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The influence of forest-forming tree species on diversity and spatial distribution of algae in forest litter

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Abstract

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The forest litter plays a significant role in forest ecosystems. The composition of the litter biota comprises micro- and mesofauna, and a great diversity of microorganisms, including unrecognized algae (eukaryotic representatives and Cyanoprokaryota). The aim of this work was to study the diversity of algae in the different types of forest litters and to clarify the relationship between the algae composition and the forest-forming tree species. Our results show that the pine forest litter is the most appropriate habitat for the development of green and yellow-green algae and that this litter type limits the variety of blue-green ones. The admixture of deciduous leaf litter to pine litter caused an increase in the species richness of blue-green algae and diatoms. The algae were unevenly distributed across the sub-horizons of pine litter. The highest species richness of algae was identified in the enzymatic sub-horizon of litter. The peculiarity of the composition of leaf litter algae was a significant variety of green, yellow-green and blue-green algae. The spatial organization of algae communities in the leaf litter was characterized by equal distribution of algae species in the litter-subhorizons.

Keywords

algae, ash content, biota of the litter, leaf litter, pH of the litter, pine litter

Introduction

Forest biogeocoenoses of Ukraine are valuable natural resources that need protection, rational use and overall study. A significant role in the functioning of forest ecosystems is played by forest litter (Chornobay, 1995; Ayres et al., 2006; Song et al., 2010; Kitikidou, 2012; Chertov, 2016; Fu et al., 2017.). There exists neither unique definition of ‘forest litter’ types, nor unequivocal approaches to their classification, indexing, and diagnostics (Dubina, 1987; Sapozhnikov, 1987; Bogatyirev, 1996). The two governing approaches for understanding the essence of the litter are: 1. the forest litter is the upper organogenic soil layer and 2. the forest litter is an integral part of the soil profile. The question whether the forest litter belongs to the soil horizons or components of biogeocoenosis does not seem represent a contradiction, but a consequence of various research aspects.

The most interest has been given to the organic matter decomposition processes running in litter, the organ-

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isms driving these processes (animal-saprophages, including invertebrates, fungi, actinomycetes, various groups of bacteria) (Rakhleeva et al., 2011; Gömöryová et al., 2013; Brygadyrenko and Svyrydchenko, 2015; Brygadyrenko, 2015; Gergócs and Hufnagel, 2016; Komarov et al., 2017; Kooch et al., 2017) and the changes occurring in the forest litter and biota under the influence of anthropogenic factors (McCay et al., 2013; Lucisine et al., 2015; Gašová et al., 2017; Mikryukov and Dulya, 2017).

The forest litter is, however, inhabited also by algae, eukaryotic and prokaryotic – Cyanoprokaryota (Chornevych and Nikorych, 2008; Maltseva, 2009; Maltseva et al., 2017; Maltsev et al., 2017a, 2017b). Thus, along with the decomposition of organic matter in the forest litter, there also occurs converse synthesis – as algae can provide oxygenic photosynthesis, and some of them nitrogen fixation. The information about the algae in forest litter, representing a block of producers in the composition of the forest litter biota, is fragmented and incomplete. The composition of algae in forest litter has special features, related, as reported by Aleksakhina and Shtina (1984), to the abundance of organic matter and accumulation of nutrients in the litter, colonization with heterotrophic microflora, and similar. The litter differs from the soil by a considerable seasonable variation of its thickness and by physicochemical properties depending on the accumulation and decomposition of the organic matter. Nevertheless, the information about the characteristics of algae groups is important for specifying the impacts on their biological activity of forest litter, the formation and functioning of biocoenoses in the litter, and biodiagnostical properties of the litter and their variation under anthropogenic impact (Scherbina et al., 2014; Shekhovtseva and Maltseva, 2015).

Forests of Ukraine have been founded with more than 30 different tree species. The dominant species is the pine, forming the pine and oak-pine forests. It takes about 35% of the state forest fund of Ukraine. In the steppe zone pine forests occupy areas on the second (upland, sandy) terraces of the river valleys. Among hardwoods, the leading forest-forming tree species is *Quercus robur* L. Equally as the pine, the oak is a drought-resistant species, but it most often grows on rich and moist soils. It forms pure or mixed forest stands in all the natural zones of Ukraine. In the steppe zone, oak forests are spread in ravines and bottomland conditions. *Robinia pseudoacacia* L. (*Robinia pseudoacacia*, white acacia) have been introduced with success for landscaping and the creation of protective stands in the steppe zone of Ukraine. This species has low demands on the soil fertility and moisture content, it can grow on sands, saline and eroded soils. The robinia stands are characterized by high forest ameliorative properties; they fully carry out soil protection and water regulating functions. However, it is a species with a thin tree crown, so it shades the ground poorly, it is not able to choke the weeds and to form a powerful forest litter and the microclimate peculiar for the forest, which can lead to the fragility of robinia stands.

It has been found that the tree species composition has not only a significant impact on the morphological, physical and chemical parameters and the decomposition rate of forest litter, but that it also affects the composition and structure of biota (Aubert et al., 2010; Song et al., 2010; Szanser et al., 2011; Rakhleeva et al., 2011; McIntosh et al., 2013; Perez et al., 2013; Wang et al., 2013; Ferreira et al., 2016; Gergócs and Hufnagel, 2016; Sun and Zhao, 2016; Lin et al., 2017). Most researchers point out a close connection between the type of forest litter, composition of decomposer species and decomposition rate of forest litter. However, this approach does not show fully what is happening to the forest litter processes and to the composition of the organisms involved in them. Algae of out-of-water habitats are connected by various relationships with different groups of organisms (Maltseva, 2007). Due to the high reproduction rates, their primary production multiplies the biomass in tens and hundreds times, and according to various data, it reaches from 127.5 kg ha^{-1} in the forests in the steppe zone up to 2,580 kg ha^{-1} in the forests in forest zones (Maltseva, 2009). The organic matter of algae (in vivo selection, live cells and after the death) quickly becomes involved in the trophic chains. Thus, in the study of various issues related to the diversity of the forest litter biota, biological activity of forest litter, decomposition processes of the organic mass of forest litter, the impact of human interventions, etc. it is necessary to consider its autotrophic component, i.e. algae.

Therefore, the aim of this work was to study the relationship between the forest-forming tree species, forming the litter, and the diversity and spatial distribution of algae communities in the forest litter. The hypothesis to confirm in this study was existence of relationships between the type and characteristics of the forest litter and the diversity of algae and their distribution within different sub-horizons of the litter. To meet the research task, we worked with forest sites dominated by different tree species, the main parameters of the forest litter (power, dry weight of organic matter, pH and ash content), in relationships with algal community parameters (diversity, dominant and subdominant taxa). The analyses of the community similarity index were performed using the data on the algal species composition from different forest biogeocenoses.

Materials and methods

The study material represents forest litter sampled in the years 2010–2014 in various pine, oak and robinia stands within the steppe zone of Ukraine (Table 1). It is necessary to note that the concerned pine forest in the valley of the Samara river is one of the most southern-situated pine forests in the territory of Ukraine. Further to the South, the origin of pine forests growing on sandy terraces of river valleys and in estuaries has been artificial – Staro-Berdiansk and Altahyr forests. With increasing climate aridity, the stands of *Pínus sylvestris* L. are replaced by the stands of *Pinus pallasiana* D. Don.

Table 1. Sampling locations for the study of algae, with GPS coordinates

Sample area No.	The sampling site	Forest forming species
1	Sandy terrace of the river Samara valley (Dnipro), the Samara forest, the area of village Kocherezhky, Novomoskovsk district, Dnipropetrivsk region N 48°38'10.15", E 35°40'41.47"	*Pinus sylvestris*
2	Sandy terrace of the river Molochna, the Staro-Berdiansk forest, the area of village Lisne, Melitopol district, Zaporizhia region N 46°56'10.24", E 35°29'26.71"	*Pinus pallasiana*
3	Sandy terrace of Molochnyi estuary, the Altahyr forest, the area of village Altahyr, Yakymivka district Zaporizhia region N 46°37'12.71", E 35°16'50.95"	*Pinus pallasiana* *Quercus robur*
4	Bottom land of the river Samara (Dnipro), the Samara forest, the area of village Kocherezhky, Novomoskovsk district, Dnipropetrivsk region N 48°39'29.29", E 35°38'59.13"	*Quercus robur*
5	Upland, outskirts of village Andriivka, Novomoskovsk district, Dnipropetrivsk region N 48°45'18.49", E 35°28'8.92"	*Robinia pseudoacacia*
6	Bottom land of the river Molochna, the Staro-Berdiansk forest, the area of village Lisne, Melitopol district, Zaporizhia region N 46°54'24.24", E 35°29'55.51"	*Quercus robur*
7	The third terrace of the river Molochna valley the Staro-Berdiansk forest, the area of village Lisne, Melitopol district, Zaporizhia region N 46°55'5.79", E 35°30'1.31"	*Robinia pseudoacacia*
8	Sandy terrace of Molochnyi estuary, the Altahyr forest, the area of village Altahyr, Yakymivka district Zaporizhia region N 46°37'20.12", E 35°17'15.65"	*Quercus robur*
9	Sandy terrace Molochnyi estuary, the Altahyr forest, the area of village Altahyr, Yakymivka district Zaporizhia region N 46°37'19.37", E 35°17'8.33"	*Robinia pseudoacacia*

Each sample consisted of 5–10 individual samples, each with an area of 25 cm^2, selected within the relevant forest ecosystem. In each ecosystem, the samples were collected seasonally (in spring – in April, in summer – in July, in autumn – in October). There were collected 158 forest litter samples. The forest litter was gathered from sub-horizons at a distance of 1–1.5 m from the tree trunks: A0^1 (L) – fresh litter, A0^2 (F) litter which has already undergone decomposition, but some components remained original; A0^3 (H) – advance decomposed litter. The litter was characterized by its morphological (structure, composition, power) and chemical parameters (pH, ash content) (Dubina, 1987).

The species composition of algae was determined on the basis of methods working with cultures. There were used catching glasses placed on the surface of the litter in Petri dishes and delivering agar culture on the Bould's medium (3N BBM) (Gaysina et al., 2008). On the surface of agar medium, the fragments of plant remnants from the litter were placed and poured with a few drops of distilled water. The cultures were exposed to a light-supplying system working in a regime of 12:12. The microscopic examination of cultures, if needed, continued up to 12 months. The determination of algae was carried out with an optical microscope 'XSP–128B' at a magnification × 1,000, and using oil immersion. For taxonomically critical species of algae, the method of algological pure cultures was used, with highlighting separate cells by streak seeding or by micropipetting under the inverted microscope. At microscopic examination, the samples were stained intravital with a Lugol's iodine solution: in case of starch examination 0.1% solution of methylene blue, and in case of the general outline and structure of mucus 1% solution of ink. The microscopic examination was performed with using light microscopes with immersion lenses XSM–20, MBI. Based on the cultures from the catching glasses, considered as the best simulating the natural conditions, the dominants and the subdominants were determined by using a seven-point scale of abundance. The species with abundance score of 7 and 6 were considered to be the dominants, and with 5 and 4 abundance score – the subdominants.

The referential system of blue-green algae taxa (Cyanoprocaryota) was used in accordance to the reports of I. Komarek and A. Anagnostidis (Komárek and Anagnostidis, 2005; Komárek, 2013), the rest of the groups – according to 'Algae of Ukraine' (Tsarenko et al., 2006, 2009, 2011, 2014).

The obtained data were analyzed, using the methods of comparative floristics and statistics. The Jaccard similarity coefficient for the complete species lists of algae for individual litter samples (Shmidt, 1984) was calculated in the following way:

$$KJ(\%) = \frac{N_{AB} \times 100}{N_A + N_B - N_{AB}} \ ,$$

where KJ is the Jaccard coefficient, N_{AB} is number of common species, N_A and N_B is number of species found in the first and the second communities. For a comparative analysis of the floral lists, the Serensen similarity coefficient was used (Shmidt, 1984):

$$K_C = \frac{2C}{A + B} \ ,$$

where K_C is the Serensen coefficient, A is the number of species in the first flora, B is the number of species in the second flora, C is the number of species common to the two floras.

Results

Algae diversity in the forest litter of pine stands

The litter of the studied pine stands reaches a thickness of 6.5 cm, and it consists of two or three sub-horizons, with dominant sub-horizon of fermentation, A0^2 (F) and sub-horizon of humification A0^3 (H). From the upper layers to the lower ones, the ash content in the litter increases, with pH changing from 3.91 to 4.98 (Table 2).

The algae group in forest litter sampled from the pine stands of Samara and Staro-Berdiansk forests, with no broadleaved species in their understorey, was found consisting of 41 species: Cyanoprokaryota – 1 (2.4%), Eustigmatophyta – 2 (4.9%), Xanthophyta – 8 (19.5%), Bacillariophyta – 5 (12.2%), Chlorophyta – 23 (56.1%), Charophyta – 2 (4.9%). In the case of pine litter enriched with the leaf litter, such as the pine stands with admixture of oak in the Altahyr forest, the diversity of Cyanoprokaryota increased up to 15.4% of the total species richness (Fig. 1). In general, the different pine stands exhibited 66 species of algae: Cyanoprokaryota – 7 (10.6%), Eustigmatophyta – 2 (3.0%), Xanthophyta – 14 (21.2%), Bacillariophyta – 6 (9.1%), Chlorophyta – 35 (53.1%), Charophyta – 2 (3.0%).

The distribution of algae species composition in various layers of pine litter has its own specific features. The highest number of species is concentrated in the sub-horizon A0^2 (F), with a clearly evident increase in the species richness of Xanthophyta and Chlorophyta (Table 3).

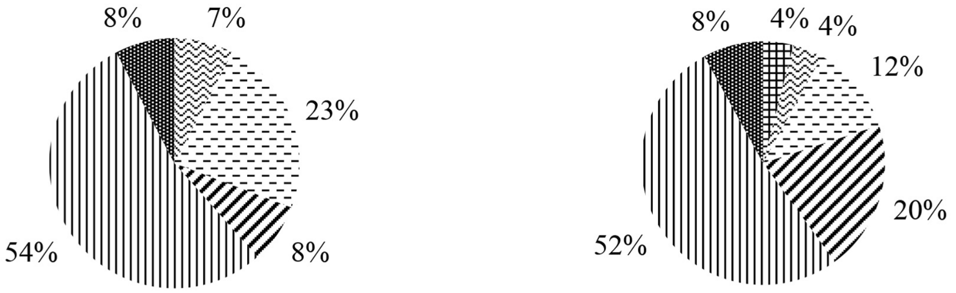
The dominant algae identified in the pine litter are: *Bracteacoccus minor* (Chodat) Petrová*, Klebsormidium flaccidum* (Kütz.) P.C. Silva et al., *Ellipsoidion anulatum* Pascher, *Eustigmatos magnus* (J.B. Petersen) Hibberd, *Chlorococcum* sp. 3, *Pseudococcomyxa simplex* (Mainx) Fott, *Stichococcus bacillaris* Nägeli, *Myrmecia incisa* Reisigl*, Hantzschia amphioxys* (Ehrenb.) Grunow*, Elliptochloris subsphaerica* (Reisigl) H. Ettl et G. Gärtner. After adding the leaf litter to the pine litter, the dominant algae were: *Nostoc punctiforme* (Kütz. ex Hariot) Hariot, *Nostoc paludosum* Kütz. ex Bornet et Flahault, *Phormidium jadinianum* Gomont, *Hantzschia amphioxys*, *Planothidium lanceolatum* (Bréb. in Kütz.) Bukht.*, Schizochlamydella* cf. *delicatula* (G.S. West) Korschikov, *Pseudococcomyxa simplex, Klebsormidium flaccidum, Ellipsoidion oocystoides* Pascher.

Algae diversity in the forest litter of hardwoods

The leaf litter of hardwoods (oak and robinia) had a thickness of 5–6.5 cm, and it was structured into two sub-ho-

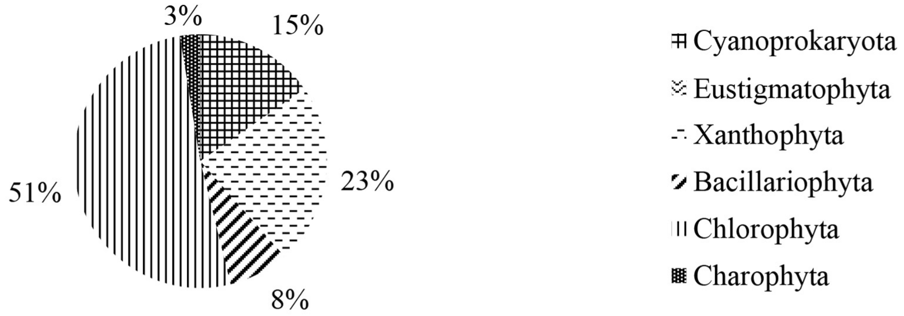
Table 2. The main parameters of the forest litter in the main forest-forming tree species (fluctuation ranges by the study years and seasons)

Sub-horizon of the litter	Power (cm)	Dry weight of organic matter (kg m^{-2})	pH	Ash content (%)
Pinus sylvestris (sample area 1) and *Pinus pallasiana* (sample areas 2, 3)				
A0^1 (L)	0.52	0.269–1.158	3.91–4.71	7.11–19.76
A0^2 (F)	1–4	0.463–2.252	4.21–4.97	19.09–52.71
A0^3 (H)	0–4	1.088–1.575	4.3–4.98	62.63–84.94
Quercus robur (sample areas 4, 6, 8)				
A0^1 (L)	0.5–2	0.217–1.125	4.71–6.26	14.8–46.9
A0^2 (F)	2–6	0.500–2.888	5.23–6.21	28.0–93.7
Robinia pseudoacacia (sample areas 5, 7, 9)				
A0^1 (L)	0.5–2	0.156–0.817	5.5–6.82	18.2–36.7
A0^2 (F)	1–3	0.731–2.575	5.91–6.83	58.13–83.9



Pine forest (Samara forest)

Stands of pine (Staro-Berdiansk forest)



Stands of pine mixed with hardwoods (Altahyr forest)

Fig. 1. The distribution of algae species composition in various pine stands according to the departments.

Table 3. The distribution of algae species composition in sub-horizons of the forest litter of pine stands according to the departments (units (%))

Department	Sub-horizons of forest litter			Total
	A0^1 (L)	A0^2 (F)	A0^3 (H)	
Cyanoprokaryota	5	5	3	7 (10.6)
Eustigmatophyta	1	2	2	2 (3.0)
Xanthophyta	5	14	5	14 (21.2)
Bacillariophyta	3	5	3	6 (9.1)
Charophyta	2	2	2	2 (3.0)
Chlorophyta	12	25	16	35 (53.1)
Total	28	53	31	66 (100)
Part of total number of species (%)	42.4	80.3	46.9	100

rizons, of which the fermentation sub-horizon was more developed (Table 2). In contrast to the pine needle litter, the leaf litter is characterized with higher pH values (4.71–6.83). The least acidic was found the litter of robinia stands. The pH value increased in the direction from top to bottom sub-horizons of litter.

The algae group of hardwoods litter comprised 80 species: Cyanoprokaryota – 10 (12.5%), Eustigmatophyta – 3 (3.75%), Xanthophyta – 14 (17.5%), Bacillariophyta – 3 (3.75%), Chlorophyta – 48 (60.0%) and Charophyta – 2 (2.5%). Green and yellow-green algae are characterized by high diversity. Cyanoprokaryota were present in higher number of species, in contrast to the pine litter, and the diatom algae were present in lower numbers of species. The algae communities of the forest litter of oak stands were found richer in species than those of robinia stands (Table 4). Compared to the pine stands, the leaf litter sub-horizons are evenly populated with algae species in both natural and artificial stands (the only exception was the linden-ash grove of the Samara forest).

The dominant algae species in the oak litter in natural stands were: *Phormidium* cf. *autumnale* (C. Agardh) Gomont, *Klebsormidium flaccidum,* cf. *Mychonastes homosphaera* (Skuja) Kalina et Punčoch.*, Trichromus vari-*

Table 4. The distribution of algae species composition in sub-horizons of the forest litter (A01, A02) of hardwood stands according to the departments

Department	Oak litter (sample areas 4, 6, 8)			Robinia litter (sample areas 5, 7, 9)			Total
	A0^1 (L)	A0^2 (F)	Total	A0^1 (L)	A0^2 (F)	Total	
Cyanoprokaryota	5	6	8 (12.1)	3	3	3 (10.0)	10 (12.5)
Eustigmatophyta	3	3	3 (4.5)	1	–	1 (3.3)	3 (3.75)
Xanthophyta	8	11	13 (19.7)	2	1	3 (10.0)	14 (17.5)
Bacillariophyta	3	3	3 (4.5)	1	1	1 (3.3)	3 (3.75)
Charophyta	2	1	2 (3.1)	1	1	1 (3.3)	2 (2.5)
Chlorophyta	27	24	37 (56.1)	13	14	21 (70.1)	48 (60.0)
Total (n)	48	48	66 (100.0)	21	20	30 (100.0)	80 (100.0)
Total (%)	72.7	72.7	100.0	70.0	66.7	100.0	–

abilis (Kütz. ex Bornet et Flahault) Komárek et Anagn., *Schizochlamydella* cf. *delicatula* (G.S. West) Korschikov, *Chlorella vulgaris* Beij., *Nephrodiella phaseolus* Pascher, *Gloeobotrys sphagnophilus* Ettl, *Ellipsoidion oocystoides, Stichococcus bacillaris, Gloeobotrys* cf. *bichlorus* Ettl, *Chloromonas* cf. *rosae* (H. Ettl et O. Ettl) H. Ettl, *Spongiochloris excentrica* R.C. Starr; in artificial stands – *Stichococcus bacillaris*, *Myrmecia incisa*, *Pseudococcomyxa simplex*, *Chlorella vulgaris,* '*Chlorella*' *mirabilis* V. Andr. (taxa incertae sedis), *Desmococcus olivaceus* (Pers. ex Ach.) I.R. Laundon, cf. *Mychonastes homosphaera*, *Trichromus variabilis, Chlamydomonas noctigama* Korschikov in Pascher, *Trebouxia aggregata* (P.A. Archibald) G. Gärtner, *Hantzschia amphioxys, Elliptochloris subsphaerica*.

The dominant species in the robinia litter were: *Coenochloris signiensis* (Broady) Hindak, *Phormidium* cf. *autumnale*, *Hantzschia amphioxys, Klebsormidium flaccidum*, *Bracteacoccus minor*, *Fottea stichococcoides* Hindák, *Chlamydomonas* sp. 1, *Myrmecia incisa*, *Dictyococcus varians* Gerneck emend. R.C. Starr, *Desmonostoc muscorum* (C. Agardh ex Bornet et Flahault) Hrouzek et Ventura. In the composition of the dominant species complex of robinia litter, *Phormidium* cf. *autumnale* is constantly present, which distinguishes it from the other litter types.

Discussion

Recently, as a result of studies on various land ecosystems, lots of materials have been collected about the peculiarities of soils algae composition, including forest ecosystems (Shalar, 1993; Chornevych and Nikorych, 2008; Maltseva, 2009; Novakovskaya and Patova, 2011; Kramarets et al., 2014; Maltseva et al., 2017). This has helped to solve a significant part of theoretical and practical issues. However, without the information about the structural-functional peculiarities of forest litter algae groups organization, it is impossible to solve one of the key tasks of the ecology – ensuring the sustainability and high productivity of forest ecosystems. The principle of the system method for biological systems research is based on this fact.

The forest litter of different tree species varies in the morphological parameters and the physical-chemical properties. In the pine forests of the steppe zone of Ukraine, the litter thickness reaches 10–12 cm, the litter can be two-layered or three-layered. As a rule, the litter accumulation prevails over its destruction intensity (Dubina, 1987). The peculiarity of pine litter is the presence of substances difficult to decompose by microorganisms, which leads to more accumulation of litter in coniferous forests compared to the deciduous ones (Bogatyirev, 1996). The pine litter saturation with lignin, tannins and polyphenols can slow down the mineralization process in this litter type. The presence of hardwood admixture in pine litter accelerates the transformation processes and increases the intensity of biotic turnover in general (Kotovich et al., 2003). Robinia litter is decomposed faster than the oak litter (Zhytska and Khanenko, 2011). Slow decomposition of hardwood and oak litter, in particular, is associated with high content of substances, resistant to the biological effects: lignin (30%), cellulose (15–18%), hemicellulose (16%) (Chastuhin and Nikolaevskaya, 1969).

Broad-leaved species, compared to pine, draw much more mineral nutrients, including calcium, potassium, phosphorus into the biological cycle (Dubina, 1997, Kotovich, 2003; Zhytska 2009), so the ash content in leaf litter is higher than in the pine one. The ash content in the litter regardless the tree species differs in layers and seasons. The ash content increase in the lower litter layers is associated with accumulation of poorly migrating elements (silicon, aluminum, iron) (Dubina, 1997, Yakuba, 2002; Zhytska, 2009). The ash content in the litter increases in autumn, due to leaching of potassium, calcium, and accumulation of poorly migrating elements. The migration of nitrogen and phosphorus is more active in the bottom sub-horizons of litter than in the top ones.

The forest litter is characterized by very specific properties in comparison with aerosphere and soil conditions. Besides, the litter of various broad-leaved and pine species differs in morphology, structure, fractional composition, environment-forming role, chemical properties, allopathical activity (Eremenko, 2012), which can affect the composition of organisms which inhabit it.

A specific feature of algae communities in pine litter is a significant diversity of green and yellow-green algae. The properties of pine litter restrict the development of Cyanoprokaryota. Adding leaf litter to the pine litter accelerates the processes of mineralization, increases the content of mobile compounds such as: calcium, phosphorus, potassium, which in turn, contributes to the development of the representatives of departments Cyanoprokaryota and Bacillariophyta.

In pine litter, the following algae were met most often: *Klebsormidium flaccidum* in 63% of samples, *Pseudococcomyxa simplex* – 46.7%, *Bracteacoccus minor, Hantzschia amphioxys, Stichococcus bacillaris* – 40.0%, *Myrmecia incisa* – 26.7%.

The similarity of dominants and subdominants of algae communities in the studied pine stands litter lists on Jaccard's coefficient (JC, %) and Serensen one (%) is low (Table 5). The highest similarity was observed between the stands without admixture (Samara and Staro-Berdiansk forests) of broad-leaved litter in the pine litter type. The isolated position is taken by algae community of pine stand of Altahyr forest, where the forest stand comprises broad-leaved species.

Most of the dominant algae of pine forest litter are cocoid single-celled algae which do not form mucus, or form it in small amounts (*Stichococcus bacillaris*, *Pseudococcomyxa simplex*). In the composition of dominants of pine stands litter the following are most often met: *Klebsormidium flaccidum*, *Pseudococcomyxa simplex*, *Stichococcus bacillaris*, *Ellipsoidion oocystoides, Hantzschia amphioxys*.

In general, in algae groups of pine litter the cocoid morphotype of algae dominates. The characteristic feature is quite great variety of *Chlamydomonas*-like algae.

The characteristic feature of pine litter is the uneven settling of its various sub-horizons by algae. The highest species variety of algae corresponds to the average layer of litter.

The peculiarity of algae composition of the leaf litter is a significant variety of green, yellow-green algae and Cyanoprokaryota. The spatial organization of algae communities of leaf litter, in contrast to the pine one, is characterized by equal distribution of algae species in sub-horizons of litter. The algae species composition of forest litter of oak stands is richer than of robinia ones. In the composition of dominants of leaf litter the species of different morphotypes are represented: trichal, cocoid, *Chlamydomonas*-like and others. *Chlamydomonas*-like and cocoid morphotypes of algae dominate. The following were most often met in leaf litter: *Stichococcus bacillaris* – 53.2% of samples, *Hantzschia amphioxys*, *Phormidium* cf. *autumnale* – 38.3%, *Bracteacoccus minor* – 34.0%, *Klebsormidium flaccidum* – 31.9%*, Desmococcus olivaceus* – 23.4%.

The similarity of dominants and subdominants of algae communities of the studied oak stands litter lists on Jaccard's coefficient (JC, %) and Serensen one (%) is not high (Table 6). The greatest similarity was observed between the stands located in the bottom-land of the river Molochna and in the near-terrace area in the bottom-land of the river Samara. The distinct group consists of the algae community dominants of linden-ash grove litter of the Samara forest, located closer to the river-bed in the central part of the bottom-land. In the composition of dominants of oak stands litter, there were most often noted: *Klebsormidium flaccidum*, cf. *Mychonastes homosphaera, Chlorella vulgaris, Trichromus variabilis*.

The similarity of composition of dominant algae taxa among communities of robinia stands was at the level of 20% in Jaccard's coefficient and 40% in Sorensen's coefficient comparing between the stands of Samara and Staro-Berdiansk forests; and 30% and 60%, respectively – between the stands of Staro-Berdiansk and Altahyr forests. In the composition of dominants of robinia stands litter the following were most frequent: *Phormidium* cf. *autumnale, Hantzschia amphioxys*.

Conclusions

The forest litter investigated in the pine and hardwoods stands (oak and robinia) differed in the layer thickness, internal structure, physical and chemical parameters. This was responded by the different species composition of eu-

Table 5. The similarity of species composition of dominants and subdominants of algae communities in the studied pine stands litter lists on Jaccard's and Serensen coefficient

Pine stand of forest area	Samara forest Sample area 1	Staro-Berdiansk forest Sample area 2	Altahyr forest Sample area 3
Samara forest, sample area 1	**12**	6	4
Staro-Berdiansk forest, sample area 2	35.3 (52.2)	**11**	6
Altahyr forest, sample area 3	18.2 (26.7)	26.1 (40.0)	**18**

Diagonally – the number of species of dominants and subdominants in algae communities which were compared; above diagonal – the number of joint species for pairs of algae communities which were compared; under the diagonal – the value of Jaccard's coefficient (JC), in brackets – the value of Sorensen's coefficient.

Table 6. The similarity of the species composition of dominants and subdominants of algae communities of oak stands litter on Jaccard's and Serensen coefficient

Stand, forest area	Linden-ash grove, Samara forest Sample area 4	Elm-ash grove, Samara forest Sample area 4	Oak stand, Staro-Berdiansk forest Sample area 6	Oak stand, Altahyr forest Sample area 8
Linden-ash grove, Samara forest Sample area 4	**16**	4	4	5
Elm-ash grove, Samara forest Sample area 4	15.4 (26.7)	**14**	3	3
Oak stand, Staro-Berdiansk forest Sample area 6	19.1 (38.1)	15.0 (26.1)	**9**	4
Oak stand, Altahyr forest Sample area 8	17.9 (30.3)	10.7 (19.4)	18.2 (30.8)	**17**

Diagonally – the number of species of dominants and subdominants in algae communities which were compared; above diagonal – the number of joint species for pairs of algae communities which were compared; under the diagonal – the value of Jaccard's coefficient (JC), in brackets – the value of Sorensen's coefficient.

karyotic algae and Cyanoprokaryota, and by their distribution in the sub-horizons of the forest litter. The thickness forest litter layer in the studied pine stands reached 6.5 cm, and the layer consisted of two or three sub-horizons, with prevailing sub-horizons of fermentation, A0^2 (F) and of humification A0^3 (H). From the upper layers to the lower ones, the ash content in pine litter increased, with pH increasing from 3.91 to 4.98. The forest litter layer in the hardwood stands (oak and robinia) had a thickness of 5–6.5 cm, structured into two sub-horizons, of which the fermentation one was more developed. For the leaf litter, in contrast to the pine litter, the higher pH values (4.71–6.83) were characteristic. The robinia stands litter was the least acid. The pH values of the litter increased from the top to the bottom sub-horizons.

The photosynthetic eukaryotic algae and Cyanoprokaryota are an integral part of the forest litter biota. The pine forest litter is the most appropriate habitat for the development of green and yellow-green algae and, in contrast, this litter type limits the diversity of Cyanoprokaryota. The admixture of leaf litter to the pine litter resulted to the increase of the species diversity of Cyanoprokaryota and Bacillariophyta. The characteristic feature of pine litter is an uneven distribution of in this litter sub-horizons by algae. The highest species diversity of algae has been found in the fermentation sub-horizon A0^2 (F) of this litter type. The peculiarity of the algae species composition in the leaf litter is a significant diversity of green, yellow-green and blue-green algae. The spatial organization of algae communities in the leaf litter is characterized by a uniform distribution of the algae species in the sub-horizons of litter. The algae species composition in the forest litter in the oak stands is richer than those in the robinia stands.

The composition of dominant and subdominant algae species in the forest litter depends on the forest-forming tree species. The characteristic dominant species in the pine litter have been found: *Klebsormidium flaccidum*, *Pseudococcomyxa simplex*, *Stichococcus bacillaris*, *Ellipsoidion oocystoides, Hantzschia amphioxys*, in the oak stands: *Klebsormidium flaccidum*, cf. *Mychonastes homosphaera, Chlorella vulgaris, Trichromus variabilis*, in the robinia stands: *Phormidium* cf. *autumnale, Hantzschia amphioxys.*

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Basic density and crown parameters of forest forming species within Steppe zone in Ukraine

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Abstract

Sytnyk, S., Lovynska, V., Lakyda, P., Maslikova, K., 2018. Basic density and crown parameters of forest forming species within Steppe zone in Ukraine. *Folia Oecologica*, 45: 82–92.

The parameters of wood density (WD), bark density (BD) and tree crown characteristics are not only important for estimation of the aboveground biomass, but they also serve as indicators for the timber quality. This study had two objectives: Black locust (*Robinia pseudoacacia* L.) – an introduced species; Scots pine (*Pinus sylvestris* L.) – an aboriginal species. Black locust and Scots pine from the Steppe zone in Ukraine were compared in their WD and BD, and in the morphological parameters of their tree crowns. There were determined basic WD and BD for differently aged individuals of Black locust and Scots pine. Generally, a higher WD was found for Black locust trees. The average Black locust WD was 518 kg m^{-3}, ranging from 375 kg m^{-3} to 612 kg m^{-3}; with the average BD – 294 kg m^{-3}, ranging from 214 kg m^{-3} to 421 kg m^{-3}. The average Scots pine WD was 414 kg m^{-3}, ranging from 254 to 491 kg m^{-3}; with average BD – 317 kg m^{-3}, ranging from 178 to 433 kg m^{-3}. The dependences between WD, BD and biometric tree parameters were identified by correlation analysis. The crown diameter for Black locust and Scots pine was described with fixed prediction models. We proposed particular equations for relationships between foliage biomass and branch biomass, derived from the crown volume of the investigated species.

Keywords

Black locust, Scots pine, forestry, prediction models, tree biometric parameters, trunk wood and bark

Introduction

Human activities such as commercial felling, fuelwood gathering, fires, various agricultural and industrial activities, disturb forest ecosystems through their deforestation and forest degradation (Goussanou et al., 2016; Mykolenko et al., 2018).

There is an increasing pressure on the forest resources in Ukraine and elsewhere. Forest ecosystems in the Ukrainian Steppe play an important commercial and ecological role. This includes both higher demands on economic profitability and a stronger restricions for saving the forest land for nature conservation. To meet these conflicting demands, wood production per a unit area must be increased for the forests subject to cutting.

Databases on wood density and tree crown parameters of the forest-forming species have been developed in many countries of Europe (Hakkila, 1979; Hasenauer and Monserud, 1996; Ahtikoski, 2000; Tahvanainen and Forss, 2008; Mateyko, 2013; Schneider et al., 2015; Kovalska, 2017; Roaki et al., 2017; Viherä-Aarnio and Velling, 2017; Husmann and Möhring, 2017; Polláková et al., 2017); Southern America (Alves and Santos, 2002; Fajardo, 2016); Africa (Goussanou et al.,

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2016); and Asia (Hoffmann and Usoltsev, 2002; Chen et al., 2017).

An increase in demand for wood for energy production is leading to more intensive harvesting of timber, including crown biomass. To predict the harvested biomass in an integrated industrial and energy wood harvesting, the vertical distribution of crown biomass also needs to be known. Individual tree stem volume and biomass equations are commonly used to predict the total amount of tree crown biomass.

The commercial and ecological potential of a tree species basically consists of the trunk and the utilizable aboveground biomass of the crown. Wood formation and growth allocation are the results of mechanical and nutritional conditions, water conductivity, and the hormonal growth control agents (Lakyda et al., 2011).

Wood basic density is an important wood property for both solid wood and fiber products in both conifers and hardwoods. A high wood density implies a higher production of wood biomass per unit volume. However, wood density and crown parameters are important quality traits in mechanical processing, because they affect practically all mechanical strength properties and the hardness of timber.

The available literature sources suggest that the topic has not yet been comprehensively discovered in the Ukrainian Steppe zone.

Lakyda et al. (2016) have compiled all the available allometric equations for other natural zones, but similar equations were taken only few for the Ukrainian region. The recent studies have not included the main forest-forming tree species growing in the Northern Steppe of Ukraine. In harsh drought conditions typical for such natural zone as the Steppe, it is thought-provoking to study the mechanisms used by the trees to regulate their wood formation and to adapt to the environmental requirements.

Black locust (*Robinia pseudoacacia* L.) is a pioneer hardwood species occupying various habitats over its wide area of distribution in the temperate and cold regions of all the continents (Vítková et al., 2017).

In the Ukrainian Steppe, Black locust is used as a tree species for remediation of industrially damaged areas (Lokhmatov and Gladun, 2004). Scots pine stands have always been recreational forests. Scots pine timber is mainly used as plywood in sawmilling industry.

In the Northern Steppe, the total area of Scots pine stands is 21,472.9 ha, that of Black locust is 17,683.7 ha, which accounts for 24.6 and 20.3% of the whole forest-covered area, respectively. By origin, Scots pine stands are divided into naturally and artificially regenerated forests; natural stands cover an area of 3,693.8 ha (17.2%), whereas planted forests of this species cover 17,779.1 ha, which corresponds to 82.8% (Lovinska and Sytnyk, 2016; Sytnyk et al., 2017).

Long-term forest development programs in Steppe Zone of Ukraine aim to increase the area of the artificial forest stands. This means that the commercial importance of the two forest-forming tree species – Black locust and Scots pine is expected to increase.

Prediction models with a higher precision have not been developed yet. The aim of this study is to fill this gap – with evaluating wood density and development of prediction model for the economically usable crown parameters of Black locust and Scots pine in the Steppe forest within South Ukraine.

Materials and methods

The study was conducted in Black locust and Scots pine stands in the Dnipropetrovsk region, located in the Northern Steppe of Ukraine and covering 31,974 km^2 (47–49°N; 33–37°E).

The research sites were chosen in four forestry enterprises governed by the State Agency of Forest Resources: Dnipro, Novomoskovsk, Vasylkivka, Verchnodneprovsk (Fig. 1). A total of 30 sample plots were established in Scots pine and Black locust stands. Their forestry-related and biometric parameters are in Table 1.

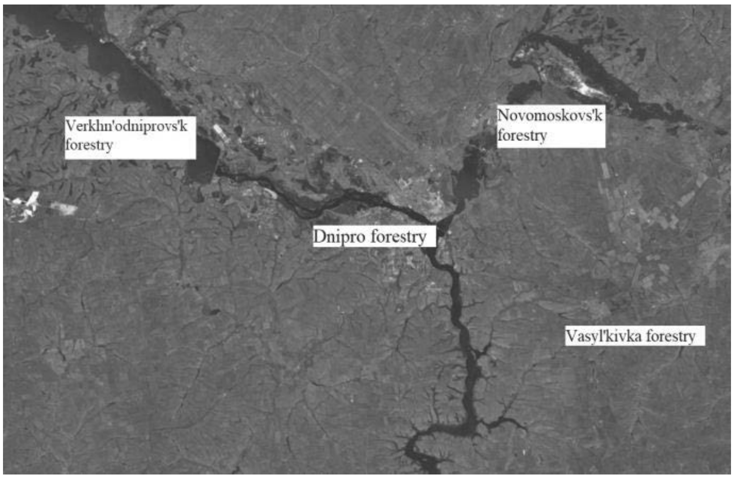


Fig. 1. Location of the study sites in Dnipropetrovsk region, Ukraine. Map. Source: Google Earth®.

Table 1. Structural characteristics of Black locust and Scots pine stands within temporary sample plots

Stand	Stand area (ha)	Total trees on TSP	Age (years)	*dbh* (cm)	Height (m)	Number of trees (trees/ha)	Basal area (m^2 ha^{-1})
Bl1	0.18	182	32	12.2	12.5	1,011	11.90
Bl2	0.16	70	63	16.4	15.3	1,750	37.00
Bl3	0.20	158	12	5.7	5.7	790	2.00
Bl4	0.40	103	36	22.4	21.1	589	44.64
Bl5	0.50	107	3	3.9	5.2	506	0.61
Bl6	0.49	205	48	23.9	19.9	500	22.44
Bl7	0.25	352	58	26.0	20.0	473	25.16
Bl8	0.50	213	82	24.4	21.5	488	22.85
Bl9	0.25	99	77	24.8	16.1	396	19.17
Bl10	0.25	282	56	16.2	17.0	1,128	23.30
Bl11	0.25	227	47	16.4	14.6	908	19.30
Bl12	0.29	168	50	24.7	20.2	579	27.84
Bl13	0.18	184	43	18.6	17.4	1,106	30.18
Bl14	0.25	274	34	15.8	16.2	1,096	21.45
Bl15	0.25	197	33	15.2	13.2	792	4.46
Sp1	0.30	222	68	29.1	20.7	740	49.24
Sp2	0.20	278	33	22.0	19.9	695	26.40
Sp3	0.20	119	11	4.6	2.8	595	0.98
Sp4	0.12	92	41	26.1	23.6	417	22.27
Sp5	0.11	170	9	5.6	3.8	1,070	2.63
Sp6	0.25	214	57	20.7	21.8	856	28.90
Sp7	0.25	197	62	22.4	23.6	756	29.84
Sp8	0.25	129	61	22.4	19.7	516	20.25
Sp9	0.25	104	66	29.3	30.4	416	28.01
Sp10	0.25	112	87	24.2	22.7	448	20.57
Sp11	0.25	110	76	23.9	19.5	440	19.79
Sp12	0.25	128	83	24.5	16.8	512	24.22
Sp13	0.25	124	76	23.2	22.5	496	22.13
Sp14	0.25	51	71	40.2	30.5	204	25.89
Sp15	0.25	190	58	19.9	18.2	760	23.74

Bl, Black locust stands; Sp, Scots pine stands.

The temporary sample plots (TSP) were selected using the analysis of the non-indigenous range of the studied species within the Northern Steppe zone of Ukraine, their economic and ecological values. The areas selected for TSP were surveyed, a biometric description was made for each one, determining the average values of age, height and diameter of the plantation and its productivity. If the area corresponded to the requirements, i.e. if it was a representative unit of the plantation of these species, it was selected for establishing TSP. TSP were chosen based on the stand age, and then the replicate sampling locations were randomly assigned within each forest both for Scots pine, as well Black locust stands. Number of all trees was counted within the TSP, and diameter and height were measured for each tree.

A tree is described by the following set of key indexes: age (*a*), diameter at breast height (*dbh*), trunk height (*h*), crown diameter (*cd*), crown radius (*cr*), crown length (*cl*), crown volume (*cv*), crown surface area (*csa*), the ratio of crown length to crown diameter (*cl/cd*), the ratio of crown length to trunk height (*cl/h*), foliage biomass (*fb*) and branches biomass (*bb*). For evaluation of the influence of the sample tree age on its basic density and crown parameters, there were used tree age classes (1 class equal to 10 years).

As the first step, wood density (WD) and bark density (BD) were assessed. After cutting the sample trees within the TSP, sampling disks (of about 2–3 cm in thickness) were cut along the stem at the root collar, at 1.3 m (*dbh*) or at 0.1 relative height of trees, and at 0.25, 0.50, 0.75 of the relative tree height (Fig. 2).

The sampling disks were weighed in freshly-cut state. The volume of the studied sampling disks was analyzed as a sum of volumes of the sectors (1) into which it was divided using a special device shown in the Fig. 3

$$v = \sum_{i=1}^{n} \frac{\pi \cdot r_i^2 \cdot k \cdot t_i}{360} \ , \qquad (1)$$

where v is volume of the section, cm^3; π is constant (3,1415); r_i is length of the *i* side of the sector angle, where *i* = 1, 2, 3, …, *n* is sequential number of the side of the angle, *k* is the value of the angle of the sector, degrees; t_i is thickness of the section within sector *i*, cm.

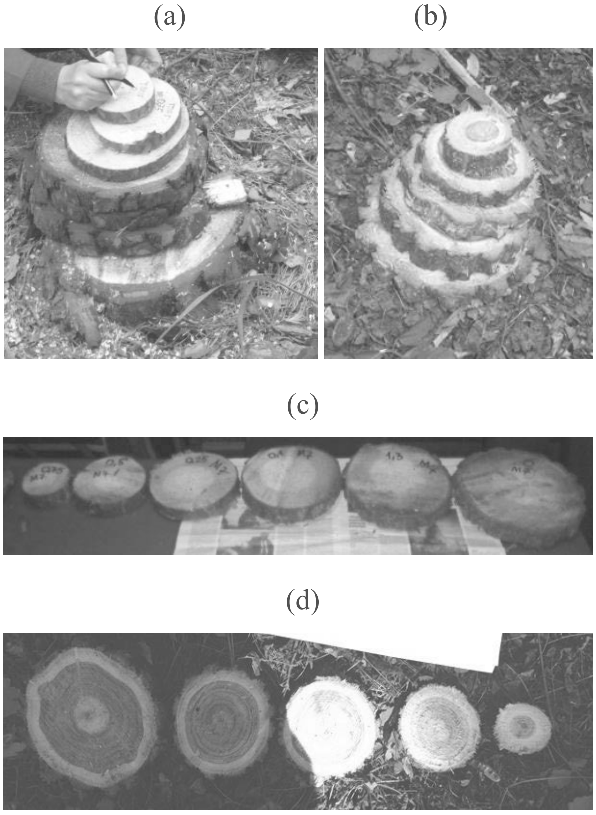


Fig. 2. Sampling disks from Scots pine (a, c) and Black locust (b, d).

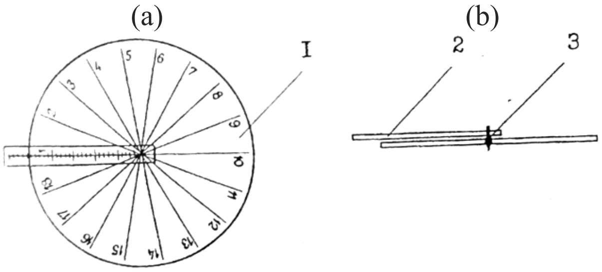


Fig. 3. Device for determining volume of sampling disks: (a) view from above; (b) side view. 1, circle with sectors; 2, ruler; 3, metal rod.

The angle was considered to equal 20º, when every section was conditionally divided into 18 sectors. Then the formula is as follows:

$$v = \frac{\pi}{18} \sum_{i=1}^{18} r_i^{\;2} \cdot t_i \qquad (2).$$

Statistical analysis of the measurements of such sections was made using the software ZRIZ (Version 2002), PLOT (Version 2002) (Lakyda 2002; Lakyda et al. 2007), where there was calculated the sum of the volumes of 18 wood cross-sections.

The bark was mechanically separated from the wood of sampling disks. The calculation of the basic density required of drying the samples at a temperature of 105 °C. The wood and bark basic density was defined as:

$$basic\ density = \frac{over\ dry\ weight\ (kg)}{green\ volume\ (m^3)} \qquad (3).$$

For definition of branch biomass, from each tree there were cut samples from different crown levels (lower, middle, top of the crown) and weighed fresh within TSP, in the same way as in case of the stem sampling disks. All branches with leaves and needles from sample trees were used for the measurement of moisture content and basic density in the laboratory. The calculation of the average basic density of branches was carried out with selected sample branches and there were also determined their volume and basic density as in the stem sampling disks (formula 1, 2, 3). Branches biomass (*bb*) was calculated using Eq. 4:

$$bb = (v_{small\ branches} + v_{big\ branches}) \cdot p_{branches} \qquad (4),$$

where $v_{small\ branches}$ (below 1 cm in diameter)$_,$ $v_{big\ branches}$ (above 1 cm in diameter) are volume of branches with bark (m^3), and $p_{branches}$ is average basic branch density (kg m^{-3}).

The foliage biomass is the mass of branches with a diameter less than 1 cm, with leaves (needles), determined by weighing method within the TSP.

The crown parameters of Black locust and Scots pine trees were investigated based on the data obtained for 120 sample trees. Correlation analysis was conducted to identify the closeness of the relationship between the studied parameters.

The measurements of the projection crown length and crown diameter were carried out in two mutually perpendicular directions – North-South, West-East in accordance with the international method for determining the crown parameters (Fischer et al., 2010).

The crown volume was determined as the identical geometric figure volume: Black locust as an inverse cone, Scots pine – two paraboloids, touching by their bases.

The black locust crown surface area was calculated according to the formula 5:

$$csa = \pi \frac{1}{2} cd{\cdot}cl + \pi \left(\frac{1}{2} cd\right)^2, \qquad (5)$$

where *csa* is crown surface area, m^2; *cd* is crown diameter, m; *cl* is crown length, m.

The crown volume was calculated according to the formula 6:

$$cv = \frac{1}{3} \pi \left(\frac{1}{2} cd\right)^2 \cdot cl\,, \qquad (6)$$

where *cv* is crown volume, m^3; *cd* is crown diameter, m; *cl* is crown length, m. ,

The Scots pine crown surface area and crown volume were calculated according to the formula 7, 8:

$$csa = \frac{\pi cr}{6h^2}[(cr^2 + 4h^2)^{3/2} - cr^3]\,, \qquad (7)$$

where *csa* is crown surface area, m^2; *cr* is crown radius, m; *h* is tree height, m.

$$cv = \frac{1}{2}\pi cr^2 h, \quad (8)$$

where *cv* is crown volume, m³; *cr* is crown radius, m; *h* is tree height, m.

The prediction models working with the received data of basic density and crown parameters were statistically verified using PRETZSCH and DIELER (2011) and the software STATISTICA (Version 12.6, 2015).

$$cd = \exp((k_0 + k_1 \cdot \ln(dbh) + k_2 \cdot h + k_3 \cdot \ln(\frac{h}{dbh}))), \quad (9)$$

where *cd* is crown diameter; k_0; . . . ; k_3 is the inversion coefficients; *h* is tree height, m; *dbh* is diameter at breast height, cm.

Results

The wood and bark density had average values ranging from 518 to 294 kg m^{-3} for Black locust, and between 414 and 317 kg m^{-3} for Scots pine (Table 2). As these data show, the average wood density was higher in Black locust. The average wood basic density of this species increased from 375 to 612 kg m^{-3} and bark density from 214 to 421 kg m^{-3}. For Scots pine these values were lower: from 254 to 491 kg m^{-3} in wood and from 178 to 433 kg m^{-3} in bark. The variations in the tree basic density for the two investigated species showed significantly greater differences in the Black locust wood and in the Scots pine bark.

The data for the Black locust WD and the Scots pine BD were indicated conditions of normal distribution, because their factual indexes of skewness and kurtosis were lower than their critical values $A\text{cr} = 0.711$ ($p \leq 0.05$), $E\text{cr} = 0.907$ ($p \leq 0.01$) (YANTSEV, 2012). Most of the Black locust parameters were characterized by negative values of kurtosis (except for BD) which suggested top-flatness of the distribution curve. At the same time, kurtosis for these parameters had positive values for Scots pine and corresponded to peakedness of the distribution curve.

The reliability of correlation coefficient was evaluated with regard to the critical index which is equal to 0.42 (YANTSEV, 2012). The analysis of the obtained data of correlation coefficients for Black locust showed a moderate correlation of WD with the tree height ($r = 0.45$), and a significant correlation with *dbh* ($r = 0.54$) and the tree age ($r = 0.54$). The inverse correlation was observed for the relationship between BD with the measured indices of trees. These values were less significant. The significant correlation coefficient was only found for the tree age ($r = –0.46$).

For Scots pine, the correlation coefficients for basic density had positive values in almost each studied tree biometric factor. The most significant coefficients were registered for WD with age ($r = 0.55$), tree height ($r = 0.48$) and *dbh* ($r = 0.60$). There were weak direct and inverse correlations of BD with all the measured parameters.

Figures 4–5 demonstrate that WD and BD varied axially within the tree age class. The tendencies were the same for both Black locust and Scots pine. The black locust WD values were the lowest in the sample trees of 1–2 age classes, but in course of the time there was an increase to eighty years followed by a slight decrease later.

The maximum BD value was reached by the tree age 40 years, then this parameter decreased with age. The same tendency was recorded for the Scots pine BD, with a maximum at the tree age of fifty years. The situation was quite different with WD for which two maximum paeks were established – by the age of 40 and 90.

For Black locust, there were moderate positive correlations between the crown diameter and *dbh* ($r = 0.60$), and trunk volume ($r = 0.59$) (Table 3). Contrarily, there were recorded positive correlation between the crown volume and the crown area surface ($r = 0.98$), crown diameter ($r = 0.90$) and trunk volume ($r = 0.72$).

The Pretzsch function was a basic one for modeling the dependence of the crown diameter (*cd*) and its parameters on *dbh* and tree height. The obtained coefficients for calculation of crown diameter for sample trees of the two studied species were derived using the equations (Table 4).

Table 2. Main statistics of biometric indexes sample trees and basic density of trunk Black locust and Scots pine

Index/ Parameter	Value		Statistics			
	Min	Max	$\dot{X}$	*Σ*	*A*	*E*
			Robinia pseudoacacia L.			
Age (years)	3	89	40.8	23.2	0.514	–0.437
Dbh (cm)	4.5	28.6	16.6	7.1	–0.256	–0.851
Trunk height (m)	5.3	22.7	14.0	5.2	–0.380	–0.628
Wood density (kg m^{-3})	375.0	612.0	499.8	68.7	0.011	–0.839
Bark density (kg m^{-3})	214.0	421.0	300.8	46.6	0.485	1.406
			Pinus sylvestris L.			
Age (years)	9	90	5.49	24.57	–0.652	–0.542
Dbh (cm)	7.0	39.0	1.54	6.89	0.093	1.643
Trunk height (m)	4.5	30.0	1.46	6.54	–1.040	0.958
Wood density (kg m^{-3})	254.0	491.0	13.38	59.82	–1.182	1.348
Bark density (kg m^{-3})	178.0	433.0	13.82	61.81	–0.263	0.581

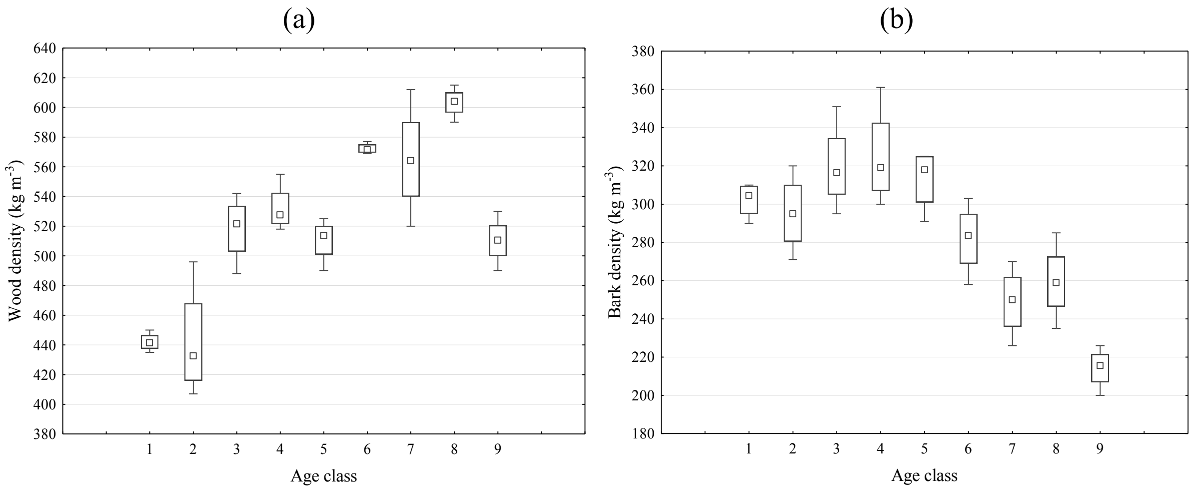


Fig. 4. Changes in wood (a) and bark (b) density of Black locust in relation to its age class. Box plots show the range, median, and 25% and 75% quartiles of basic density.

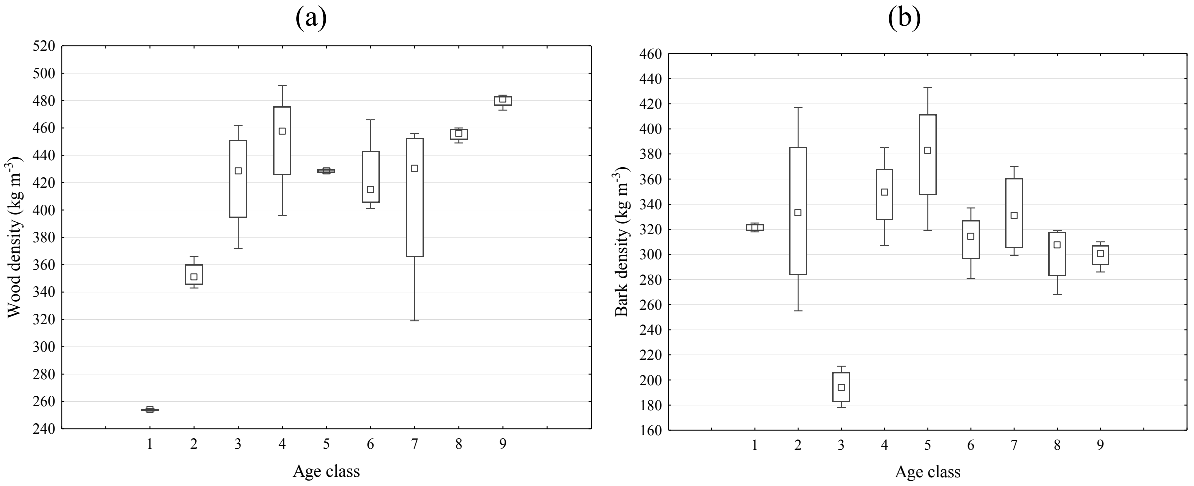
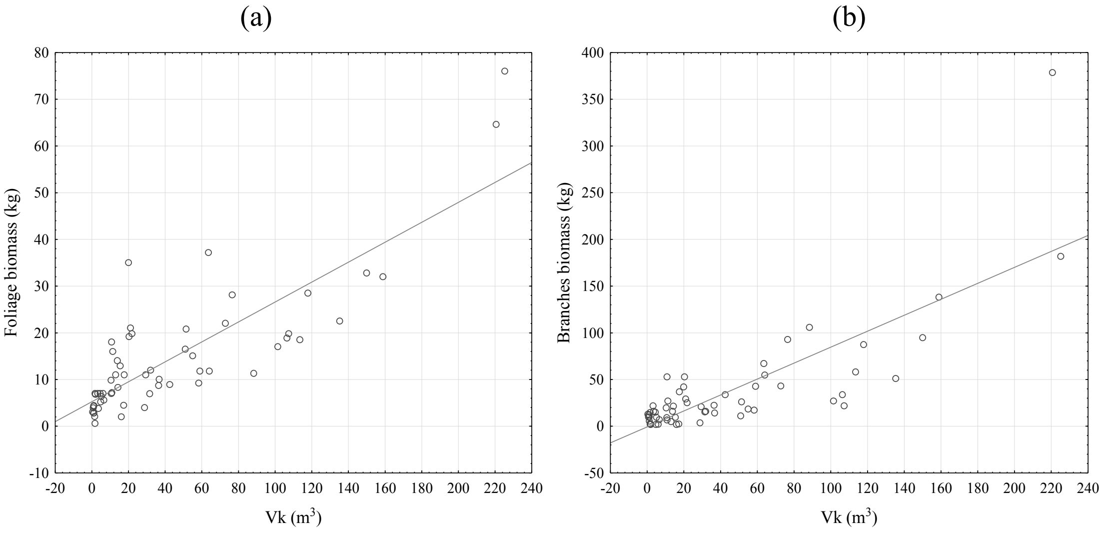


Fig. 5. Changes in wood (a) and bark (b) density of Scots pine in relation to its age class. Box plots show the range, median, and 25% and 75% quartiles of basic density.



$fb = 5.260 + 0.2134 \cdot cv$

$bb = -0.621 + 0.854 \cdot cv$

Fig. 6. Relationships between foliage (a) and branches (b) biomass from crown volume for Black locust trees

Table 3. Coefficients of correlation of crown parameters with biometric indices of trees

Index of tree	*a* (Year)	*dbh* (cm)	*h* (m)	*Cd* (m)	*cl* (m)	*cl/cd*	*cv* (m^3)	*cl/h*	*csa* (m^2)	*fb* (kg)
dbh (cm)	0.76 0.69	1								
h (m)	0.75 0.73	0.90 0.82	1							
cd (m)	0.34 0.20*	0.60 0.60	0.56 0.66	1						
cl (m)	0.62 0.35	0.67 0.47	0.75 0.40	0.41 0.23	1					
cl/cd	0.19* 0.20*	–0.05* –0.05*	0.03* 0.01*	–0.63 –0.54	0.33 0.65	1				
cv (m^3)	0.43 0.26	0.63 0.69	0.58 0.43	0.90 0.88	0.53 0.51	–0.42 –0.24	1			
cl/h	–0.36 –0.57	–0.44 –0.52	–0.48 –0.75	–0.29* –0.21*	0.14* 0.23*	0.44 0.34	–0.14* –0.08*	1		
csa (m^2)	0.46 0.30	0.69 0.70	0.66 0.48	0.93 0.87	0.63 0.64	–0.39 –0.12*	0.98 0.98	–0.15* –0.05*	1	
fb (kg)	0.36 0.35	0.62 0.70	0.48 0.33	0.45 0.69	0.47 0.39	–0.07* –0.20*	0.48 0.79	–0.10* –0.07*	0.53 0.75	1
bb (kg)	0.29 0.33	0.62 0.60	0.47 0.29	0.44 0.49	0.43 0.33	–0.12* –0.11*	0.62 0.59	–0.11* –0.08*	0.61 0.57	0.65 0.84

Conventional signs*:* *Scots pine, Black locust*; * the value not significant at the level $p < 0.05$.

Table 4. Models and coefficients of determination of crown diameter and volume

Robinia pseudoacacia L.		*Pinus sylvestris* L.	
Non-linear model	Coefficients of determination	Non-linear model	Coefficients of determination
$cd = \exp(((-0.063) + (0.313) \cdot \log(dbh) + (0.027) \cdot h + (-0.269) \cdot \log(h/dbh)))$	0.602	$cd = \exp(((0.283)+(0.055211) \cdot \log(dbh) + (0.030) \cdot h + (-0.767) \cdot \log(h/dbh)))$	0.627
Linear model	Coefficients of determination	Linear model	Coefficients of determination
$vc = -52.69 + 0.70dbh + 21.90dc + 3.40lc$	0.923	$vc = -67.7+0.40dbh + 21.73dc + 3.40lc$	0.894

Discussion

Wood density indicates the amount of actual wood substance present in a unit of wood volume. Basic density is a gross wood characteristic; it defines wood properties and function of the tracheid structure. Basic density is correlated to the yield, the strength and volumetric shrinkage properties of sawn wood (Lindström, 1996).

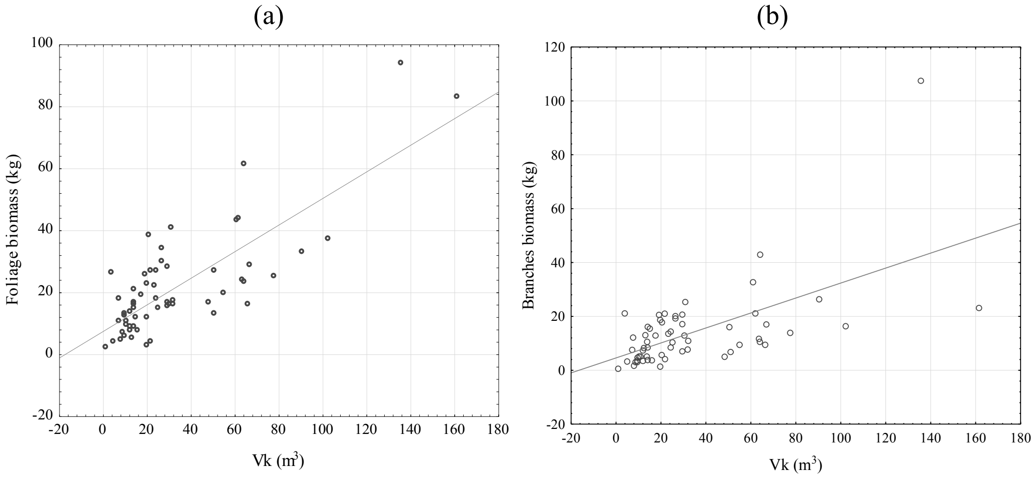
In this research, there have been obtained unique results concerning the dependencies of the basic density and crown parameters on the biometric indexes for Black locust and Scots pine growing in the forest plantations of the Steppe.

In this study, the WD significantly differed among the species investigated. This is an expected result, consistent with the studies carried out elsewhere.

At the species level, this study has found the WD for *P. sylvestris* (414 kg m^{-3}) lower than for *P. massoniana* found by Zhang et al. (2012) – 484 kg m^{-3} and Deng et al. (2014) – 477 kg m^{-3}. Pine wood density depends on cambium maturity, with density usually increasing towards the outer rings with progressive tree ageing over long time periods (Karenlampi and Riekkinen, 2004).

The mean values for the Scots pine wood density reported in our study did not deviate significantly from the data reported in the literature for another natural zone of Ukraine (Kovalska, 2017; Lakyda et al., 2016; Pasternak et al., 2014). For instance, the mean value of WD in our study was only 3% higher than the value reported by Lakyda et al. in the conditions of the Ukrainian Polissya (2016). The value of BD in our research is higher by 20 and 13% than in Polissya and Forest-Steppe of Ukraine, respectively.

Tomczak studied technical parameters of juvenile wood in Scots pine (2013). The values he obtained for the basic density of juvenile wood for pine from a regular stand were in the range 401–432 kg m^{-3}. In the study carried out by Repola (2006), there was investigated the vertical



fb = 7.517+0.429 · *cv*   *bb* = 4.584 + 0.278 · *cv*

Fig. 7. Relationships between foliage (a) and branches (b) biomass from crown volume for Scots pine trees.

distribution pattern of the basic density in Scots pine, with possible implementation for determining the average stem wood density. Compared with our data, the result received by this author indicates lower density of the stem at breast height (412.2 kg m^{-3}) in the conditions of mineral soil sites in southern Finland. Zeller et al. (2017) report the tree-ring-wood density in Scots pine lower in mixed stands compared to monocultures. These researchers showed the lower tree-ring-wood density in mixed stands. Biomass in mixed stands calculated from stem volume and tree-ring-wood density is lower (12%) than in pure stands -- despite the measured over-yield in volume in mixed stands. Auty et al. (2014) developed a nonlinear mixed-effects model for predicting wood density in Scots pine as a function of annual ring number, radial growth increment and height of the stem.

Black locust has not been spread as a forest-forming species in other natural zones of Ukraine, that is why there were not available data about the investigated characteristics in the scientific literature. In the Steppe zone, this species has formed forest plantations over a significant area.

The average WD of Black locust displayed a typical increase with age. The established dependence may be explained by proportional variations in the xylem structural elements and in the parenchymal tissue. In addition, tracheid and wood fiber size and morphology can influence the WD significantly.

Water loss from the tissue with age and deposing secondary metabolites in the cell walls were characteristic features for this species. These factors can induce increasing basic density with the tree age.

The review of Lindström (1996) focused on variables related to the crown development and basic density. According to the author's statement, the given four independent theories of wood formation indicate that the crown development acts as a primary regulator for wood structure and basic density. In general, wood formation theories state that the stem cambial activity, growth allocation, and wood structure are functions of crown development.

Despite several studies on crown parameters, these indexes has never been modeled for the Steppe forest-forming species. Therefore, a comparison of our results with other studies would not be correct. However, important parameters for studying trees crown were proposed in a publication carried out for different forest types and species (Pretzsch and Dieler, 2011; Pretzsch et al., 2015).

Hoffmann and Usoltsev (2002) studied tree-crown biomass estimated for forest species of the Ural and of Kazakhstan. Regressions relations stated based on the foliage and green shoot biomass at various complexity levels were used as predictors diameter at the base of the crown, diameter at breast height and age. Gargaglione et al. (2010) derived allometric relations for partitioning the biomass of *Nothofagus Antarctic* to different crown classes along a site quality gradient.

Crown architecture affects the tree growth by controlling the leaf area and its capacity for effective light capture and photosynthesis (Choi et al., 2001). It seems reasonable to quantify crown traits for effective use of intensive silvicultural practices to improve the tree growth in forest plantations. Chmura et al. (2007) examined growth and crown characteristics in two families of loblolly pine (*Pinus taeda* L.) with contrasting growth – superior and average, and one slash pine (*Pinus elliottii* Engelm.) family, growing in the West Gulf Coastal Plain of Texas and Louisiana, USA, their need for light-capture and greater carbon assimilation, as this family also produces the most aboveground biomass.

Viana et al. (2012) carried-out a spatial estimation of above-ground biomass and crown biomass of *Pinus pinaster* stands and shrublands in a region located in Centre-North Portugal, by means of different approaches including forest inventory data, remotely sensed imagery and spatial prediction models. Tahvanainen and Forss (2008) proposed individual tree models for the crown biomass distribution for Scots pine, Norway spruce and birch in Finland.

The work Roaki et al. (2017) presents data on the crown structure and branch/trunk growth for 400-year-old *Pseudotsuga menziesii* trees in an old-growth forest in western Washington, USA.

The article Rautiainen et al. (2008) describes a pine and spruce crown shape modeling from the perspective of optical, passive remote sensing. The authors discuss the requirements of global crown shape models in optical remote sensing and field measurement techniques related to these approaches, and present a measurement and modeling study on the crown shape of Scots pine and Norway spruce.

Conclusions

The wood and bark basic density in Black locust within the Steppe forest plantation in Ukraine had average values of 518 and 294 kg m^{-3}, respectively, the Scots pine wood and bark density over the same territory were 414 and 317 kg m^{-3}. In both tree species investigated, the wood density increased from the youngest sample trees to the oldest ones.

Moderate correlation coefficients were obtained characterizing the relation between the Black locust wood density and tree height. The correlation dependence between the ratio of wood density to *dbh* and the tree age was significant. The most significant correlation coefficient for the Scots pine wood density was registered with the tree age, height and *dbh*.

There have been proposed predictor models for Black locust and Scots pine tree crown diameter. These models will facilitate the determining of the crown diameter in Black locust and Scots pine in the forest stands within the Steppe zone. There were also derived predictor models for the dependence of foliage and branches biomass on the crown volume.

Black locust and Scots pine foliage biomass accumulation increased with increasing crown volume. The determination coefficient in these regression equations shows their reliability and opportunity for their use in the Steppe forestry.

Therefore, it is suggested to conduct more intensive research regarding other aspects and properties of Scots pine and Black locust, such as silvicultural aspects and chemical properties of the woods, to ensure the potential utilization of these wood species.

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