rackl et al. (2019) compared two types of wood chip quality including high (without fine materials) and low (with fine materials). Their study indicated fine contents acted as solid lubricant between large particles. This resulted in higher flowability of a blend during feeding biomass to the combustion unit.

Sweden

There have been extensive research efforts on wood biomass characteristics in Sweden. Willow (Salix) is one of the fast-growing species dedicated to biomass production meant to feed small and large bioenergy plants. Willow stands can be harvested using intact stem removal systems with or without baling. Natural air drying is applied when moisture content reduction is desired. SP Technical Research Institute of Sweden (2015) have considered the following characteristics for willow wood chips including moisture content (that can change over the storage period of the willow bales/bundles), ash content and net calorific value. Kons (2015) reported that biomass terminals in Sweden play a key role in improving logistic efficiency and biomass quality. Kons' thesis showed that harvesting residues are mostly chipped at the terminals and their quality can be improved using screening that could reduce the share of fine material (<3.15mm) especially for logging residues created from tops and branches. Wästerlund et al. (2017) received wood chips from Latvia that were mostly produced from chipping logging residues and small stems (mainly spruce) (Figure 4). The impact of storage and natural air drying (for a period of 5.5 months) on wood chip properties was investigated. Moisture content, dry matter content and calorific value were the main biomass quality parameters in their trial.

Anerud et al. (2019) indicated that any degradation during the storage of the biomass material can result in increased environmental and economic risks/losses. Exposure to sun and air during the storage period could reduce dry mass losses due to microbial activities in the biomass materials. From an end-user perspective chipping to larger particle size can decrease the risk of surface exposure to the microbial activities. Coverage of residue/biomass piles can reduce the risk of re-wetting due to the rain and the recommended storage period is 3 to 4 months (Anerud et al. 2019). Anerud et al. (2020) reported another similar research that storage of wood chips could result in higher energy content and lower moisture. Stands consisted of a mix of pine (*Pinus spp*.), spruce (*Picea abies*), aspen (*Populus spp*.) and birch (*Betula spp*.) harvested during thinning. The coarse wood chips had lower moisture content than fine wood chips which resulted in 2-6% of the economic gain for large chip size production. Building on previous research Anerud et al. (2021) reported that biomass fuel quality can increase when wood chips are covered which depends on the type of cover material.

Considering the importance of forest fuel quality assessment, Fridh (2018) pointed out that accuracy and precision of measurements of moisture content and ash

Figure 4. Uncovered cross section of wood chips pile in Sweden (Wästerlund et al. 2017)

content is critical. He used several methods/tools such as electric capacitance (CAP), magnetic resonance (MR), near infrared spectroscopy (NIR), and X-ray technologies for moisture content measurement. MR was not impacted by fuel type and had highest accuracy while CAP resulted in the lowest accuracy in the trials. Ash content and particle size distribution could be measured using an X-ray tool. For particle size measurement the tool required calibration before usage to ensure high level of accuracy.

OCEANIA

Australia

Australia has mandatory standards for biofuel quality, but Boucher (2018) reported that biomass producers and users should ensure that moisture content (Figure 5) and contaminant levels are low. The main sources of wood biomass in Australia are harvesting residues from plantations such as Eucalypt (*Eucalyptus sp*.) and softwoods such as radiata pine (*Pinus radiata*) (Ghaffariyan and Dupuis, 2021). The utilisation of native forests is very much limited due to environmental issues in various states. In 2018, Victoria had 11 wood chips boilers - the large ones could accept wood chips with various particle size and moisture contents, however, the small boilers prefer to combust lower moisture content and more homogenous woodchip particle sizes (Boucher, 2018 and 2019). Other important criteria are calorific value (Ghaffariyan et al. 2013), particle size, rot/mold/contamination, amount of dirt, species (Boucher, 2018) and fraction of biomass components considered in Australian biomass recovery case studies (Ghaffariyan et al. 2014; Ghaffariyan et al. 2012; Ghaffariyan et al. 2011; Strandgard et al. 2020; Strandgard et al. 2022).

Major findings from international literature review are summarised in Table 1. This table provides an overview of location, biomass feedstock type and studied biomass quality characteristics by various scholars around the world.

Figure 5. Measuring moisture content of wood chips in Australia (Boucher, 2019)

Table 1. Summary of biomass characteristics studies for different regions and woody biomass feedstocks

Region/ country	Biomass feedstock	Species	Most important biomass attributes	Reference
America Brazil	barks	*Eucalypt* sp.	moisture/ash content, calorific value	Caraschi et al. 2019
Brazil	wood chips	*Eucalyptus hybrids E. urophylla* x E. *grandis*	moisture/ash content, bulk density, calorific value	Rebeiro et al. 2021
Canada	logs, chunks, firewood, hog fuel, green wood chips, dry shavings, solid and engineered wood, sawdust, construction and demolition waste, processing residue	N/A	moisture content/calorific value, biomass compositions, soil contamination, bulk density, foliage/bark content, ash, lignin, carbohydrate, extractive contents	Thiffualt et al. (2019) https://www.ontario.ca Marinescu (2013)
Canada	yield samples from biomass crop	*Miscanthus*, switchgrass, willow, and poplar (Species unknown)	gross calorific value, ash (%), ash elemental analysis	Mann (2012)
USA	wood chips from whole tree chipping	Willow (Species unknown)	moisture/energy content, size classification and ash content	Eisenbies et al. 2008 Eisenbies et al. 2016
USA	wood chips from slab wood from sawmills	*Eucalyptus grandis*	bulk density, particle size distribution, ash/volatile matter content, calorific value	Turn et al. 2005
USA	wood chips from whole tree chipping	Loblolly Pine	calorific value, moisture content, ash/bark/nutrient content	Cutshall (2012)

USA	wood chips	Sweetgum and pine (Species unknown)	ash content and particle size	Pradhan (2015)
USA	pellets	Pine and hardwood (species N/A)	density, ash/moisture content, calorific value	Sharma et al. (2017)
USA	wood chips	*Pinus taeda, Pinus elliottii*	calorific value, ash/moisture contents, carbon/nitrogen/ sulphur content	Saha et al. (2017)
Asia India	various parts including leaf, branches, bark and root	*Vachellia nilotica, Azadirachta indica,* other speciece	calorific value, fixed carbon content, moisture/ash content, bulk density	Lenka (2016) Chakradhari and Patel (2016)
Indone-sia	various parts of trees grinded	*Fordia splendidissima* and others fast-growing species	moisture content, calorific value, wood density	Yuliansyah et al. (2022)
Europe	wood chips from logging residues	N/A	moisture/ash content, calorific value	Moskalik and Gendek (2019)
Croatia	wood chips	*Abies alba, Picea abies, Fagus sylvatica*	moisture/ash content, calorific value, particle size	Vosic et al. (2021)
Ger-many	wood chips from logging residues	N/A	moisture content, ash quality and content, calorific value, particle size and shape.	Kuptz and Hartmann (2019)
Ger-many	wood chips from logging residues	N/A	bulk density and moisture content	Rackl et al. (2019)
Roma-nia	woody waste in pulp and paper mills	N/A	calorific value, moisture/ash content and elemental analysis (c, h, s, n, o)	Gavrilescu (2008)
Slova-kia	wood chunk and wood chips	*Picea abies, Betula pendula, Fagus Silvatica*	ash content and moisture content	Nosek et al. (2016)
Sweden	wood chips	Willow ((Species unknown)	moisture/ash content, net calorific value	SP Technical Research Institute of Sweden (2015)
Sweden	wood chips	*Picea abies*	moisture/dry matter content, calorific value	Wästerlund et al. 2017
Sweden	wood chips	*Pinus* spp., *Picea abies, Populus spp. Betula* spp	moisture/ash content, net calorific value, particle size	Anerud et al. 2020
Oce-ania Aus-tralia	wood chips, slash bundles	*Eucalypt* sp., *Pinus* sp.	moisture content, calorific value, particle size, rot/mold/ contamination, amount of dirt, species, biomass fraction	Boucher, 2018; Ghaffariyan et al. 2012; Ghaffariyan et al. 2011

Conclusions

Overall understating from international studies (Table 1) is that the key biomass characteristic which was consistently measured in almost all research projects is moisture content of the biomass. Ash content and calorific value are classified as second place in terms of frequency in the biomass studies. Attributes such as bulk density, contamination, particle shape and nutrient (elemental) content had a lower rate of mention in the literature.

Thiffault et al. (2019) concluded that woody residues (especially sawdust) have high levels of contaminant and aluminium can have negative impacts on the quality of wood pellets as products. They suggested considering higher quality control practices to ensure the woody residues meet the required specifications of the end users. From wood chip size perspective, research finding showed that increased target chip size can increase the competitiveness of forest biomass through decreased production costs and reduced storage costs. It can also ensure higher and more consistent fuel quality (Anerud et al. 2020).

From application perspective, German scholars such as Kuptz and Hartmann (2014) suggested that wood chip quality is a function of their usage type. For small furnace systems (<1 MW) the quality of wood chips is critical, however, for application in large furnace systems (>1 MW) the quality is less important and a secondary issue. Increased wood chips quality for large furnace systems only adds unnecessary costs that should be avoided.

Natural Resources Canada pointed out that reducing moisture content and fine materials in biomass wood chips can help to minimise some risks including microbiological activities, composting and self-ignition. Thus, covering the low moisture wood chips piles is suggested where possible (Natural Resources Canada https://www.nrcan.gc.ca). Increasing chip size during chipping operation can reduce production and storage costs; that can result in enhanced competitiveness of forest biomass (Anerud et al. 2020). Coverage of wood chips can generally increase the annual utilisation of trucks and chippers which can reduce operating costs (Anerud et al. 2021).

Biomass characteristics can change over the life of trees. Thus Mann (2012) suggested monitoring the changes of fuel characteristics over the life of the plantation to understand which species are the most suitable for bioenergy production.

Different measurement methods yield different levels of accuracy. In addition to current laboratory methods to measure biomass characteristics (calorific value, moisture/ash content etc.) Saha et al. (2017) and Fridh (2017) suggested using NIR spectroscopy, X-ray and electric capacitance and magnetic resonance which provide low error of measurement with quicker and easier application.

Future research projects can fill the knowledge gap by studying the biomass quality characteristics from biomass feedstocks and species that have not been yet investigated. In Oceania, the biomass quality of some commercial species (in different types of biomass feedstocks) could be further investigated. The suggested species include *Corymbia maculate*, *Pinus radiata, Pinus elliottii, Pinus caribaea, Pinus taeda, Araucaria cunninghamii, Eucalyptus globolus, Eucalyptus nitens, Eucalyptus dunnii* and *Eucalyp-*

tus cloeziana. In Asia, there is a gap of knowledge on quality characteristics of main species (in various types of biomass feedstocks) such as Chinese fir (*Cunninghamia lanceolata*) [in China], sugi (*Cryptomeria japonica*), hinoki (*Chamaecyparis obtusa*), pines (*Pinus spp.*) and Japanese larch (*Larix leptolepis*) [in Japan], Rubber (*Hevea brasiliensis*), teak (*Tectona spp.*), pines and *Acacia mangium* [in Indonesia and Thailand]. There is also a knowledge gap in Africa in the exploration of a variety of biomass types and commercial woody species including pine, eucalyptus and wattle (*Acacia spp*.). European forest biomass quality studies have been mainly published in Sweden and Germany. Future research could be carried out in some Central and Eastern countries to meet with the current demands of bioenergy. South America is another region that could benefit from further research projects on forest biomass quality assessment with various commercial species including pines (*Pinus spp.*), acacia (*Acacia spp*.) and teak (*Tectona spp*.) under various biomass feedstocks (wood chips, bundles etc.). Most of the current knowledge covers the application of woody biomass for bioenergy generation such as heat/power. Future studies around the world could evaluate the quality of biomass for other applications such as biofuels and bioproducts.

Acknowledgement

The author thanks Prof. Mark Brown and the board members of IEA Bioenergy Technology Collaboration Programme for their support and funding of this research. Ian Last (from HQP company) provided useful comments on this report which is appreciated. The author appreciates the suggestions provided by reviewers and editors of Silva Balcanica to improve the quality of this article.

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Silva Balcanica 24(3): 95-100 (2023)
doi: 10.3897/silvabalcanica.24.e115337

RESEARCH ARTICLE

First record of *Chlorophorus herbstii* (Brahm, 1790) in Greece and new localities of *Xylosteus bartoni* Obenberger & Mařan, 1933 (Coleoptera, Cerambycidae)

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Academic editor: Georgi Georgiev | Received 6 November 2023 | Accepted 14 December 2023 | Published 28 December

Citation: Bolanakis G. and Trichas A. 2023. First record of *Chlorophorus herbstii* (Brahm, 1790) in Greece and new localities of *Xylosteus bartoni* Obenberger & Mařan, 1933 (Coleoptera, Cerambycidae). Silva Balcanica 24(3): 95-100. https://doi.org/10.3897/silvabalcanica.24.e115337

Abstract
In this study, *Chlorophorus herbstii* (Coleoptera, Cerambycidae) was reported for the first time for Greek fauna. Another longhorn beetle, *Xylosteus bartoni*, has been found in two new localities in the country.

Keywords
Saproxylic, Cerambycidae, Greek Forests

Introduction

Saproxylic beetles are in the spotlight of conservation biology, being the only beetle group that is systematically approached by conservation biologists, e.g., in Red catalogues (Nieto, Alexander, 2010; Cálix et al., 2018) or as “umbrella species” (Eckelt et al., 2017). In essence, saproxylic Coleoptera act as a proxy to assess and protect a plethora of beetle families that participate or depend on the decaying of the dead wood, as well as other forest dwelling species. The saproxylic beetle fauna of Greece is not adequately known. In fact, Greece is leading among other European countries in Data Deficient species (Cálix et al., 2018). The issue of Data Deficient species and species of poor knowledge is pivotal in conservation biology, since we cannot estimate their threat status, their ecological functions in bio-communities or even their inclusion in protected areas (see Hortal et al., 2015; Borgelt et al., 2022). Thus, it is evident that the expansion of our knowledge concerning the distribution and the ecology of saproxylic beetles is important for their conservation. In Greece, due to the lack of concrete knowledge for its saproxylic fauna, it is quite common to introduce novel data on this subject, especially near the northern borders of the country where European/Balkan species may exhibit the southern part of their distribution (e.g., Dascălu et al., 2012; Mpamnaras, Eliopoulos, 2017). Here we record for the first time the presence of *Chlorophorus herbstii* (Brahm, 1790) in Greece. Moreover, we expand the dataset for *Xylosteus bartoni* Obenberger & Mařan, 1933.

Methods and materials

The beetles were collected via handpicking and pitfall trapping during Natural History Museum of Crete (NHMC) expeditions in northern Greece. The specimens were morphologically examined under stereo microscope (Leica M205C, Wetzlar, Germany), photographed with CANON 5Ds and MP-E 65mm f/2.8 1-5x macro lenses and the images have been stacked with Zerene Stacker 1.04, 64-bit software. The specimens (being initially stored in 99% pure alcohol in the wet collections of NHMC), were dry-mounted subsequently for the microscopic examination/identification & photographic documentation.

Results

***Chlorophorus herbstii* (Brah, 1790)**

Material examined

Greece: 1 ♂, Kotyli (Xanthi), 41.333200N; 24.884300E, 618 m a.s.l., 10.7.1996, Trichas A. leg., (NHMC).

C. herbstii (Fig. 1.c) has a Eurosiberian distribution (Georgiev et al., 2022). Primary expands in Central Europe, while it is generally absent in the south. Its range does not include Italy (Bense, 1995; Mannerkoski et al., 2009; Danilevsky, 2023), while it is probably extinct in France (Mannerkoski et al., 2009). It is also reported in Spain, from a locality in Pyrenees (Vives 2001), while it has recently expanded to the northern part of its range, in Norway (Sovelåg & Ødegaard, 2012). The beetle develops in various broadleaf trees (especially on *Tilia*, but also on *Quercus*, *Carpinus*, *Ulmus*, *Betula*, *Padus*, *Crataegus*) (Bense, 1995). The adults can be observed on flowers (Bense, 1995), but for a short time-period, rendering difficult the sampling or adult detection (Schmidl, 1999).

Here we expand its distribution range with the first record from NE Greece. Aside from the population in Pyrenees, this is the southernmost record of this species, although it is probable to be found in lower latitudes in Albania, North Macedonia (which for the moment are not included in its distribution) and Greece. The specimen was found near Kotyli village (Xanthi, Thrace, NE Greece). This location is relatively close to known locations from Bulgaria (Orehovo: Gradinarov et al., 2020; Bansko: Georgiev et al., 2022; Smolyan: iNaturalist, 2022). As in the case of *Xylosteus bartoni* (see below), it appears that woodboring cerambycids dwelling in southern Bulgarian forests are commonly found in the nearby bordering areas of Greece. The question arising is if they are established elements of the Greek cerambycid fauna or these observations are trails of evanescent range shifts. Furthermore, no additional records have occurred since 1996, although this can be attributed to the lack of systematic sampling effort focusing on the saproxylic fauna of Greece. Further research on this subject could unveil new localities for this species in Greece and outline its southern Balkan limits or indicate that it is indeed an impermanent element to the Greek saproxylic fauna.

***Xylosteus bartoni* Obenberger & Mařan, 1933**

Material examined

Greece: 1 ♂, Mikromilia E, 41.4212N; 24.1725E, 755 m a.s.l., 7.7.1996, Trichas A. leg., (NHMC); 1 ♀, Stravorema, Elatia E, 41.497679N; 24.344096, 1380 m a.s.l., 9.7.1996, Trichas A. leg., (NHMC).

X. bartoni (Fig. 1.a, b) is a rare, montane, Balkan endemic, Lepturinae species associated with conifers (*Picea, Pinus*) (Bense, 1995). The species is distributed in the south Balkans (Bulgaria and North Macedonia) and has been quite recently recorded in Greece, at 1150 m a.s.l., near Veironia village, Kerkini (Dascălu et al., 2012). The locality is a mixed forest of *Fagus* and *Picea*, matching the species' habitat preferences. Additionally, Rapuzzi, Sama (2018) described a subspecies of *X. bartoni* (*X. b. migliaccioi*) which is now considered a synonym of the nominal species (Danilevsky, 2023) using specimens from Bulgaria and Greece (Rhodope). They reported 10 specimens from Elatia forest, close to the second location provided herein. We report two new localities for Greece from the Rhodope mountain range. The presence of *X. bartoni* in the Greek side of the Rhodope mountain range was expected, since the species has been recorded from nearby sites from Bulgaria (Gradinarov et al., 2020; Georgiev et al., 2022), with the closest locality being in Trigrad (Gradinarov et al., 2020). It appears that there is ground for further research regarding the range of this rare species in the northern part of Greece. Our records are older than those of Dascălu et al. (2012) and Rapuzzi, Sama (2018), implying an established presence of the species in the Greek side of the borders. Of course, *X. bartoni* individuals and genetic material exchange between Bulgarian, Greek and North Macedonian populations is most likely to occur. Further research regarding the species' distribution in northern Greece could shed more light in its taxonomy, biogeography and conservation status.

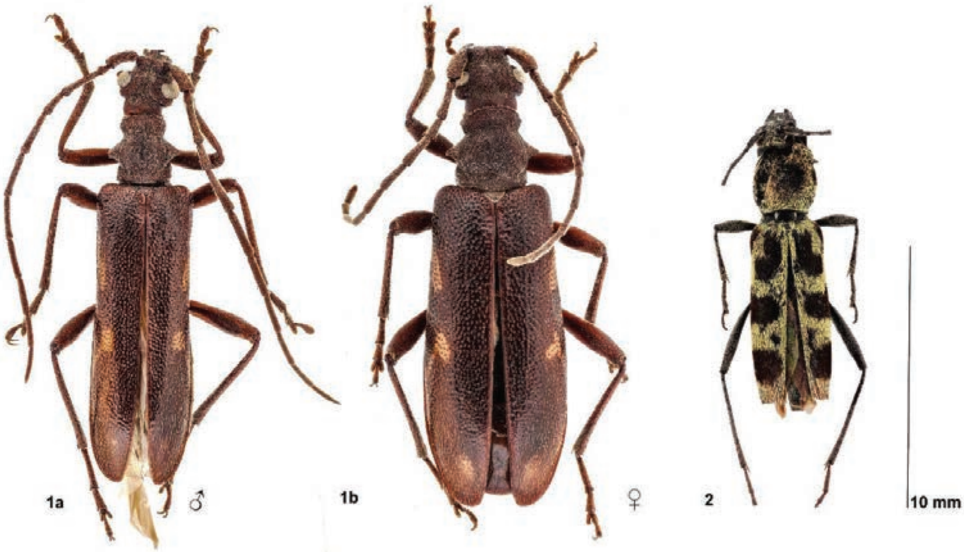

Figure 1. The specimens of: (a) *Xylosteus bartoni* (male); (b) *Xylosteus bartoni* (female); (c) *Chlorophorus herbstii,* in NHMC collections

Discussion

There are frequent records of new cerambycid faunal elements in the peripheral areas of Greece (e.g., Dauber, 2004; Wełnicki and Przewoźny, 2007; Mpamnaras and Eliopoulos, 2017). It appears that there is an -expected- interplay between the saproxylic fauna of Greece and those of its adjacent countries in its northern borders. Discoveries such as *X. bartoni* and *C. herbstii* in the Greek fauna, encourage us to examine carefully the fluidness of saproxylic biodiversity in the northern part of the country. Do these species form established populations or not? Is there a continuous exchange with the saproxylic faunas of the other Balkan countries, with populations migrating and extirpating from one country to another? These biogeographical and conservational questions can be answered with extensive sampling, monitoring and the use of molecular tools and require interborder collaborations. Given the species turnover as a result of climate change (Vitali et al., 2023), we can assume that populations at the limits of a species distribution are more likely to exhibit fluctuations or local extinctions. Therefore, a close monitoring of these populations could provide an empirical framework for the estimation of the impact of climate change to these species.

Systematic focus on the continental Greece – especially in its northern regions – is required in order to obtain a satisfactory knowledge of the synthesis of the Greek saproxylic beetle fauna, as well as to delimit the range of the species that constitute it.

Acknowledgements

The authors would like to thank the two reviewers for their quick response and all their valuable remarks.

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