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CROWN BIOMASS OF SCOTS PINE AND BLACK LOCUST IN NORTHERN STEPPE OF UKRAINE

Petro Lakyda[1*], Svitlana Sytnyk[1], Viktoriia Lovynska[2], Ivan Lakyda[1], and Yuriy Gritsan[2]

[1]Department of Forest Mensuration and Forest Management, National University of Life and Environmental Sciences of Ukraine, 15 Heroiv Oborony str., 03041, Kyiv, Ukraine.
[*]E-mail: lakyda@nubip.edu.ua
[2]Department of Garden and Parks, Dnipro State Agrarian and Economic University, 25 S. Yephremova str., 49060, Dnipro, Ukraine. Email: glub@ukr.net

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Abstract

The formation of live biomass of forests is premised on many factors, among which the dominant ones are stands growth conditions and biometric characteristics. The purpose of this research is to develop reference materials for the evaluation of crown live biomass structural components for stands of black locust (*Robinia pseudoacacia* L.) and Scots pine (*Pinus sylvestris* L.) for the conditions of the Northern Steppe of Ukraine. The field research has been carried out in Scots pine and black locust stands of artificial origin subordinated to the State Forest Resources Agency of Ukraine. The research employed the classical forest mensuration techniques for collecting and processing experimental material on 40 test plots. The modelling was preceded by the stage of statistical analysis of the input dataset, which characterizes the live biomass of forest stands' crown. Mean age, diameter, and height of stands, as well as their relative stocking, have been identified as informative and statistically significant predictors. We have developed the two- and three-factor allometric regression equations for assessment of crown live biomass components – branches over bark and foliage based on the biometric indices of stands. The adequacy of the models has been estimated by the determination coefficient (0.47–0.71) and 'Fisher's F-test. In black locust and Scots pine stands with the same average diameter and relative stocking, live biomass of branches and foliage will be larger in those, where the mean height of the main species is smaller. The obtained allometric equations for assessing the biophysical indices of live biomass subject to this research can be used for practical forestry purposes in the course of forest inventory, determination of harvest volumes, and assessment of ecosystems services.

Keywords: allometric models, biometric parameters, branch biomass, foliage biomass, *Pinus sylvestris*, *Robinia pseudoacacia*.

Introduction

Assessment of the forests' ecosystem services is based on the understanding of peculiarities of accumulation of aboveground biomass of stands, including growth features, biological productivity patterns, and disturbance regimes (Lakyda et al. 2019). This is especially valid for the assimilative fraction, which secures the process of photosynthesis (Uri et al. 2012, Nord-Larsen and Nielsen 2015, Schepaschenko et al. 2018**).** The approach in forest management currently widely applied for assessing actual biomass of forest-forming tree species both at the level of an individual tree and of a tree stand is based on mathematical models. Allometric regression equations, highlighted in the scientific literature, have been developed taking into account the corresponding edaphic, climatic, and forest growth conditions, and, therefore, they cannot be used for performing this kind of assessments in Ukrainian Steppe, since the factors mentioned above are crucially important from the point of view of the formation of live biomass in forest stands.

Investigation of peculiarities of functioning of tree crowns is an important question from the point of view of automation and facilitation of interpretation of 'stands' parameters, as well as silvicultural, bioecological, and physiologic research linked with advanced research of 'forests' structure and functions.

The study of the forest crown biomass is mainly based on the three most common methods – the method of an average tree; the method of ratios of basal areas of sample trees and stands, and mathematical regression modelling (Satto and Madgwick 1982, Lakyda 2002, Romanovsky et al. 2009).

The most universal and reliable, from the standpoint of statistical significance, is the method by which sample trees are selected in proportion to their diversity in trunk diameter. After that, the obtained initial data are aligned using regression analysis (Lakyda 2002; Vasylyshyn 2016). To evaluate the live biomass components of tree crowns, pipe models developed on the basis of the theory of balance of the xylem transport system of substances in plants have been proposed. In the formulated theory of pipe models, or 'tube models', a tree trunk and a branch are considered as a set of elementary xylem vessels, each of which ends with an elementary mass of the assimilating apparatus (Vasylyshyn 2016).

Usoltsev (1997) states that searching for a rational determination of the number of TSPs and the maximum number of sample trees that should ensure the accuracy of assessing the components of stand live biomass should be based on the variability of the main biometric indices – age, site index, forest type, and cost (time, funds) of field stage of research. Studies by Usoltsev (1999) show that an increase in the number of average sample trees over three units has a very limited on the accuracy of the experiment.

Black locust (*Robinia pseudoacacia* L.) is an introduced species natively present in Northern America. In Ukrainian Steppe, it is used for planting forests and shelterbelts. The multidirectional vectors of management potential of this species are addressed in the scientific publications **(**Rédei 2002, Sitzia et al. 2016, Yuan et al. 2018, Zverkovskyy et al. 2018). Mainly in the introduction ranges, black locust stands of artificial origin are created to stabilize the disturbed and eco-hazardous environment – Loess Plateau (Yuan et al. 2018, An et al. 2019), Western Donbas (Zverkovsky et al. 2018), to obtain the main forest resource – high-quality wood (Rédei et al. 2014, Carl et al. 2018) as a fast-growing 'energy species' for biomass production (Dünisch et al. 2010, Böhm et al. 2011, Mantovani et al. 2014) and as sources of biologically active secondary metabolites (Tian and McLaughlin 2000). Aboveground live biomass of black locust has a substantial business potential due to its compositional structure of biologically active metabolites, mainly polyphenols – robinetin and dihydrobinetin (Tian and McLaughlin 2000, Sanz et al. 2011, Sergent 2014). Bostyn et al. (2018) present the establishment of industrial production of extracts from aboveground live biomass enriched in flavonoids for use in pharmacology. The effectiveness of the use of black locust leaves as biomonitors for assessing air pollutants, the presence of which in the air was determined according to the protocol EPA 3550 C 2007 has been established (Capozzi et al. 2017). Live biomass of Robinia leaves is proposed for use as a raw material for animal fodder by ensiling using lactic acid bacteria (Ni et al. 2016).

Scots pine is a native tree species in Ukrainian Steppe. However, the vast majority of the areas occupied by this species are of artificial origin.

The total area of Scots pine stands within the Dnipropetrovsk region is 21,472.9 ha, black locust stands occupy 17,683.7 ha, which accounts for 24.6 % and 20.3 % of the total forest-covered area, respectively. In conditions of the Steppe zone, black locust is used as a tree species for remediation of industrially damaged areas, with 35.2 % of the total area of *Robinia*'s stands in the study region (Lokhmatov and Gladun 2004, Gulchak et al. 2011). For Scots pine stands, the main functional categories are recreational and therapeutic forests (31.1 % from the total area in the region).

The crown components – branches and foliage – are, in fact, a border zone between the biotic sphere and abiotic medium (Lawlor 1995). They form the inner surface of the forest canopy, act as a filter of atmospheric precipitation, numerous emissions, light and heat fluxes, wind, and noise. The assimilative part is a zone where the main physiological processes are realized in a vegetal organism – photosynthesis, respiration, and transpiration determine links of material transformation and energy fluxes. Currently, the questions related to the research of forest crowns' parameters have been highlighted in publications by scientists from many countries (Parresol 1999, Pretzsch et al. 2002, Sytnyk et al. 2017). Usoltsev (2013) notes that the parameters of absorption of solar radiation by a tree canopy mainly depend on the fractional biomass structure.

In Scots pine trees, the upper and middle sections of a crown play a leading role in the energy transformation, since they have the highest needle packing. Nearly 40 % of active photosynthetic radiation is absorbed by upper crown layers (Usoltsev 2013). The upper crown layer 2–3 m thick is characterized by the highest proportion of foliage (Dilis 1969).

Lokhmatov and Gladun (2004) noted a decrease in the number of shoots and leaves per unit crown volume in black locust, resulting in a progressive increase in its openness and transparency of crowns. Along with the age-driven increase of openness and transparency of crowns of this tree species, intensification of sodding is associated, which leads to a decrease in tree growth.

Due to the absence of similar scientific research for Scots pine and black locust stands in the natural zone of Ukrainian Steppe (Schepaschenko et al. 2019), a study of dependencies of crown live biomass components on biometric indices of stands and development of appropriate reference materials for evaluation are recognized as the main purpose of this research.

Material and Methods

Collection of the experimental material has been carried out on 40 temporary sample plots (TSPs) on the territory of the Northern Steppe of Ukraine, 20 TSPs for each species under research (Fig. 1). The results obtained after the establishing 40 TSPs were statistically significant, as TSPs are homogeneous by their origin and types of forest growth conditions, microclimatic and edaphic conditions. To develop models for assessing the biomass of stands' crowns, we also used biometric data of the actual stands in the steppe zone with the corresponding number of stands of 4739 for black locust and 5158 for Scots pine (Anonymous 2020).

The TSPs were established and processed in accordance with the methodology proposed by Lakyda (2002). Establishing TSPs started with selecting representative forest sites in Scots pine, and black locust stands. Afterward, the compliance of the pre-selected sites with the requirements for forest mensuration sample plots

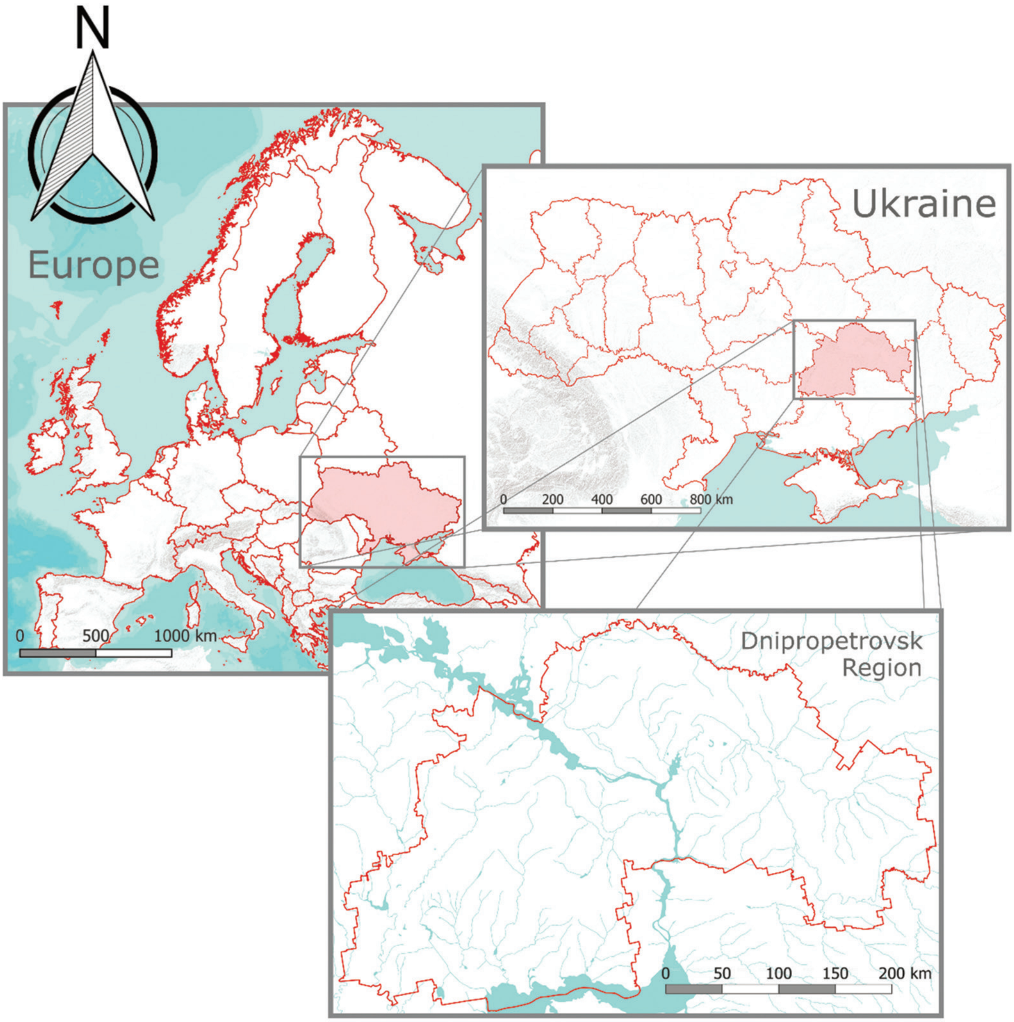


Fig. 1. Study region.

was evaluated.

The predominant shape of TSPs was rectangular or square, with a minimum width and length of sides 50×50 m. After demarcation, a forest mensuration description of TSPs is performed, which begins with determining the terrain characteristics. The TSPs are laid out in single-layer stands located within flat terrain. Tree enumeration in the form of a list of trees at the TSP with identification of their species and diameter at breast height was further carried out.

In order to determine the crown components biomass for the stands under research, at least 3 sample trees (STs) were selected and felled at the TSPs. MTs were selected by the method of tree diameter classes (Zou et al. 2015). The size and shape of the selected sample trees were close to the average for the entire set of trees at a TSP. For each growing sample tree, we have measured the diameter at breast height, and height of a tree. After cutting down, ST's total height and crown length were measured. Further, the crown of each ST was separated from its stem, and the weight of each separate crown component (tree greenery, live and dead branches) was determined by weighing.

To evaluate the density of wood and bark of branches, 2–3 cm thick samples were cut out from the middle parts of live branches of different lengths. The samples were annotated, put into a hermetic bag, and sent to the laboratory. Wood and bark density of the samples was further determined using their measured weight and volume. Subsequently, the samples were dried in an oven at 105 ºC until oven-dry. Re-weighing determined the weight of the samples in an oven-dry state. The volume of samples was determined using the original method proposed by Lakyda (2002).

To determine the percentage of foliage in tree greenery and the dry matter content in foliage, from the lower, middle, and upper parts of an ST's crown, three sample branches were randomly selected. The freshly cut sample branches were weighed, then the foliage fraction was separated, and the defoliated shoots were re-weighed. To determine the dry matter content, three 10-grams samples of fresh foliage were formed, each of which was dried in a drying oven until oven-dry and then weighed again. The total live biomass of ST's foliage in the oven-dry state was calculated employing the content of dry matter in foliage.

To identify the patterns of distribution of biometric indices of stands, determine homogeneity of the experimental data, carry out statistical analysis, we have formed an experimental dataset containing the following parameters: A – mean age of the main tree species, years; D –mean diameter of the main tree species, cm; H – mean height of a stand, m; P – relative stocking of a stand; Ph_{br} – live biomass of crown branches; Ph_f – live biomass of foliage.

Based on the initial data, a regression analysis was performed, which resulted in two- and three-factor allometric equations (1–3) for assessment of the structural crown components of stand live biomass for the two studied tree species:

$$Y = a \times D^b \times H^c \tag{1}$$

$$Y = a \times A^b \times D^c \times H^d \tag{2}$$

$$Y = a \times D^b \times H^c \times P^d \tag{3}$$

Impact factors in the mathematical models are represented by mean age, height, diameter of the main tree species, and relative stocking of a stand.

Biometric parameters of the distribution of absolute values of the main biometric indices of the studied stands are presented in Table 1.

Table 1. Descriptive statistics for the investigated species.

Stand biometric characteristics	Value		Statistics			
	min	max	$\dot{X}$	SD	Skewness	Kurtosis
			Scots pine			
A, years	9	87	54.5	22.9	-0.808	-0.116
D, cm	4.6	40.2	21.8	8.0	-0.416	1.604
H, m	2.8	30.5	19.4	7.2	-1.005	1.225
P	0.13	1.04	0.56	0.17	0.349	3.803
			Black locust			
A, years	3	82	44.8	21.4	-0.175	0.139
D, cm	3.9	26.0	17.7	6.8	-0.704	-0.096
H, m	5.2	21.5	15.7	5.0	-1.065	0.661
P	0.21	1.08	0.74	0.24	-0.039	0.676

Note: SD – standard deviation.

When analyzing the descriptive statistics, the considerable variance of biometric indices of stands becomes obvious. This fact testifies to the significant variability of the experimental data for all the parameters under scrutiny. The statistical sample of experimental data with a degree of freedom of 20 units has a critical value of skewness 0.711 ($p \leq 0.01$), and kurtosis 0.877 ($p \leq 0.01$) (Yancev 2002).

The obtained (actual) skewness values for most of the investigated biometric parameters of stands (except for the mean height for the two species and the mean age for Scots pine) do not exceed the critical values. The predominance of negative values of skewness (except for the relative stocking of Scots pine stands) indicates right-handed asymmetry, testifying a predominance of actual values greater than the arithmetic mean. The excess of the critical value of kurtosis is actually recorded for all the biometric indices of Scots pine stands, whereas such facts have not been registered for black locust stands.

Results and Discussion

The regression coefficients for estimation of Scots pine and black locust crown biomass are presented in Table 2, graphical interpretation of the regression equations residuals – in figures 2 and 3.

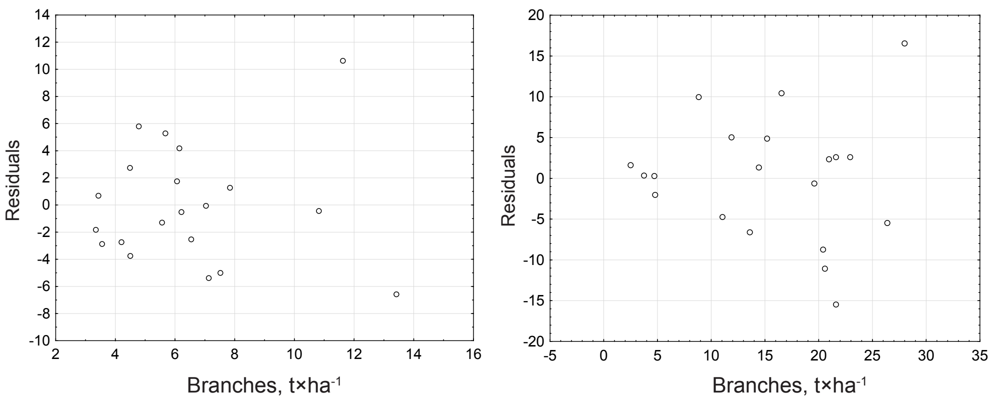
The calculated equations have statistically significant coefficients of determination. Their actual values do exceed the critical value (R^2 = 0.25), which justifies their application as the reference materials for assessing live biomass of structural components of tree crowns of Scots pine and black locust in forest stands of the Northern Steppe of Ukraine.

Determination of adequacy of the obtained models by the Fisher criterion has allowed us to establish statistically significant equations: for fractions of branches and needles of Scots pine – model (3) where the driving factors are mean height and diameter of the main species and relative stocking of a stand. For the two studied live biomass fractions (branches and leaves) of crowns of black locust stands,

Table 2. Crown biomass equations for investigated species.

Crown component	*a*	SE[*a*]	*b*	SE[*b*]	*c*	SE[*c*]	*d*	SE[*d*]	R^2	*F*-test	
										F_{real}	F_{table}
Pinus sylvestris L.											
$Y = a×D^b×H^c$ (1)											
Needle	0.596	1.020	-0.665	0.695	**1.244**	**0.263**	-	-	0.58	0.55	3.29
Branches	0.465	0.817	-0.273	0.672	**1.128**	**0.245**	-	-	0.59	0.91	3.29
$Y = a×A^b×D^c×H^d$ (2)											
Needle	1.043	1.443	-0.463	0.417	0.292	1.046	0.683	0.540	0.61	0.44	3.29
Branches	0.578	1.136	-0.087	0.452	-0.132	1.043	1.027	0.587	0.59	0.73	3.29
$Y = a×D^b×H^c×P^d$ (3)											
Needle	0.335	0.406	1.220	1.028	-0.233	1.029	**1.842**	**0.576**	0.53	2.38	3.24
Branches	0.477	0.555	1.785	0.968	-0.778	0.968	**1.503**	**0.515**	0.54	**6.66**	3.24
Robinia pseudoacacia L.											
$Y = a×D^b×H^c$(1)											
Foliage	1.585	1.073	**-1.800**	**0.823**	2.122	1.010	-	-	0.47	2.85	3.29
Branches	3.234	0.378	-1.341	1.016	**2.936**	**1.294**	-	-	0.69	**8.68**	3.29
$Y = a × A^b × D^c × H^d$ (2)											
Foliage	1.485	0.989	-0.470	0.305	-0.919	1.018	1.869	1.013	0.56	**5.33**	3.24
Branches	0.244	0.418	-0.088	0.378	-1.255	1.133	**2.951**	**1.339**	0.69	**5.55**	3.24
$Y = a×D^b×H^c×P^d$(3)											
Foliage	1.930	1.729	**-1.792**	**0.842**	2.052	1.031	0.072	0.225	0.49	1.79	3.24
Branches	0.465	0.818	-1.228	1.046	2.610	1.336	0.464	0.420	0.71	0.50	3.24

Note: differences at the significance level α = 0.05 are in bold; *a*–*d* – regression coefficients; SE – standard error; R^2 – correlation coefficient; *F*-test – Fisher's test.



a b

Fig. 2. Residuals of regression equation $Y = a×D^b×H^c$ for estimation of branch biomass: a – Scots pine, b – black locust.

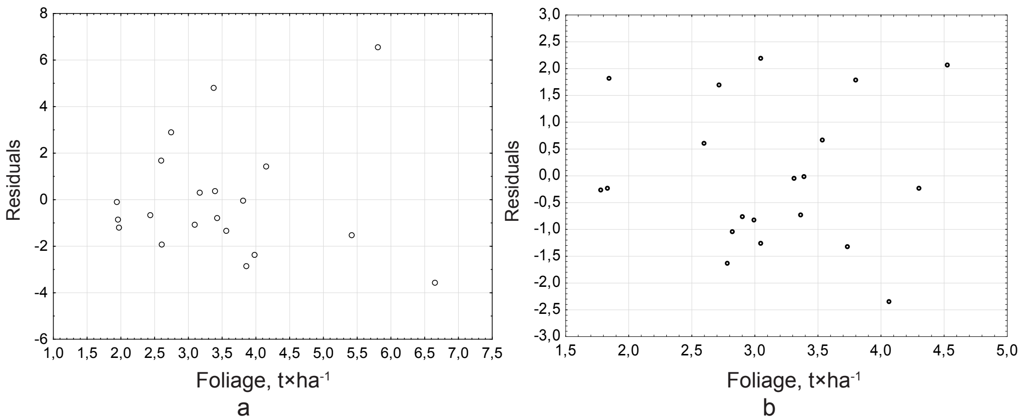


Fig. 3. Residuals of regression equation $Y = a{\cdot}D^b{\cdot}H^c$ for estimation of foliage biomass: a – Scots pine, b – black locust.

the equation (2) accounting for age, mean diameter, and height of a stand was assessed as the adequate one. In other models, the calculated value of Fisher's criterion did not exceed its critical value, which, given the number of degrees of freedom (n) = 20 and the number of driving factors (m) = 2, is equal to 3.29, m = 3–3.24.

The two-factor models developed for assessing live biomass of the studied crown components of both Scots pine and black locust are characterized by a negative coefficient for the mean diameter.

Three-factor models for assessing live biomass of Scots pine branches and needles had negative coefficients when inputting the parameters of age (2) and height (3) of a tree. It should be noted that a negative coefficient for the mean diameter is available to assess the parameter of the branch component parameter.

In the three-factor model (2) for assessing live biomass of Robinia branches and leaves, given the introduction of driving factors – age, mean diameter and mean height, the first two arguments have negative values of regression coefficients.

The basis of changes in the morphological structure of black locust stands' crowns is the course and rate of formation of shoots, live biomass production and increase in leaf area, the nature of their onset to maximum levels.

With the development of black locust stands, there is a change in the energy of trees' growth: the absolute levels of shoot formation and leaf area in trees to a certain age increase and decrease later on. The size of trees increases all the time, and the corresponding growth of shoots and leaves does not occur. This gap increases with age: the number of shoots and leaves per unit volume of a crown decrease, which causes a progressive increase in the finesse and transparency of a crown. Intensification of sod formation in stands of this tree species is associated with the increase in the finesse and transparency of tree crowns, which leads to a weakening of tree growth (Lokhmatov and Gladun 2004).

Figures 4 and 5 visualize the dependency of live biomass of crown components on the main biometric parameters – diameter, height, and age of a stand. Table 3 presents mathematical models of the mentioned dependencies in an analytical form.

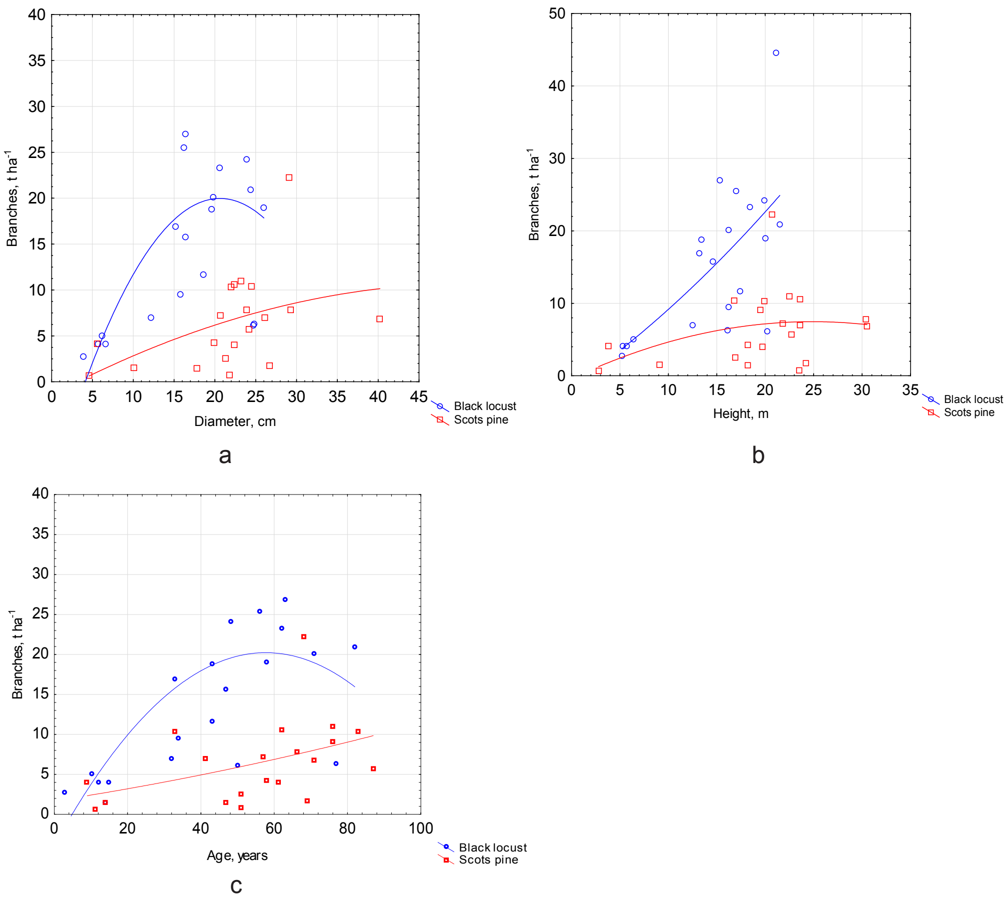


Fig. 4. Non-linear models for Scots pine and black locust describing relationships between branch biomass and mean stand diameter (a), height (b), and age (c).

The weight of the photosynthetic surface fraction is more variable than the stem or total aboveground biomass, as this component responds to age and changes in stand structure (Forrester et al. 2017). A more significant variance of the obtained values of crown live biomass components, as compared with trunk components, is also registered in our research. Within the European continent, a sufficient number of aggregated data on the assessment of crown live biomass for Scots pine stands have been reported to date (Solymos 1973, Albrektson 1980, Vyskot 1983, Bugaev et al. 1988, Santa Regina et al. 1997, Nord-Larsen and Nielsen 2015). A considerable number of equations for Scots pine 'stands' live biomass dependency on biometric parameters is presented in the scientific literature. However, many types of models are still insufficiently described (Forrester et al. 2017). To compare the results for pine stands in the natural zone of Ukraine's Northern Steppe obtained in this research, it was interesting to compare them with the data for the regions, which would have some similarity of natural and climatic conditions. When com-

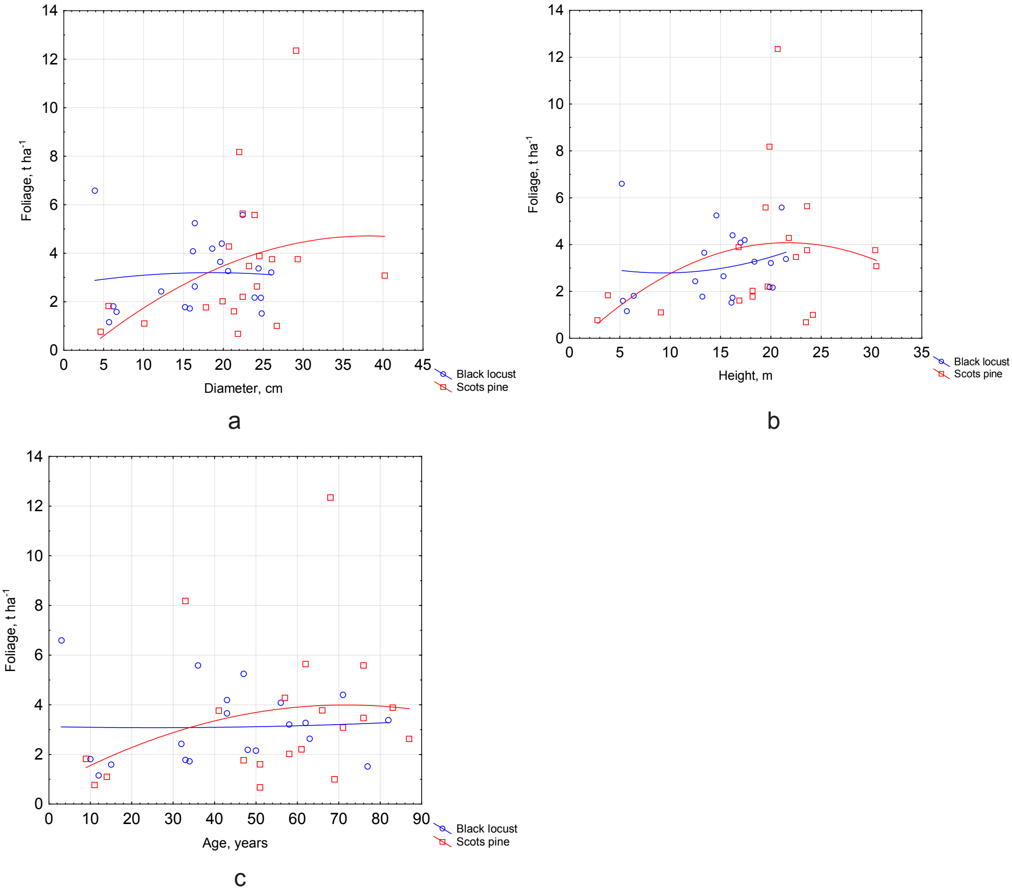


Fig. 5. Non-linear models for Scots pine and black locust describing relationships between foliage biomass and mean stand diameter (a), height (b) and age (c).

Table 3. One-variable regression models for estimation of biomass crown components.

Component of crown	Scots pine		Black locust	
	Equation	R^2	Equation	R^2
Branches	$Ph_{br} = 0.256 \cdot D^{0.964}$	0.49	$Ph_{br} = 0.758 \cdot D^{1.023}$	0.54
	$Ph_{br} = 0.616 \cdot H^{0.703}$	0.41	$Ph_{br} = 0.442 \cdot H^{1.272}$	0.60
	$Ph_{br} = 0.304 \cdot A^{0.702}$	0.45	$Ph_{br} = 1.074 \cdot A^{0.681}$	0.52
Foliage	$Ph_f = 0.741 \cdot D^{0.820}$	0.28	$Ph_f = 1.906 \cdot D^{0.142}$	0.28
	$Ph_f = 0.516 \cdot H^{0.608}$	0.22	$Ph_f = 1.331 \cdot H^{0.286}$	0.38
	$Ph_f = 0.878 \cdot A^{0.591}$	0.23	$Ph_f = 2.516 \cdot A^{0.030}$	0.26

Note: R^2 – determination coefficient.

paring our results with those reported by Dimitrov et al. (1987) for the conditions of Plovdiv (Bulgaria) for coniferous stands in the same age group (30 years), this research shows 35 % higher values for foliage, but one third lower for branches.

When compared with the results by other researchers, the data for 30-years old pine stands did not have a clear trend and showed both similarities (Vyskot 1983, Usoltsev 2010) and significant differences (Bugaev et al. 1988). 11-years old pine stands on sandy soils in Hungary (Solymos 1973), Kazakhstan (Usoltsev 1998), steppe part of Russia (Bugaev et al. 1988) were characterized by significantly higher amounts of crown live biomass (over six times) compared to the results obtained for Northern Steppe of Ukraine.

The aboveground live biomass of black locust stands is assessed to a much smaller extent as compared to Scots pine (Converse and Betters 1995, Burner et al. 2006, Unruh Snyderet al. 2007). Kostov et al. (1992) present the results for Bulgaria (Byala Slatina), noting the following live biomass amounts of crown components (*D* – 14 cm, *H* – 16 m): branches – 11.4 $t \cdot ha^{-1}$, leaves – 1.9 $t \cdot ha^{-1}$. In forests of Slovakia, black locust stands with *D* – 18 cm, *H* – 20 m were characterized by the following amounts of live biomass of crown components: branches – 22.7 $t \cdot ha^{-1}$, leaves – 2.55 $t \cdot ha^{-1}$ (Bencat 1989). Under edaphic and climatic conditions of the Northern Steppe of Ukraine, with a modal relative stocking of 0.9 and equivalent biometric parameters (*D* = 14 cm, *H* = 16 m) and (*D* = 18 cm, *H* = 20 m), the fraction of crown branches amounts to 21.2 $t \cdot ha^{-1}$ and 27.7 $t \cdot ha^{-1}$, leaves – 4.2 $t \cdot ha^{-1}$ and 4.4 $t \cdot ha^{-1}$, respectively. This means that for black locust stands in the study region, the amounts of live biomass of crowns' structural components are higher.

Conclusions

The research results on the characteristics of live biomass of structural components of crowns of tree stands can be used for monitoring the state of forests and assessing ecosystem services in the Northern Steppe of Ukraine, including by remote methods, as well as in the course of interpretation of the annual production; in the modelling of the transformation of the active photosynthetic radiation by forest canopy in the analyzed species.

In black locust stands in an even-aged stand under the condition of constant height, an increase in mean diameter leads to a decrease in live biomass of three crown components. At the same time, in Scots pine stands with the same average diameter and height, live biomass of branches and foliage will be larger at a younger age. In other cases, for three-variable models for Scots pine, where the stand's diameter, height, and relative stocking were selected as input parameters, live biomass of crown's components decreased when the stand's mean height decreased at a constant diameter and relative stocking.

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