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A methodological approach for the assessment of basic crown parameters in Scots pine stands

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Abstract

Among other measurement techniques applied for the assessment of leaf area index, direct methods are still valued as the most accurate measures and often implemented as calibration tools. Even though more attention has been given to indirect measurements of tree crown properties in forest ecosystems over the last decades, the present study was designed to discuss the direct (destructive) and indirect (non-destructive) methods used for the assessment of crown measures in the stands defoliated from 20 to 90%. The stands with similar stand characteristics and representing relatively wide range of defoliation served as an appropriate target for the assessment of foliage mass variations.

Overall, this study showed that the foliage mass or its surface area and defoliation at the stand level can be determined by the conventional methods used for the assessment of defoliation in forest monitoring programme as well as the PAR transmission methods. The findings showed that needle surface area decreased with the increase of tree defoliation; however, the changes of branch and stem surface areas were insignificant. Otherwise, the branch and shoot area contribute significantly to the total vegetation surface area at least in Scots pine stands. This study also strengthened the idea that the indirect measurement of vegetation area index underestimated vegetation area index at least in Scots pine stands defoliated less than 60%. The multivariate regression models were developed using tree diameter at breast height and tree crown defoliation ranges to estimate needle surface area.

Keywords: *Pinus sylvestris*, crown defoliation, needle area index, regression model

Introduction

Tree crown is the main forest component to be monitored to assess tree health condition by several variables, including the crown defoliation, needle mass and leaf area index (LAI). In a long run, the crown defoliation could be related to environmental stress factors and could be used to assess the intensity of forest damage (De Vries et al. 2000, Michel and Seidling 2014). Commonly, crown defoliation is assessed as measure of forest health (Michel and Seidling 2014). Visually estimated crown defoliation is described as relative amount of foliage loss compared with the reference tree. Defoliation has been extensively assessed for several decades, and earlier estimates of defoliation relatively well correlated with the effects of environmental stress (Van Leeuwen et al. 2000, Dobbertin et al. 2010). Despite several factors causing foliage loss, insects were assumed as the most common reason of defoliation (Ciesla et al. 2008). It is noticeable that defoliation could affect growth through the reduction of the photosynthetic surface, however, more sunlight, penetrating through the foliage, could compensate for the loss of leaves/needles while increasing the photosynthetic efficiency of the remaining foliage.

Previous studies showed relatively strong correlation between the foliage mass and visually estimated parameters of crown condition (Horntvedt 1993, Ozolinčius and Stakėnas 1998). In some studies, visually estimated tree defoliation of slightly defoliated trees had relatively higher foliage mass (Horntvedt 1993).

Leaf area index (LAI), half of the total green leaf area per unit horizontal ground surface, is an important biophysical feature of tree crown for ecophysiological functions of the tree, such as photosynthesis, transpiration and growth (Cowling and Field 2003, Jonckheere et al. 2004, Ryu et al. 2010, Lopes et al. 2014). Overall, it reflects the tree condition in a changing environment.

Several references indicated direct and indirect methods of LAI estimation (Norman and Campbell 1989, Gower et al. 1999, Jonckheere et al. 2004, Weiss et al. 2004). The direct methods, based on the precise measurements of foliage area at the tree or stand level, usually are expensive and time-consuming, i.e., foliage harvests as the destructive measurement technique are often applied. The indirect methods, as faster and fully automated, are becoming more important in forestry. The most common method used for estimating LAI is based on measurements of the fraction of visible light transmitted through the canopy to the ground (Pierce and Running 1988, Gower and Norman 1991). As the indirect method, optical measurement techniques describe radiation transmission through forest canopies.

For leaf area index determination of stands various optical instruments (LAI-2000, SunScan) are used but their accuracy is still limited by the complexity of the canopy structure (Pokorny et al. 2004, Laubhann et al. 2010). The measurements of leaf area index using optical methods could be also used to compare the condition of differently damaged stands, and forest monitoring practice.

Among the basic crown parameters, the intensity of photosynthetically active radiation (PAR), which is needed for photosynthesis and plant growth, is determined by the amount and spatial distribution of the stand phytoelements. The PAR interception in the stand in some level reflects the amount of foliage mass or stand condition. Both, LAI and PAR are classified as biophysical variables because they have a direct impact on the radiative transfer of vegetated canopies. The remote sensing of LAI and PAR absorbed by plants could be effectively used to monitor the health and growth of forests globally (Rullan et al. 2013, Lausch et al. 2017).

The difference between these methods usually identifies the application scales, i.e. the direct methods allow obtaining the data for smaller spatial scales, while the indirect methods for larger spatial scales. The increased application of indirect methods, including remotely sensed data, for environmental monitoring and modelling underlines the need for ground truth data under the scientific level. As indicated by Lausch et al. (2017), for various important forest health indicators, including defoliation, there are still no standardized metrics nor direct measure procedures available.

The indirect methods, such as aided with optical instruments, do not separate foliage from woody structures (stems and branches) and give the output of optical measurements which corresponds to the Plant Area Index (PAI). Although most branches (80–90%) are masked by leaves and needles in the boreal coniferous forest, the stem remains visible (comprising 30–50% of the total woody area), and thus the contribution of the woody area cannot be ignored (Kucharik et al. 1998). Some researchers have argued that in addition to shoot-level clumping, a second correction for clumping at scales larger than a shoot (i.e., crowns, whorls, branches; hereinafter referred to as crown-level clumping) should also be applied (Chen and Cihlar 1995, Leblanc et al. 2002). In more open canopies, the vertical and horizontal distribution of leaves becomes important because certain configurations alter the normal exponential decrease in the net radiation and wind speed from the top of a canopy downward (Shuttleworth 1989).

The objectives of this study were the following: (1) to determine the conventional crown measures of differently defoliated Scots pine trees, (2) to compare the vegetation area index obtained by non-destructive and destructive methods, and (3) to find out the best fit models of the needle surface area in respect to crown defoliation and tree diameter (DBH).

Materials and methods

Study area and selected stands

The study was performed in southern Lithuania, approximately at a site with coordinates 54°04′55″ N, 24°22′36″ E. For this study, 40-years old Scots pine (*Pinus sylvestris* L.) stands of different damage extent (defoliation ranged from 20 to 90%) were selected. The stands represented forest type of *Pinetum vacciniosum*, and the forest site type Nb, i.e., oligotrophic mineral soil of a normal moisture regime, according to the Lithuanian classification (Vaičys et al. 2006). The mean annual air temperature was 6.5°C and the mean annual precipitation was 686 mm. The soils were determined to be well-drained Haplic Arenosols. The ground vegetation was typically composed of the mosses and lichens. To avoid seasonal impact, all field measurements were performed during the intensive vegetative season, during summer period (July–August).

The crown defoliation, as needle loss in the assessable crown when compared to a reference tree, was assessed. The 5%-defoliation steps were used for the visual assessment of the crown defoliation. In this study, the sample

Table 1. Main characteristics of the study plots in Scots pine stands

Study plot	Tree number	DBH,* cm	Crown diameter, m	Basal area, m^2 ha^{-1}
Control 1	77	13.5	1.9	30.0
Control 2	103	11.2	2.1	27.3
Control 3	79	12.8	1.9	27.3
Mean	*86 ± 8*	*12.5 ± 0.7*	*2.0 ± 0.1*	*28.2 ± 0.9*
Moderately damaged 1	91	13.0	1.6	32.3
Moderately damaged 2	77	14.4	1.7	33.7
Moderately damaged 3	87	13.0	1.6	31.2
Mean	*85 ± 4*	*13.5 ± 0.5*	*1.6 ± 0.0*	*32.4 ± 0.7*
Strongly damaged 1	71	13.6	1.9	28.0
Strongly damaged 2	99	10.8	1.6	26.5
Strongly damaged 3	82	12.2	1.8	26.5
Mean	*84 ± 8*	*12.2 ± 0.8*	*1.8 ± 0.1*	*27.0 ± 0.5*

* DBH stands for the tree diameter at breast height (1.3 m above the ground).

plots were selected to represent three groups of stands with different defoliation: the trees with 0–25% defoliation were referred as the control (with insignificant loss of needles); the trees with 30–50% defoliation, i.e., moderately damaged trees, and the trees with the defoliation higher than 60% were referred as strongly damaged trees. In each group, three 20×20 m plots were taken as replicates. Main characteristics of the sampled Scots pine stands are given in Table 1. The main stand characteristics within each group differed insignificantly.

The diameter at breast height (DBH), tree height, mean crown width (as two measurements of crown projection taken perpendicular to each other), and the defoliation of all trees (the crown and one-third top-crown) were measured in each plot.

The leaf area index (LAI) was evaluated directly by the model tree (model branch) method and indirectly by using the photosynthetically active radiation (PAR) dependencies on LAI. The PAR interception in the stand was used as an indicator of crown condition.

Non-destructive method application

The field measurements of PAR were performed in 30 points systematically selected on 4×3 m grid in each plot using the Sunfleck PAR Ceptometer. The device included 80 independent sensors, which measured PAR in the 400 to 700 nanometer waveband (Decagon 1992). Each measurement was replicated by 3 times. The control measurements were performed in the open field at the distance of 50 meters from the forest stand.

The LAI, one-sided area of leaf tissue per unit ground surface area (m^2 m^{-2}), was calculated according to the formula (Norman and Jarvis 1974):

$$L = \frac{\left[\left(1-\frac{1}{2K}\right)f_b - 1\right]\ln\tau}{A(1-0.47f_b)} , \tag{1}$$

where: L is the leaf area index; K is the extinction coefficient for the canopy; f_b is the fraction of incident PAR which is beam (fractional beam radiation); A is the canopy absorption coefficient; τ is the ratio of PAR measured below the canopy to PAR above the canopy.

The extinction coefficient was calculated according to the simplified formula (Campbell 1986):

$$K = \frac{1}{2\cos\Theta} , \tag{2}$$

where Θ is the zenith angle of the sun.

Destructive method application: sample tree selection and leaf area determination

The model trees for the analyses of needle mass and LAI were selected in four diameter classes (7–9 cm, 11–13 cm, 17–19 cm and 21–23 cm) and in five classes of crown defoliation (5–15% – undamaged trees, 25–35% – slightly damaged, 45–55% – moderately damaged, 65–75% – strongly damaged and 85–95% – severely damaged trees). Totally 20 model trees were measured. For the selected model trees, the mean tree DBH, tree height, crown width and crown defoliation were measured.

Total surface areas of the shoots, branches and stems were measured to estimate the vegetation surface area, which was used for the comparison of the values obtained by indirect (PAR intercept) and direct (measurements of the model trees) methods. For the analysis of foliage mass and branch area index (BAI), one model branch per each whorl was taken from all the model trees. The shoots with needles were separated from the model branches, the needles were sorted according to the age, as the current-year, 1st- and 2nd-year needles.

For each sample, mass, and length of randomly selected 50 needles, number and mass of shoots were measured. For the determination of surface area of model tree needles (LAI) the simplified method modified from Tselniker et al. (1981) was used. First, the needle mass of 1 cm needle length was estimated for each needle sample, and then the plot area (in dm^2) of 1 gram of needle was calculated from the conversion tables. The total surface area of the needles was calculated from the total needle mass per each year.

The surface area of branches and shoots was estimated by measuring their sum length in each whorl in every thickness class (thickness classes were divided in every 2 mm). The mass of shoots in individual thickness classes correlated well with their area (Table 2).

The branch area index (BAI, m^2 m^{-2}) of the model tree was calculated when the total area of the model shoots and branches was multiplied by the number of branches.

Stem area index (SAI, m^2 m^{-2}) was measured as one-sided stem area per ground area, where stem did not include branches and needles.

The sum of LAI, BAI and SAI is vegetation area index (VAI, m^2 m^{-2}), the one-sided plant area per ground area.

A total needle mass in all sample plots was calculated according to the given relationships among the crown defoliation, tree DBH and needle mass of the model trees:

$$M = a + b \cdot D^c \cdot (100 - Df) , \tag{3}$$

where: M is the needle mass; D is the tree DBH; Df is the crown defoliation; a, b, c are coefficients (determination coefficient of the model was $R^2 = 0.90$, $p < 0.05$).

Table 2. The linear equations representing dependence between shoot surface area (y) and shoot mass (x) in Scots pine trees for the different classes of shoot thickness ranges

Class of shoot thickness, mm	R^2	Linear equation (y is the shoot surface area, dm^2; x is the shoot mass, g)
2–4	0.93	$y = 234.64x + 127.27$
4–6	0.97	$y = 135.64x - 0.0795$
6–8	0.98	$y = 116.47x - 52.976$
8–10	0.98	$y = 71.644x - 78.3$

Statistical analyses

Multiple linear and non-linear regression models were used for the search of needle surface area (m^2) fitting in respect to independent variables tree crown defoliation (%) and tree DBH (cm).

Multivariate linear regression model (4) was developed to reveal dependence of needle surface area on two variables – tree crown defoliation and DBH.

$$y = a + b_1 x_1 + b_2 x_2 + \varepsilon \quad , \tag{4}$$

where: y is the needle surface area; x_1 is the tree DBH; x_2 is the defoliation; a is the constant; b_1, b_2 are regression coefficients to be fitted, ε is the error term.

To check if model fits the requirements of standard linear regression, we run normality test for model residuals. If the normality hypothesis is rejected, we fit a non-linear regression model (5) and check again for requirements.

$$y = a + b_1 x_1 + b_2 x_2 + c_1 x_1^2 + c_2 x_2^2 + d x_1 x_2 + \varepsilon \quad , \tag{5}$$

where: y is the needle surface area; x_1 is the tree DBH; x_2 is the defoliation; a is the constant; b_1, b_2 are linear regression coefficients; c_1, c_2 are quadratic regression coefficients; d is the mixed effect regression coefficient, ε is the error term.

All analyses were performed using STATISTICA 12 software package (StatSoft 2013).

Results

Conventional crown measures

The average crown defoliation between three groups of plots, representing different defoliation intensity, differed significantly (Table 3). Significantly higher mean crown defoliation was found in the strongly damaged stands in comparison to both the moderately damaged stands and the control stands. The strongly damaged stands had the highest mean defoliation, which ranged between 84% and 92%. Compared with strongly defoliated trees, by 1.5 times lower defoliation or the defoliation of 56–59% was obtained in the moderately damaged stands. In the control stands, the mean defoliation was 22–26% or by 3.7 times lower than mean defoliation in strongly damaged stands.

Table 3. Mean crown defoliation (%) in three groups (strongly damaged, moderately damaged stands and the control) of sample plots in Scots pine stand of Kraft class 1–3

Plot	Crown defoliation, %	Defoliation of one third of the upper part of the crown, %
Control 1	23.1 ± 1.0	20.3 ± 1.0
Control 2	22.3 ± 0.9	20.8 ± 0.8
Control 3	26.0 ± 1.3	24.1 ± 1.2
Mean	*23.8 ± 1.1*	*21.7 ± 1.2*
Moderately damaged 1	59.4 ± 2.2	54.1 ± 2.2
Moderately damaged 2	57.0 ± 2.1	50.3 ± 2.1
Moderately damaged 3	56.1 ± 2.4	53.8 ± 2.6
Mean	*57.5 ± 1.0*	*52.7 ± 1.2*
Strongly damaged 1	92.2 ± 0.8	88.8 ± 1.1
Strongly damaged 2	84.3 ± 1.1	80.6 ± 1.5
Strongly damaged 3	87.8 ± 0.7	84.9 ± 0.9
Mean	*88.1 ± 2.3*	*84.8 ± 2.4*

The needle mass varied in a range from 6.8 to 93.3 g depending on the tree diameter (DBH) and defoliation of the model tree. The first-year needle mass comprised 34.3%, and the second-year needle mass was 51.9% from the total needle mass. No significant changes in needle mass within each needle age group between different defoliation intensities and DBH of model trees were found. The exception was found only for the third-year needle mass, which significantly decreased with increasing crown defoliation.

When analysed the needle mass dependence on defoliation individually for each tree thickness class (the diameter of 8–9, 12–13, 17–18 and 22–23 cm), strong dependence (R^2 = 0.75–0.93, p = 0.01–0.04) were found for all tree thickness classes, except that of DBH = 8–9 cm (R^2 = 0.61). The weaker correlation for the thinner trees was possibly caused by the defoliation assessment errors.

The dependence between the model tree needle mass and tree DBH for the trees with similar defoliation showed also statistically significant result (Table 4).

The surface area of model tree needles depended on tree DBH and crown defoliation and varied within the

Table 4. The linear equations representing dependence between needle mass (y) and tree diameter at breast height, i.e., DBH (x) in Scots pine trees of different defoliation ranges

Defoliation, %	R^2	Linear equation (y is the needle mass, kg; x is the DBH, cm)
10	0.99	$y = 420.36x – 2831.5$
30–50	0.83	$y = 107.8x – 541.03$
60–70	0.64	$y = 87.75x – 690.18$
85–90	0.85	$y = 34.06x – 152.02$

Table 5. The linear equations representing dependence between needle mass (y) and tree diameter at breast height, i.e., DBH (x) in Scots pine trees of different defoliation ranges

DBH, cm	R^2	Linear equation (y is the needle surface area, dm^2; x is the crown defoliation, %)
8–9	0.72	$y = –10.133x + 1021.5$
12–13	0.58	$y = –25.253x – 2542.2$
17–18	0.82	$y = –53.298x + 5282.9$
22–23	0.96	$y = –55.698x + 5572.9$

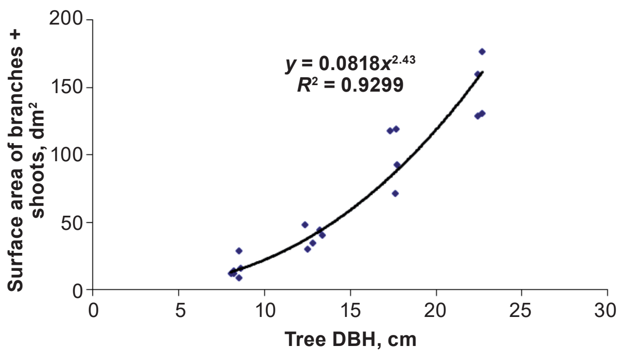

Figure 1. Dependence between branch and shoot surface area (dm^2) and tree diameter at breast height (DBH, cm)

range of 5.5–113.4 dm^2. The relatively strong dependence between surface area of model tree needles and crown defoliation in different tree thickness classes were obtained (Table 5).

Our data showed that the surface area of branches and shoots of the model trees ranged from 9.1 to 176.8 dm^2 depending on tree DBH (Figure 1). The surface area of branches and shoots significantly increased with the increase of tree DBH (R^2 = 0.93).

Vegetation area indices

In average, 14.5 ± 0.5% of the total photosynthetically active radiation (PAR) penetrates through the crown in the control plots (open area of clear-cut) (Table 6). In the moderately damaged stands the penetration of PAR through the crown is more by a factor of 1.6, and in strongly damaged stands is 2.4 times more compared with the control plots. The highest mean vegetation area index (VAI), measured by the indirect method, was found in the control plots, and then it has decreased with the increase of stand damage (defoliation).

The needle mass in moderately damaged stands comprised about 41.0% of needle mass in the control stands, while in strongly damaged stands it comprised only 14.8% of needle mass in the control stands (Table 6). The strongly damaged stands lost about 85% or 2.75 t ha^{-1} of needles from the control level. The needle surface area (LAI) in differently damaged stands decreased with the increase of tree damage. However, the changes of branch and stem surface areas were insignificant.

The vegetation index (VAI) for the control and moderately damaged stands was by 1.5–1.8 times higher when estimated directly from the model trees compared to the indirect measurements (Table 6). However, the VAI for strongly damaged stands (the crown defoliation higher than 80%) did not differ between the applied methods.

The dependence of PAR rate, T, on VAI was shown as exponential trend with R^2 = 0.987 (Figure 2).

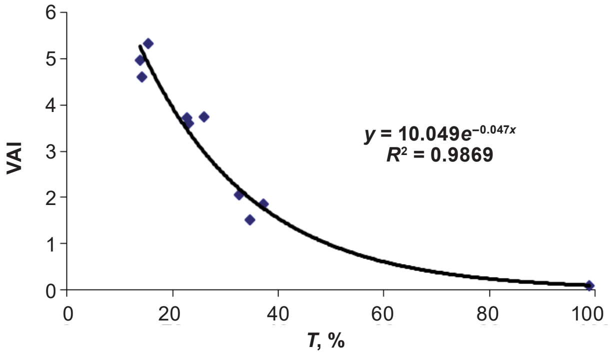

Figure 2. Dependence between photosynthetically active radiation (PAR) rate, T (%), and vegetation area index (VAI)

Strong linear dependence between PAR rate T and the mean defoliation of 1–3 Kraft class trees per stand (R^2 = 0.975) was obtained (Figure 3 A). Strong relationships between the mean defoliation of the stand and both crown parameters – needle mass (R^2 = 0.977) and needle surface area (LAI) (R^2 = 0.973) – were found (Figure 3 B, C).

Despite relatively good dependency between VAI determined by the PAR transmission and model tree methods (R^2 = 0.912), VAI determined by the PAR method was by 0–45% lower than that obtained by the model tree method (Figure 4).

Regression models

Dependence of needle surface area on two variables – tree defoliation and tree diameter (DBH) – is given in Figure 5 and Figure 6. Using the multiple linear (4) and non-linear (5) regression models for the needle surface area (m^2) fitting in respect to tree crown defoliation (%) and tree diameter (cm) allowed finding an appropriate model form. The following linear regression model (see Figure 5) was obtained:

$$y = 8.9762 + 1.8346x_1 - 0.4274x_2 \ , \qquad (6)$$

where: y is the needle surface area; x_1 is the tree diameter (DBH); x_2 is the crown defoliation.

Table 6. Main characteristics of crown (defoliation, needle mass) and surface area of needles, branches, and shoots in the study plots

Plot	Defoliation, %	Needle mass, kg ha^{-1}	T, %	VAI according to PAR (indirect method)	Characteristics according to model trees (direct method), m^2 m^{-2}			
					LAI	BAI	SAI	VAI
Control 1	23.1 ± 1.0	3585	13.8	3.11	4.45	0.33	0.18	4.96
Control 2	22.3 ± 0.9	3148	15.4	2.95	4.87	0.30	0.16	5.32
Control 3	26.0 ± 1.3	2955	14.2	3.11	4.16	0.29	0.16	4.60
Moderately damaged 1	59.4 ± 2.2	1090	23.0	2.53	3.03	0.35	0.22	3.60
Moderately damaged 2	57.0 ± 2.1	1332	22.7	2.36	3.13	0.39	0.21	3.73
Moderately damaged 3	56.1 ± 2.4	1548	26.0	2.16	3.22	0.34	0.19	3.75
Strongly damaged 1	92.2 ± 0.8	425	34.7	1.74	1.06	0.30	0.15	1.51
Strongly damaged 2	84.3 ± 1.1	495	32.6	2.08	1.64	0.28	0.15	2.07
Strongly damaged 3	87.8 ± 0.7	510	37.2	1.76	1.39	0.29	0.17	1.86

Note: T stands for the PAR penetration coefficient, BAI (branches area index) stands for the projected area of branches and shoots, SAI (stem area index) stands for the projected area of stems, LAI (leaf/needles area index) stands for the projected area of needles, VAI (vegetation area index) stands for the projected area of all foliage compartments: needles + shoots/branches + stems.

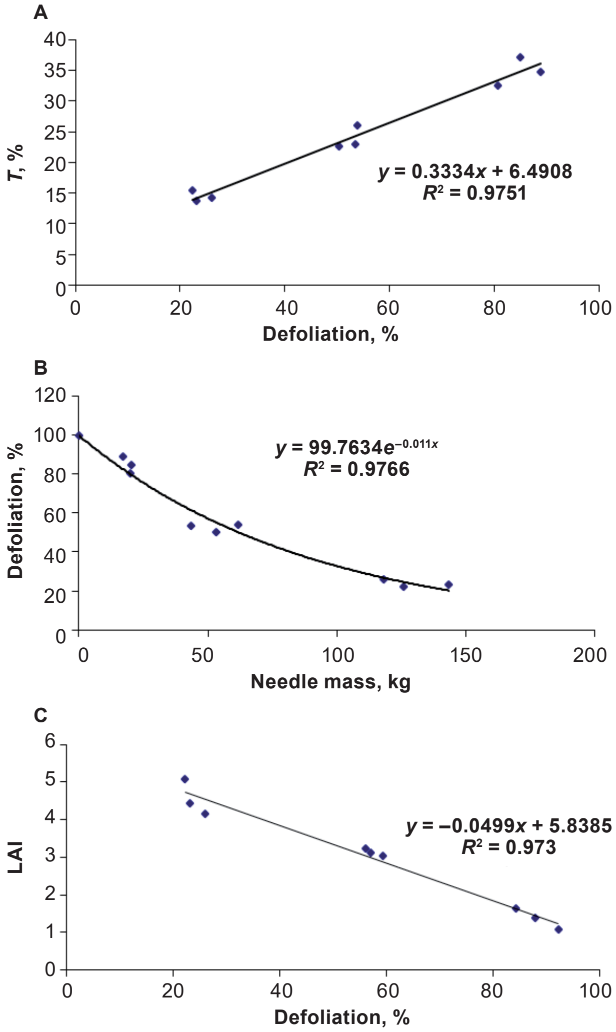

Figure 3. Dependence between: (**A**) photosynthetically active radiation (PAR) rate, T (%), and mean defoliation (%) in the stands of 1–3 Kraft class trees; (**B**) needle mass (kg) and mean defoliation (%) at the stand level; and (**C**) mean defoliation (%) and needle surface area (LAI) at the stand level

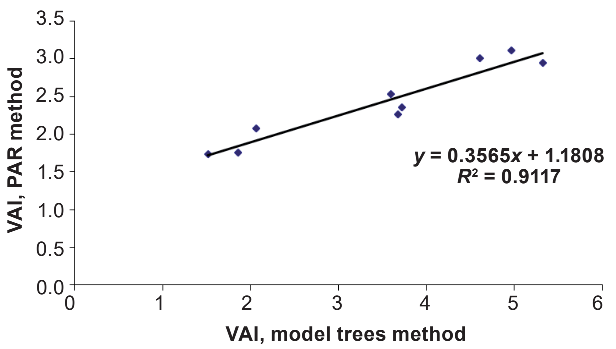

Figure 4. Dependence between vegetation area index (VAI) determined from the indirect (PAR transmission) and direct (model tree) methods

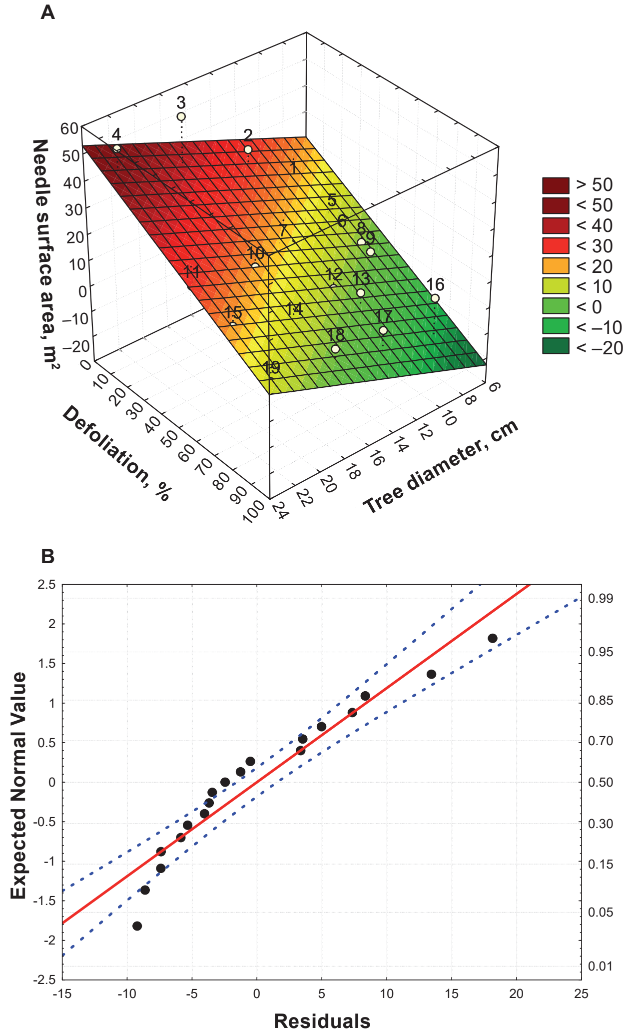

Figure 5. Linear regression fit: **A** – 3D surface plot representing relation between needle surface area (m²), tree diameter at breast height (cm) and tree crown defoliation (%); **B** – QQ plot of linear regression residuals

It turned out that residuals were not normally distributed, and the determination coefficient was $R^2 = 0.78$.

Then, the following non-linear regression model (see Figure 6) was obtained:

$$y = -10.676 + 4.37622x_1 - 0.48266x_2 - 0.03411x_1^2 + \\ + 0.005872x_2^2 - 0.03407x_1x_2 \ , \qquad (7)$$

where: y is the needle surface area; x_1 is the tree diameter (DBH); x_2 is the crown defoliation.

In this case, we found normally distributed residuals and $R^2 = 0.95$.

It was found that the non-linear regression model (7) better fits data and fulfils regression model requirements (see Figures 5B and 6B). This finding shows that the non-linear regression model is more practically applicable for needle surface area modelling.

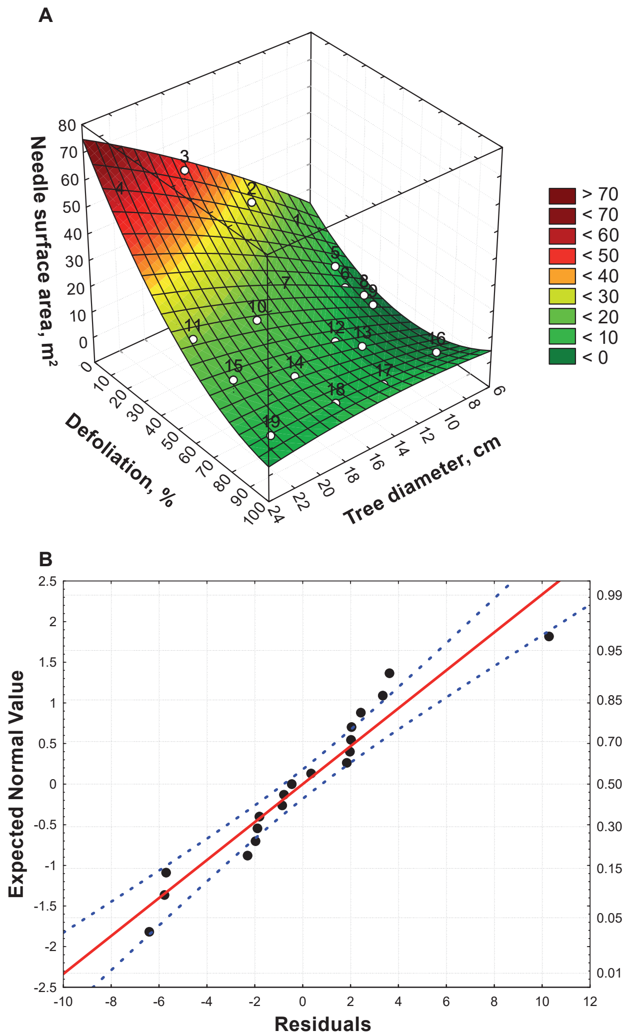

Figure 6. Non-linear regression fit: **A** – 3D surface plot representing relation between needle surface area (m²), tree diameter at breast height (cm) and tree crown defoliation (%); **B** – QQ plot of linear regression residuals

Discussion and conclusions

Crown parameters at stand level

The present study was designed to discuss the direct (destructive) and indirect (non-destructive) methods used for the assessment of crown measures in Scots pine stands. The stands with equal conventional stand characteristics and representing relatively wide range of defoliation served as an appropriate item for the assessment of foliage mass variations. Earlier findings showed strong correlation between Scots pine trees defoliation and their needle mass (Ozolinčius and Stakėnas 1996). Such dependencies were not investigated for a stand level, except few studies that were carried out to identify the correlations between the leaf area index (LAI, m² of projected leaf area per m² of ground area) assessed by the model branch method and with the aid of optical device LAI-2000 in differently defoliated Scots pine stands in the course of the Finnish Forest Monitoring Programme (Smolander et al. 2000). Previous studies have explored that correlation coefficient between LAI measured using the method of model branches and LAI measured using optical device LAI-2000 in Scots pine stands were 0.72 and in Norway spruce (*Picea abies* (L) H. Karst.) stands it was 0.60 (Smolander et al. 2000). However, these findings were obtained from the trees with relatively narrow range of defoliation of 5–28%. The studies performed in Norway spruce stands showed the defoliation closely related to LAI and indicated the suitability of these indicators for the evaluation of stand condition (Zawila-Niedzwiecki 1996).

Overall, the defoliation parameter for estimating the condition of the entire stand is relatively complicated. The reliability of the estimated defoliation for pre-dominant and dominant trees is usually higher than that of co-dominant and suppressed trees. Therefore, European forest monitoring programme recommend excluding the trees of Kraft class 4 from the assessment (Eichhorn et al. 2010). In this study, we evaluated mean crown defoliation in the sample plots of Scots pine stands representing the trees of Kraft classes 1–3. Based on the findings obtained in this study, the mean defoliation of the stand reflected tree crown parameters well, i.e., needle mass and needle surface area. The dependence between surface area of model tree needles and crown defoliation in the stands, representing different diameter classes, was relatively strong.

Relations between vegetation area index obtained by non-destructive and destructive methods

The vegetation area index (VAI) for all foliage compartments (needles, shoots, branches, and stems), which affect the transformation of the solar radiation in the stand, can be estimated using the method of photosynthetically active radiation (PAR) transmission (Oker-Blom and Smolander 1988, Smolander et al. 1998). Therefore, the data presented earlier allowed assessing the stand condition by the PAR transmission method. It is now well established that the area of shoots, branches and stems influence the PAR transformation within the stand. The current study found exponential dependence between PAR and VAI, and this finding was comparable with the results of earlier studies (Utkin et al. 1988). Our study performed in Scots pine stands confirmed the previously found dependency in Norway spruce stands and deciduous stands. It was already clear that the surface area of the branches and stems mainly depended on stand characteristics and this did not change due to increase of tree defoliation. The obtained dependencies showed that the foliage mass or its surface area, also the defoliation or its changes at the stand level can be determined by both the conventional methods, used for the assessment of defoliation in forest monitoring programme, and the PAR transmission methods.

Among other important findings it was that the needle surface area decreased with the increase of tree defoliation; however, the changes of branch and stem surface areas were insignificant. The surface area of branches and shoots significantly increased only with the increase of tree diameter. The earlier studies performed in Scots pine stands showed that the branch surface area should be included into the calculations as it comprises about 10–20% of total vegetation surface area (Kucharik et al. 1998, Smolander et al. 2000). Generally, over 80–90% of the branch and shoot area is covered by foliage mass, still it is even more important in the defoliated stands where the foliage is significantly reduced. Therefore, we assume that the branch and shoot area should be preferably included into the calculations of total vegetation surface area at least in Scots pine stands. The results of this study indicated that the VAI values determined from the PAR transmission method were by 55–70% higher than those obtained by the model tree method in the moderately damaged and the control (healthy) Scots pine stands. No significant differences between the VAI values determined by the direct and indirect methods were obtained in the strongly damaged stands. Based on the results, the VAI values obtained using the PAR transmission method can be well applied to severely damaged stands. Alternatively, the PAR transmission method could be used when it is necessary to compare the VAI values at the stands of different condition, except the cases when the accurate values are required.

Dependence of needle surface area on tree defoliation and tree diameter

Overall, the models for estimating leaf area need to reflect accurate crown allometry. In this study, the fitted multivariate non-linear regression model developed for needle surface area modelling, using the variables as tree crown defoliation and tree DBH, explained 95% of the variation in the studied plots. Needle surface area of Scots pine can be reliably estimated with a model including tree crown defoliation and tree DBH, which gives an opportunity to estimate this parameter in the stands under different environmental stress. The previously developed models included different variables. For example, the model of Laubhann et al. (2010) used a three-dimensional measure of the crown (crown surface area) and a stand variable (height) in addition to tree DBH. The model of Rubatscher et al. (2006) predicted the dry needle mass of European larch using DBH and crown ratio. Goude et al. (2019) estimated specific leaf area, LAI at tree level and at stand level in eight experimental plots of Norway spruce and Scots pine, together with tree and stand measurements. The authors constructed models using tree DBH, height and stand basal area to estimate leaf area at tree level. Also, the conversion models were constructed for estimating LAI from the indirect measurement of LAI together with basal area, stem number and stand height. Leaf area index of Norway spruce stands, estimated indirectly using LAI-2000 PCA in relation to age and defoliation, was analysed by Pokorny and Stojnič (2012). The authors found strong linear relationship ($R^2 = 0.87$) between defoliation and LAI and indicated LAI as valuable parameter for health status of Norway spruce stand evaluation. Strong relationships between the mean defoliation of the stand and needle mass and LAI in this study corroborates earlier findings. These results confirm those obtained by Sidabras (2020), who also found similar trend between defoliation and LAI but showed lower crown total surface area index values in Scots pine stand compared to the reference projected surface area.

The findings obtained in this study may be somewhat limited as the developed models do not allow the estimation of needle surface area for other coniferous, also differences due to tree age and season must be further evaluated.

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