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LAI estimation by direct and indirect methods in Scots pine stands in Northern Steppe of Ukraine

Viktoriia LOVYNSKA [1], Petro LAKYDA [2], Svitlana SYTNYK [1], Mykola KHARYTONOV [1], Iryna PIESTOVA [3]*

[1]Department of Parks and Gardens, Faculty of Agronomy, Dnipro State Agrarian and Economic University, Dnipro, Ukraine

[2]Education and Research Institute of Forestry and Park Gardening, National University of Life and Environmental Sciences of Ukraine, Kyiv, Ukraine

[3]Department of Geoinformation Technologies in Remote Sensing of the Earth, Scientific Centre for Aerospace Research of the Earth, Kyiv, Ukraine

**Corresponding author: glub@ukr.net*

Abstract

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Leaf area index (LAI) of Scots pine (*Pinus sylvestris* Linnaeus) in the Northern Steppe of Ukraine was estimated. LAI estimated directly (LAI d, destructive sampling) was compared with LAI determined by digital hemispherical photography (indirect method, LAI id) in Scots pine stands. The studies to determine LAI were performed in pine stands of the age ranging from 57 to 87 years. The high coefficient of determination between needle weight and crown diameter as dependent variables and stand age as an independent variable was found at the tree level. LAI values of the stands estimated by the direct method were higher than those obtained by the indirect method on average by 8.8%. The results obtained by both methods were used for LAI determination from allometric relationships with tree mensuration parameters and stand biometric characteristics. There was a more significant relationship between LAI id values and tree crown diameter, basal area of stands as independent variables.

Keywords: *Pinus sylvestris* L.; leaf area index; needle area; allometric equations; age structure

The productivity of woody plants is significantly affected by the level of their structural parts functioning, and numerous geophysical factors (Ding et al. 2016; Lu et al. 2018). Tree crown is an important component of tree biomass; it comprises branches and leaves (needles) and performs a number of functions. Branches are a continuation of the stem, they form a mechanical and conduction system for the green parts of the crown where physiological processes (such as photosynthesis, respiration and transpiration) based on a gas exchange between tree and atmosphere are taking place. Leaf surface area is critically important for terrestrial ecosystems because it is a zone of implementation of main physiological processes in plants (Utkin et al. 1997; Bondeau et al. 2008).

Leaf area index (LAI) is a measure of green tree mass in forest cover. Today, LAI is the most important determinant of biophysical properties of tree crown, and it describes the vegetative state in a wide range of physiological, climatological and biogeochemical studies (Jagodziński, Kałucka 2008; Fisher et al. 2018). Almost all processes occurring in forest ecosystems, especially the process of primary production, depend on the size and area of the assimilating part of tree crown (Li et al. 2017; Sytnyk et al. 2017). LAI depends on such factors as species specificity, stage of plant development, seasonality, habitat conditions and forest management practices (Falster, Westoby 2003; Fotis et al. 2018). Combination of these factors with differences in methods of parameter determination leads to significant LAI variation (Field et al. 1995; Bussotti, Pollastrini 2015). Therefore, LAI calculation, both by domestic and foreign scientists, still remains an important milestone in the development of a forestry regulatory framework (Jonckheere et al. 2005; Matushevych, Lakyda 2014; Stankevich et al. 2017). Published LAI values in forestry ranged from less than 1 (Le Dantec et al. 2000) to ~14 (Turner et al. 2000). Generally, the highest value reported in the international literature was typical of coniferous forest canopy (Chen et al. 1997). Studies on LAI of Scots pine forest stands in Europe were conducted by many researchers who used several methods for the calculation of this index. Variations in needle specific leaf area (SLA) and LAI in different countries of Europe have already been reported (Niinemets et al. 2001; Utkin et al. 2008). A summary of published values of canopy-averaged SLA for Scots pine across Europe (Finland, UK, Sweden, Germany, Netherlands, Belgium, Czech Republic, Italy, France, Spain) was presented by Mencuccini and Bonosi (2001); it ranged from 2.867 (Mäkela et al. 1995) to 5.506 (Mencuccini, Bonosi 2001). Variability of SLA in relation to position within the crown and to needle age and LAI estimation in different needle age classes have been reported for mature Scots pine forests by Bealde et al. (1982) in southeastern England, Xiao et al. (2006) in the Belgian Campine region. Needle area has been calculated in Scots pine using allometric relationships at the tree and stand levels in the Netherlands (van Hees, Bartelink 1993) and Belgium (Jonckheere et al. 2005). Analysis of Scots pine LAI in Russia was performed by Grabovsky et al. (2015). There are two main categories of LAI estimation procedures: direct and indirect techniques. In many papers for LAI estimation in Scots pine stands across Europe techniques of indirect measurement were used. Indirect measurements are performed using optical tools such as hemispherical photography, remote sensing etc. (Bréda 2003; Jonckheere et al. 2005; Huang, Pretzsch 2010; Chaturvedi et al. 2017). In the conditions of a field survey, indirect techniques of measurement in conifer forest based on optical sensors were effective, for example with optical instruments LAI-2000 Plant Canopy Analyzer (Stenberg et al. 1994; Majasalmi et al. 2013), Landsat ETM (Nilson et al. 1999; Eklundh et al. 2001), ceptometer (Chen et al. 1997), and also by the latest method of Bayesian inversion (Varvia et al. 2018). The procedure of LAI estimation by a direct method is quite difficult, time-consuming and impossible for the whole stand (Chaturvedi et al. 2017), but it is more precise compared with optical measurements (Bréda 2003; Khan et al. 2005). In the Steppe zone, both direct and indirect techniques can be actively used to measure LAI and give accurate results due to specific characteristics of forest architecture where plantations are of artificial origin dominantly and usually one-layered (as a result of one-species culture).

The main objective of the study was an investigation of LAI variation in Scots pine stands of the Northern Steppe of Ukraine, development and comparison of allometric equations obtained by direct and indirect techniques of LAI estimation.

MATERIAL AND METHODS

Study area. The experimental site was located in the northern part of Ukraine, in Dnipropetrovsk region (48°27'N and 34°58'E). Analysed stands of all temporary sample plots (TSPs) were selected in the same forest conditions and have a flat aspect, with elevation of 112 to 140 m a.s.l. Mean annual rainfall is 500 mm, mean temperature is 9.0°C. All measurements were carried out in 6 selected even-aged stands with high representation of Scots pine (*Pinus sylvestris* Linnaeus), located within Novomoskovskiy and Vasilkovskiy forest district in Dnipropetrovsk region (Ukraine). The areas selected as TSPs were surveyed, a biometric description was made for each one that includes average values of age, tree height and diameter within the plantation. When the area corresponded to the requirements, i.e. it was a representative unit of the plantation of the investigated species, it was selected for establishing TSP. The TSPs were chosen on the basis of stand age, and then the replicate sampling locations were randomly assigned within each Scots pine stand. In TSPs, the number of all trees was counted, its basal area ($m^2 \cdot ha^{-1}$), diameter and height of each tree were measured. Biometric description of the stands is represented in Table 1.

Bonitet class of each TSP was taken from Database of Production Association "Ukrderzhlisproekt" (http://www.lisproekt.gov.ua/) for State Enterprises of the State Agency of Forest Resources of Ukraine. Bonitet scale was developed by Orlov and contains 3 parameters – average height, stand age and origin of stands (Anuchin 1982). Bonitet scale includes of 5 bonitet classes, with ranking of classes from the most productive (I^{st}) to the class with the lowest productivity (V^{th}). The bonitet class of 5 investigated

Table 1. Characteristics of surveyed Scots pine stands

Stand No.	Stand area (ha)	Scots pine (%)	Age (yr)	DBH (cm)	Height (m)	No. of trees per hectare	Basal area ($m^2 \cdot ha^{-1}$)	Bonitet class
1	0.25	100	56–66	20.7	21.8	856	28.90	I
2	0.25	100	54–84	29.3	30.4	416	28.01	I
3	0.25	100	77–90	24.2	22.7	448	20.57	II
4	0.25	100	70–80	23.9	19.5	440	19.79	I
5	0.25	100	78–84	24.5	16.8	512	24.22	I
6	0.25	90	65–80	23.2	22.5	496	22.13	I

stands was ranked as class with the highest productivity (I) and only the third TSP had IInd bonitet class.

The stands were represented by three different age classes – one premature stand (age of 57 years) and mature stands over 60 (three plots) and 80 (two plots) years. The fieldwork was conducted between April and October 2016.

In each sample plot, stem DBH, tree height, and height of the crown base of each tree were measured.

Leaf area index estimation by direct method (LAI d). LAI d was assessed directly using harvesting methods such as destructive sampling. The sample tree method consists of destructive sampling of trees out of the stand and measurement of their leaf area. Six Scots pine trees (one per each sample plot) were selected as representative samples of the stand for harvesting. Selection of sample trees for LAI determination was conducted at different stem diameter within the same (middle-old) age group; it comes from dominance of the middle-old age group in Scots pine plantations (58.5%) under conditions of the Northern Steppe of Ukraine (Lakyda, Lovinska 2015). The age of chosen trees ranged from 56 to 90 years. For each selected sample tree, the following measurements were taken: age, overbark stem DBH, total tree height, crown diameter and crown length. Dendrometric data of the sample trees are summarized in Table 2.

According to selected methodology (Lakyda 2002), in field conditions 9 samples of fresh needles (each sample was represented by 10 individual needles or 5 fascicles) were randomly selected from different parts of the sample tree crown (upper, middle and lower – three samples in each part) followed by measuring and weighing. Total surface area of pine needles was developed using three variables: displaced volume of the needle sample, cumulative needle length of the sample and number of needles per fascicle (Johnson 1984). The volume values were estimated by xylometric determination using the values of water volume displaced by the needle fascicle sample after its immersion in a measuring cylinder (Eq. 1):

$$S_{\text{needles}} = 2 \times l\left(1 + \frac{\pi}{n}\right) \times \sqrt{\frac{v \times n}{\pi \times l}} \qquad (1)$$

where:

l – total length of needles (m),

n – total number of needles,

v – total volume of needles – calculated by the method of xylometric determination (m^3),

S_{needles} – surface area of 10 individual samples of needles – 5 fascicles (m^2).

Selected fresh pine needles were weighed in the field on an electronic balance to the nearest 0.001 g, and further dried in the laboratory in a drying chamber at a temperature of +105°C until constant mass.

Leaf mass per area (LMA) was calculated as a ratio of dry mass (m_0) and foliage area ($S_{a\text{ needles}}$), as Eq. 2:

$$\text{LMA}_{m_0} = \frac{m_0}{S_{a\text{ needles}}} \qquad (2)$$

where:

LMA_{m_0} – ratio of absolute dry mass of 10 sample needles (5 fascicles) to their total area ($kg \cdot m^{-2}$).

Table 2. Dendrometric data on Scots pine sample trees destructively sampled at the study plots

Tree No.	Age (yr)	Stem DBH (cm)	Total height (m)	Crown		Fresh mass (kg)	
				diameter (m)	length (m)	foliage (needles + twigs)	needles
1	56	22.0	22.5	3.3	6.9	15.5	4
2	68	24.0	21.6	4.5	8	24.3	7.3
3	90	26.3	22.3	1.8	6	18.1	4.48
4	77	22.1	18.6	3.3	5.7	27.3	9.29
5	84	24.1	17.3	2	11.2	19.2	5.45
6	71	38.9	30.0	4.3	8.4	43.5	9.73

Total needle surface area of sample tree ($S_{tree\ needles}$) within TSP was determined as a share from the total mass of needles of sample tree designated as absolute dry matter of tree needles in LMA.

Total mass of needles of sample tree in absolute dry matter was determined using the content of dry matter in needles. In the first step of calculation, tree greenery (foliage and twigs up to diameter of 1 cm) was weighed in the field conditions and mean foliage share – P_L (%) was determined. For this, the collected fresh samples were weighed while re-weighing followed after manual defoliation described earlier (Sytnyk et al. 2017). Foliage share was then calculated using Eq. 3 (Turner et al. 2000; Lakyda 2002):

$$P_L = 100 \times \frac{(m_f - m_{def})}{m_f} \qquad (3)$$

where:

m_f – fresh mass of a model tree greenery sample (g),

m_{def} – fresh mass of a model tree greenery sample in defoliated state (g).

Thus, the tree greenery fraction was separated into twigs and foliage, and the share of foliage in the greenery of each model tree was calculated. After determining the foliage share in model tree greenery, all the previously separated foliage was collected. From that amount, a series of 10-gram samples was selected and taken to the laboratory to provide their drying to constant weight at 105°C.

Content of dry matter in foliage (S_L) was calculated using Eq. 4 (Lakyda 2002):

$$S_L = \frac{m_0}{m_{nat}} \qquad (4)$$

where:

m_0 – mass of foliage fraction dried at 105°C (g),

m_{nat} – mass of foliage fraction in fresh state (g).

Total needle mass in absolute dry matter within TSP was calculated using the percentage of needles in total tree greenery. The content of absolute dry matter in foliage was calculated from the number of trees in each thickness class. The weight of greenery in average tree of each thickness class was determined by a graphical method. For this purpose, a chart was drawn based on the ratio of DBH to the weight of tree greenery of model trees cut down on the TSP. Then, data on the mass of greenery obtained from the chart on each thickness class within TSP were multiplied by the total number of trees of this thickness class. The weight of needles in freshly weighed condition was determined from the percentage of needles in the tree greenery on TSP calculated in each thickness class. Further, these values were transferred to a completely dry condition through the content of absolute dry matter in the needles.

Total needle surface area of Scots pine stands ($S_{stand\ needles}$) was determined by the ratio of total needle mass of all trees within TSP in absolute dry matter ($m_{stand\ needles}$) to LMA.

Leaf area index (LAI) was computed by Eq. 5:

$$\text{LAI} = \frac{S_{stand\ needles}}{G} \qquad (5)$$

where:

G – area of TSP (m^2),

$S_{stand\ needles}$ – total surface area of pine needles of trees in TSP (m^2).

To assess LAI per stand area, we developed the allometric equations using DBH, tree height, basal area of stands as independent variables and needle area and needle mass as dependent variables. The best fitted regressions were selected on the basis of the coefficient of determination (R^2). We developed different models and selected for investigated stands the one with the best goodness of fit by judging the resulting R^2.

Estimation of leaf area index by indirect method (LAI id). In sampling plots of Scots pine, contactless measurements of LAI were carried out that excluded direct interaction with trees.

LAI is estimated indirectly by measuring the spatial distribution and proportion of gaps in plant canopies (Zheng, Moskal 2009) from optical remote sensing instruments. These instruments determine LAI based on an assumption of the random spatial distribution of leaves. These methods use a theoretical model of canopy gap probability (Woodgate et al. 2015). So, LAI of plant canopies can be estimated by the real-time analysis of "gap size distribution" determined from hemispherical photographs.

Leaf area index is computed from the hemispherical photographs from gap fraction estimates in different zenith and azimuthal ranges. To obtain digital hemispherical photography of the canopy we used a digital camera. Photographing is carried out from below of the canopy and in a circle in several rows with longitudinal and transverse overlap. The resulting number of photographs is stitched into a hemispherical panorama (Fig. 1) in an open-access software product Hugin (Version 2017.0.0, 2017; http://hugin.sourceforge.net/). The camera was placed on a tripod 1.3 m above ground. Photographs were taken during semi-overcast conditions to minimise the glare from direct sunlight.

Obtained hemispherical photographs were analysed by the Gap Light Analyzer software (Version

Fig. 1. Final image of the hemispherical panorama

2.0, 1999) to compute gap fraction data and LAI (Frazer et al. 1999). First, to distinguish between visible sky and foliage, a threshold value was interactively selected for each photograph. To reduce variation, all photographs were analysed by the same experienced operator. In the second step, LAI id was calculated for each hemispherical photograph from the gap fraction data obtained by inversion of the Poisson model.

Mathematic models of LAI on different biometric parameters were statistically verified using the STATISTICA program (Version 12.6, 2015).

RESULTS

In the first step, we analysed needle dry weight using LAI d calculation, surface leaf area and LAI (Table 3) for pine stands within TSP. The average weight of absolutely dry pine needles on the TSP amounted to 828.69 kg; mean total leaf area of needles per TSP was 4,157.5 m^2.

Table 3. Leaf area and leaf area index of pine stands on temporary sample plots (TSPs)

Stand No.	Needle dry weight (kg)	Total leaf area per TSP (m^2)	LAI d (m^2·m^{-2})
1	1,070.0	3,850.0	1.54
2	940.0	5,325.0	2.13
3	657.5	2,800.0	1.12
4	1,395.0	3,625.0	1.45
5	972.5	3,275.0	1.31
6	867.5	3,425.0	1.37

LAI d – leaf area index estimated by a direct method

Table 4. Allometric equations for the determination of parameters for Scots pine trees depending on age

Regression equation	R^2
$y_1 = -0.017x^2 + 2.442x - 80.371$	0.842
$y_2 = -0.005x^2 + 0.690x - 19.008$	0.856

y_1 – needle weight, y_2 – crown diameter, R^2 – coefficient of determination; slopes always significant ($P < 0.05$), unless indicated

The establishment of allometric relationships with leaf area can be conducted in individual trees by taking readily measured variables, such as DBH, height of branches (Vertessy et al. 1995; Bréda 2003). Moreover, estimating allometric relationships through destructive sampling is a reliable method of deriving LAI for an experimental site (Maguire, Bennett 1996). According to the literature, for a sample of 6 units, the critical value of the coefficient of determination is 0.569 (Yantsev 2012). Regression equations were statistically significant ($P < 0.05$) at the level of the tree in cases of dependences of needle weight and crown diameter on age (Table 4).

A statistically close relationship was recorded between LAI values obtained by direct (LAI d) and indirect (LAI id) methods (Fig. 2, Table 5).

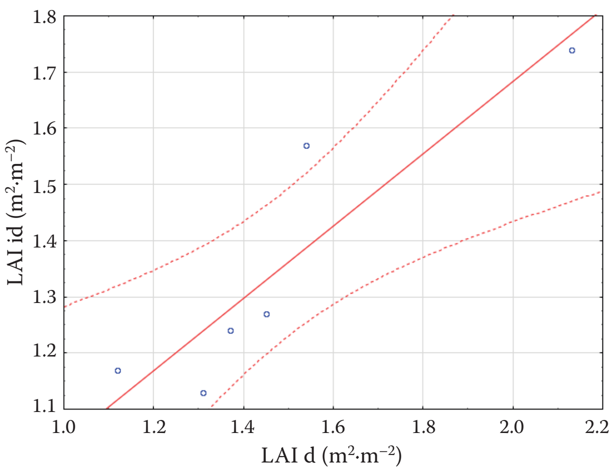

Fig. 2. Comparison of the relationship between leaf area index (LAI) values obtained by direct (LAI d) and indirect (LAI id) methods

Table 5. Main statistics of Scots pine stands leaf area index obtained by different methods

	Mean	SD	SE	Skewness	Kurtosis
LAI d (m^2·m^{-2})	1.48	0.346	0.141	1.525	3.095
LAI id (m^2·m^{-2})	1.35	0.245	0.099	0.994	–0.720

LAI d – leaf area index estimated by a direct method, LAI id – leaf area index estimated by an indirect method, SD – standard deviation, SE – standard error; slopes significant at the $P < 0.05$ level

Table 6. Allometric equations for leaf area index determination in Scots pine stands from different biometric values

x-Value	R^2	Equation	Parameter of function			
			A	*B*	*C*	*D*
LAI d						
Crown diameter	0.678	$y = a + bx$	0.492	0.343		
Basal area	0.476^{ns}	$y = ax^2 + bx + c$	0.248	–1.116	2.496	
	0.596	$y = ax^b$	0.092	0.845		
	0.613	$y = a\ln(x) + b$	1.212	–2.482		
	0.453^{ns}	$y = ae^{bx}$	0.778	0.216		
Age	0.499^{ns}	$y = ax^2 + bx + c$	–0.001	0.133	–2.634	
	0.341^{ns}	$y = a + bx$	2.725	–0.017		
	0.302^{ns}	$y = a\ln(x) + b$	–2.592	6.323		
Multiple regression: dc (x_1), lc (x_2)	0.677	$y = a + bx_1 + cx_2$	0.660	0.186	0.036	
LAI id						
Crown diameter	0.959	$y = a + bx$	0.532	0.283		
Basal area	0.802	$y = a + bx$	0.124	0.051		
	0.798	$y = ax^2 + bx + c$	0.012	–0.511	6.849	
	0.613	$y = a\ln(x) + b$	1.748	0.572		
	0.628	$y = ae^{bx}$	0.566	0.036		
Age	0.581	$y = a + bx$	2.498	0.015		
	0.582	$y = ax^2 + bx + c$	–6E-05	–0.007	2.188	
	0.604	$y = ae^{bx}$	3.073	-0.011		
Multiple regression: dc (x_1), *h* (x_2), stem DBH (x_3)	0.658	$y = a + bx_1 + cx_2 + dx_3$	0.874	0.116	0.037	–0.029

LAI d – leaf area index estimated by a direct method, dc – crown diameter, lc – crown length, LAI id – leaf area index estimated by an indirect method, *h* – total tree height, R^2 – coefficient of determination; slopes always significant ($P < 0.05$), unless indicated (ns – not significant)

LAI values in pine stands ranged from 1.12 to 2.13 $m^2 \cdot m^{-2}$ in the direct method and from 1.13 to 1.74 $m^2 \cdot m^{-2}$ in the indirect one. Both maximum LAI d and LAI id values were determined in pure 66-years-old Scots pine plantations with class I of forest capacity (refer to Table 1). Minimum LAI id value (1.12 $m^2 \cdot m^{-2}$) was determined in the oldest (87 years) pure forest stand of Scots pine, with low (II) class of performance. A similar minimum LAI value (1.13 $m^2 \cdot m^{-2}$) was obtained in 83-years-old pine plantations using the non-contact method of measurement. Mean LAI value of Scots pine stands measured by the direct method was estimated to 1.48 $m^2 \cdot m^{-2}$ and it was found higher than LAI id only by 8.8% ($r = 0.906$, $R^2 = 0.820$, $P < 0.05$).

Developed regression models are presented in Table 6 for LAI estimation by direct and indirect methods. These models are developed by combining several tree biometric parameters (age, crown diameter, crown length, stem DBH, total tree height) and such stand characteristics as basal area ($m^2 \cdot ha^{-1}$).

We obtained higher R^2 by estimation of LAI id, especially in the case of using linear regression models including crown diameter and basal area as independent variables. The models developed for estimation of LAI d had lower R^2 and higher significance both for linear and non-linear regression with using crown diameter and basal area as independent variables. During estimation of LAI irrespective of the effect of crown diameter, crown length, total height and stem DBH, we selected multiple regression models and obtained $R^2 = 0.677$ (LAI d) and $R^2 = 0.658$ (LAI id) (Table 6).

DISCUSSION

In recent years, theory prevails that forest productivity is mainly dependent on LAI, which determines the growth of woody plants in the conditions of forest ecosystems. LAI is a convenient parameter to measure; variability of its values is globally reflected in the form of theoretical mathematical models (Asner et al. 2003; Forrester et al. 2017).

Age of a tree is crucial for many of parameters of tree stands (Schleppi et al. 2011; Pokorný, Stojnič 2012), and LAI of older stands tends to slow descending (Battaglia et al. 1998; Sonohat et al. 2004). This coincides with early reached results on dependence of the studied parameter on age-class composition. LAI values obtained for mature plantings were lower (1.12 $m^2 \cdot m^{-2}$) than data of Soudani et al. (2002) with a value of 1.48 $m^2 \cdot m^{-2}$ for the 80–85-years-old stands, and significantly (1.54 $m^2 \cdot m^{-2}$ – LAI d, 1.57 $m^2 \cdot m^{-2}$ – LAI id) differ from the results given by the same authors (2.09 $m^2 \cdot m^{-2}$) for 45–50-years-old pine stands. Direct methods relate to foliage, give access to LAI and provide the reference for the evaluation of indirect methods (Bréda 2003). Indirect methods of estimating LAI in the field include the use of allometric relationships between leaf area and stand specific characteristics and show the dependence of LAI on age, stand density, tree crown size, climate (Gholz et al. 1990; Mencuccini, Grace 1995). In this study, leaf area index relationships obtained through both destructive sampling and non-destructive method are needed to compare LAI estimates by different methods. Comparison of LAI determination by methods of direct and indirect measurements was performed by many authors (Chason et al. 1991; Fassnacht et al. 1994; Dufrene, Bréda 1995; Olivas et al. 2013). Bréda (2003) reviewed direct and indirect methods and stated that indirect methods have pointed to a significant underestimation of LAI in forest stands. As reported by this author, underestimation in different literature varied from 25 to 50% in different stands (Gower, Norman 1991). In our study, we found no significant difference between the two methods used, and distinction between mean values was only 8.8%.

We compared with other researchers regression equations developed on needle weight and crown diameter (Mencuccini, Grace 1995; Jonckheere et al. 2005). We have found significant regression relationships between age as the independent variable and needle dry weight, crown diameter as dependent variables at a tree level.

We observed that the model containing crown diameter as the estimator is a better predictor of LAI of Scots pine stands. This is especially true of the indirect method of LAI estimation. Tree crown has a determining effect on canopy formation and as a result it regulates surface leaf area. LAI is also observed to be influenced by basal area of stands and developed regression equations with this value had significant R^2. We detected the linear and polynomial equations are the most appropriate for estimation of LAI obtained by indirect methods. In the case of LAI estimation by direct method the linear and logarithmic equations have the highest R^2. Also, when we tried several biometric characteristics combined together, we detected multiple regression models as good predictors ($R^2 > 0.67$) of LAI estimates.

In general, the relatively low LAI values obtained may be explained by limitations of climatic resources within the area studied, especially air and soil moisture, because environmental conditions control the time to reach maximum LAI values and its interannual summer variability (Gholz et al. 1990).

CONCLUSIONS

Average weight of absolutely dry pine needles per hectare amounted to 3,314.76 kg. The ratio gave the best fit and was significant in dependences of needle weight and crown diameter on age. Average LAI estimated in Scots pine stand was 1.45 $m^2 \cdot m^{-2}$ for direct method and 1.37 $m^2 \cdot m^{-2}$ for hemispherical photography. For both methods, the maximum LAI value was reached in the pine plantations at the age of 66 years, and minimum LAI was determined for the oldest trees. Higher R^2 values were registered during development of models for LAI id, when the application of linear and polynomial equations with the introduction of crown diameter of the tree and basal area of stands as independent parameters was used.

Thus, there is a need for further research and development of algorithms for quantitative LAI assessment in pine forests under steppe climatic conditions with the involvement of another indirect method, determination of this parameter depends on the main biometric indexes.

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