

Article

Assessment of the Mass and Surface Area of the Scots Pine (*Pinus sylvestris* L.) Needles

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Abstract: The assessment of the surface area of all leaves from a tree crown is regarded as one of the key parameters in scaling ecophysiological processes, such as growth, carbon budget, and water management. The purpose of this study was to investigate the variation of the mass and surface area of Scots pine needles, obtained from trees growing in the same habitat conditions but at different stock densities, therefore occupying different biosocial positions. The mass of needles and the leaf area index (LAI) were determined for an even-aged 33-year-old Scots pine stand located at a fresh mixed coniferous forest site in southwest Poland (50°32' N; 17°42' E). The needles, collected from all the sample trees, were subjected to a biometric analysis to determine the total mass of needles from each tree, the mass of 1000 needle pairs, the number of needles per crown, and the needle length distribution. Based on the actual measurements, we derived allometric equations for finding the fresh mass (FMN) and the surface area of the needles (SN), using the diameter at breast height (DBH) as an independent variable. The relationships between the mass of the needles and the DBH were significant ($p < 0.0001$), and so were those between the surface area of the needles and the DBH ($p < 0.001$). The fresh mass of needles for the tree stands varied from 6458 kg·ha⁻¹ to 11,102 kg·ha⁻¹. The LAI was in the range of 3.2 to 5.4 m²·m⁻². The mean value of the LAI for the Scots pine stand was 4 m²·m⁻². Further studies are required and more algorithms need to be developed for the quantitative assessment of the LAI in Scots pine trees, using a larger number of sample trees with more varied biometric features.

Keywords: mass of needles; surface of needles; LAI; allometric equation; *Pinus sylvestris* L.



Citation: Sporek, M.; Sporek, K.; Stebila, J.; Kučerka, M.; Kminiak, R.; Lubis, M.A.R. Assessment of the Mass and Surface Area of the Scots Pine (*Pinus sylvestris* L.) Needles. *Appl. Sci.* **2022**, *12*, 8204. <https://doi.org/10.3390/app12168204>

Academic Editor: Stefano Invernizzi

Received: 17 July 2022

Accepted: 15 August 2022

Published: 17 August 2022

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1. Introduction

Almost all processes occurring in forest ecosystems, especially the process of primary production, depend on the size and area of the assimilating part of a tree crown [1–3]. Studies on the mass and surface area of leaves were pioneered by Tirén [4], Burger [5,6], and Ovington [7]. The assessment of the surface area of all leaves from a tree crown is regarded as one of the key parameters in scaling ecophysiological processes, such as growth, carbon budget, and water management [3,8–11]. The parameter that is currently commonly used is the leaf area index (LAI). The LAI is defined as the projected area of green leaves

or needles per unit of the horizontal ground surface area [12,13]. It is commonly used in ecological [14–16], biogeochemical [17], and meteorological studies [18–20]. It depends on such factors as the species specificity, the stage of plant development, seasonality, habitat conditions, and forest management practices [21,22]. The values of the LAI presented in the forestry literature varied from below 1 [23] to ~14 [7,24]. Generally, the highest values were recorded for coniferous forests [25]. Studies on the LAI for Scots pine stands in Europe, which occupies more than 20% of the production area in forests, were carried out by many researchers, using several methods for calculating the index. Direct measurements of the leaf surface area of trees and stands requires a lot of work, time, and efficient organization. Therefore, indirect methods to determine the surface area of leaves are widely accepted and have become increasingly important in studies on forest ecosystems. One of the prevalent methods involves allometric equations [26–28] based on the relationships between the surface area of the leaves and easily measured tree dimensions, including diameter, height, and crown length. Indirect measurements are also carried out with optical tools, including hemispherical photography, teledetection, etc. [29–34]. Specialized optical equipment, such as the LAI 2000 Plant Canopy Analyzer, is also used [35,36]; it provides information on the surface area of leaves on a larger area in a relatively short period [36,37]. These measurements, however, give us an estimated result and often underestimate the leaf area in coniferous stands because of the grouping of needles into shoots and branches [35,38].

The distribution and morphology of needles tend to vary highly within the tree crown [39,40]. Therefore, the strategy of sample collection from the crowns of individual trees for the calculation of the surface area of needles ought to take into account the spatial distribution and morphological variation of needles within a crown [41]. Incorrect practices in sample collection as well as extrapolations from allometric relationships between younger and older tree stands may result in data on the surface area of the needles being overestimated or underestimated [3,24,42]. Differences reported in the literature may also result from the variation of habitat and climatic conditions prevailing at sites with Scots pine [30,43–46]. Its natural range extends from Spain in the west ($\approx 5^\circ$ W longitude) to northern Manchuria and the Sea of Okhotsk (130° E) in the east, and from 70° N latitude in northern Scandinavia to 38° N in Turkey [47]. The specific leaf area (SLA) is also known as the leaf mass per unit area ($\text{cm}^2 \cdot \text{g}^{-1}$), the specific leaf mass, or the leaf specific mass. The SLAs for Scots pine were recorded in various countries in Europe [48], with the values varying from 2.87 [49] to 5.51 [48]. Therefore, more empirical data on the mass or surface area of needles for Scots pine stands growing in specific climatic and habitat conditions are required.

This study aimed to assess the variation in the mass and surface area of needles in Scots pine trees growing in balanced habitat conditions in a fresh mixed coniferous forest. The investigated pine stand was even-aged but varied in stock density. The present study is part of a comprehensive research program, intended to determine the number of losses in annual wood increments for Scots pine resulting from the reduction of the surface area of needles. Information on the LAI for the species is an important factor in these studies. Two research hypotheses were proposed: (H1) there is a correlation between the DBH and the mass and surface area of needles; (H2) the mass and surface area of needles of even-aged pine trees growing in the same climatic and habitat conditions tend to vary.

2. Materials and Methods

2.1. Description of the Experimental Site

The study was carried out in an even-aged 33-year-old Scots pine (*Pinus sylvestris* L.) monoculture in southwest Poland ($50^\circ 32'$ N; $17^\circ 42'$ E). The experimental plot consisted of 25 adjacent research plots of 100 m^2 each, occupying a total area of 0.25 ha. It was a flat terrain at 204 m a.s.l. The total mean precipitation was 655 mm per year, the mean temperature was $+8.0^\circ \text{C}$. The vegetation period was 248 days long. The habitat was characterized based on soil tests, of which test samples were collected for physical and chemical analyses. Physical and chemical tests identified the substrate as podsolic soil,

and habitat conditions within the studied plots were balanced, thus eliminating the impact of the site on the variation of the parameters of interest. A detailed description of the forest, including soil type, stand history, understory species, undergrowth species, and tress density was previously published [3,50].

Every 2–3 years the investigated stand experiences increased infestation with *Acantholyda nemoralis* Thoms. Its outbreaks were controlled chemically in 2007, 2009, and 2011 [51].

The stock density was 2520 trees·ha^{−1}. According to Kraft's classification, four categories of trees were distinguished in the stand: dominant, (co-)dominant, intermediate, and suppressed. Codominant tree crowns form the main level of the canopy, with the biggest and fullest crowns of dominant trees standing out above. Intermediate tree crowns occupy a subordinate position in the canopy. They are generally narrow, one-sided, and shorter than those of the dominant and codominant trees. The crowns of the suppressed (overtopped) trees are below the main level of the canopy, are generally short, sparse, and narrow [52]. Scots pine trees at the site had four needle age classes (1, 2, 3, and 4-year-old needles).

2.2. Field and Laboratory Measurements

The sample trees were chosen in such a way as to represent trees with different DBH (and thus with different crowns, heights, etc.). The DBH measurement of all trees on the plot was used to determine the number of sample trees. The 18 sample trees were selected based on the DBH distribution. The selection was made using the English method developed by Humme, based on the formula [53]:

$$k = \frac{N}{n} \quad (1)$$

wherein:

N —total number of trees in a research area,

n —assumed number of sample trees.

Equation (1) yielded a number of 35 that indicated which tree should be felled. We began from one of the corners of the plot, and felled every k -th tree, so that the sample trees from which the needles were collected were evenly distributed over the entire plot [53]. The selected sample trees were felled in March before the start of the growing season. Each sample tree was measured to find its DBH, tree height (H), and length of the live crown (H^*). All the branches with needles were taken from the crowns of the felled trees. They were separately labeled, weighed, and transported to the laboratory in big plastic bags. In the laboratory, the needles were removed manually from all the branches (without taking into account the needle age). The branches and needles were then weighed separately. The needles lose water rapidly, and their weight changes dynamically, while the weight of the branches is more stable. The weight of the needles for a sample tree was determined from the difference in the weight of the branches with and without the needles. The conversion factor of fresh pine needles weight to their dry weight was also figured out, and the number of needle pairs in the sample trees was established. To this end, random samples of the needles were taken from the upper, middle, and lower parts of the canopy immediately after felling the trees. The samples were placed into small airtight plastic bags and transported to the laboratory, where 1000 pairs of needles were counted and weighed for each sample tree. The dry matter of needles for each sample tree was calculated by subtracting from their fresh matter the weight lost measured after drying the needles at 105 °C in a forced-air circulation oven (Digitheat-TFT, J.P. Selecta; Barcelona, Spain). Both in the laboratory and field conditions, the branches and needles were weighed using a mobile electronic scale, max. capacity 60 kg and accuracy 0.01 kg (WPT 60C4 Radwag, Radom, Poland). The 1000 needle pairs were weighed using an analytical balance, capable of weighing a maximum of 200 g with an accuracy of 0.001 g (WPT 2C Radwag, Radom, Poland).

The length of the needles (LN) was measured after collecting random samples for tests. Next, 200 needle pairs were taken from each test sample consisting of needles from individual crowns, and the longer fresh needle in each pair was measured with a ruler with an accuracy of 1 mm. The length measurement was completed before the lapse of two days from the time of the sample collection. The needles were kept at $\sim 16^{\circ}\text{C}$ until the measurements were performed.

The surface area of needles (SN) for each tree was calculated using the procedure described below. Knowing the surface area of individual needles with different lengths [54], the total surface area of needles was calculated for each sample tree, taking into account the variation of needle mass, length, and number. For the 200 measured lengths of needle pairs from each sample tree, 11 length classes ($\text{number of classes} = 3/4\sqrt{n_n}$; $n_n = 200$ needle pairs) [55] were established, determining the middle of the class interval, the number of needles for each class, and percentage share. Next, the number of needles in each length class was calculated and their surface area was computed. Details on the calculation of SN can be found in our earlier work [3].

2.3. Statistical Analysis

To assess the multidimensional data structure, the measurement results were analyzed using hierarchical cluster analysis (HCA) [56] and principal component analysis (PCA) methods [57]. The evaluated data comprised the following variables: DBH, H, H*, FMN, FMN₁₀₀₀, and LN. These data describe different parameters and are expressed in different units. As an effect, in computation results, a bias related to the absolute value of a variable can occur. To avoid misleading conclusions, the data were normalized before computations. The arithmetic mean of the variable was subtracted from each measurement outcome and the result was divided by the calculated standard deviation. For dendrogram structure determination, euclidean distances between points were considered, and for clustering, a “complete” method was used. Singular value decomposition was used for PCA. The FMN and SN for the tree stand were assessed after deriving allometric equations, using DBH as the independent variable. The best fitting regressions were selected based on the determination coefficient (R^2). Significance was evaluated at $p < 0.05$ probability levels. All calculations were performed with R software (The R Core Team 2021) [58] and Statistica 13.3 (StatSoft Inc., Tulsa, OK, USA, 2017).

3. Results

The study investigated a 33-year-old Scots pine monoculture, situated in a fresh mixed coniferous forest site.

The DBH of the tree stand was in the range of 7 to 19 cm and the mean tree height was 14 m at a stock density of 2520 trees·ha^{−1}. Characteristics of the needles were obtained for 18 sample trees having different evaluation parameters, i.e., DBH, tree height (H), and crown length (H*) (Figure 1).

3.1. Characteristics of the Sample Trees

This was reflected by the total mass of needles from those trees. The fresh mass of needles from a suppressed and thinning tree from the community was merely 0.9 kg (0.42 kg of dry mass). In a dominant tree, this value was 8.38 kg (3.92 kg of dry mass) (Figure 1). The coefficient of variation of the mass of needles was 47%. The median was 3.6 kg, and the mean fresh mass of needles was 3.9 kg.

The collected samples of 1000 needle pairs from each sample tree were characterized by a 32% differentiation of mass. The maximum mass of 1000 needle pairs was 105 g at a low total mass of needles in the crown of that tree (2 kg) and at a length of 71 mm, which was higher than average (mean length for the population was 53 mm). The lowest mass of 1000 needle pairs was 39 g at an average length of 46 mm. Taking into account the total mass of needles in the crown of that tree, which was 5.4 kg, the number of needle pairs in that tree was calculated to be more than 137,000. Compared with the crown in which the

mass of 1000 needle pairs was the highest, the difference in the number of needles in the whole crown is nearly seven fold (20,402 pcs) (Figure 1).

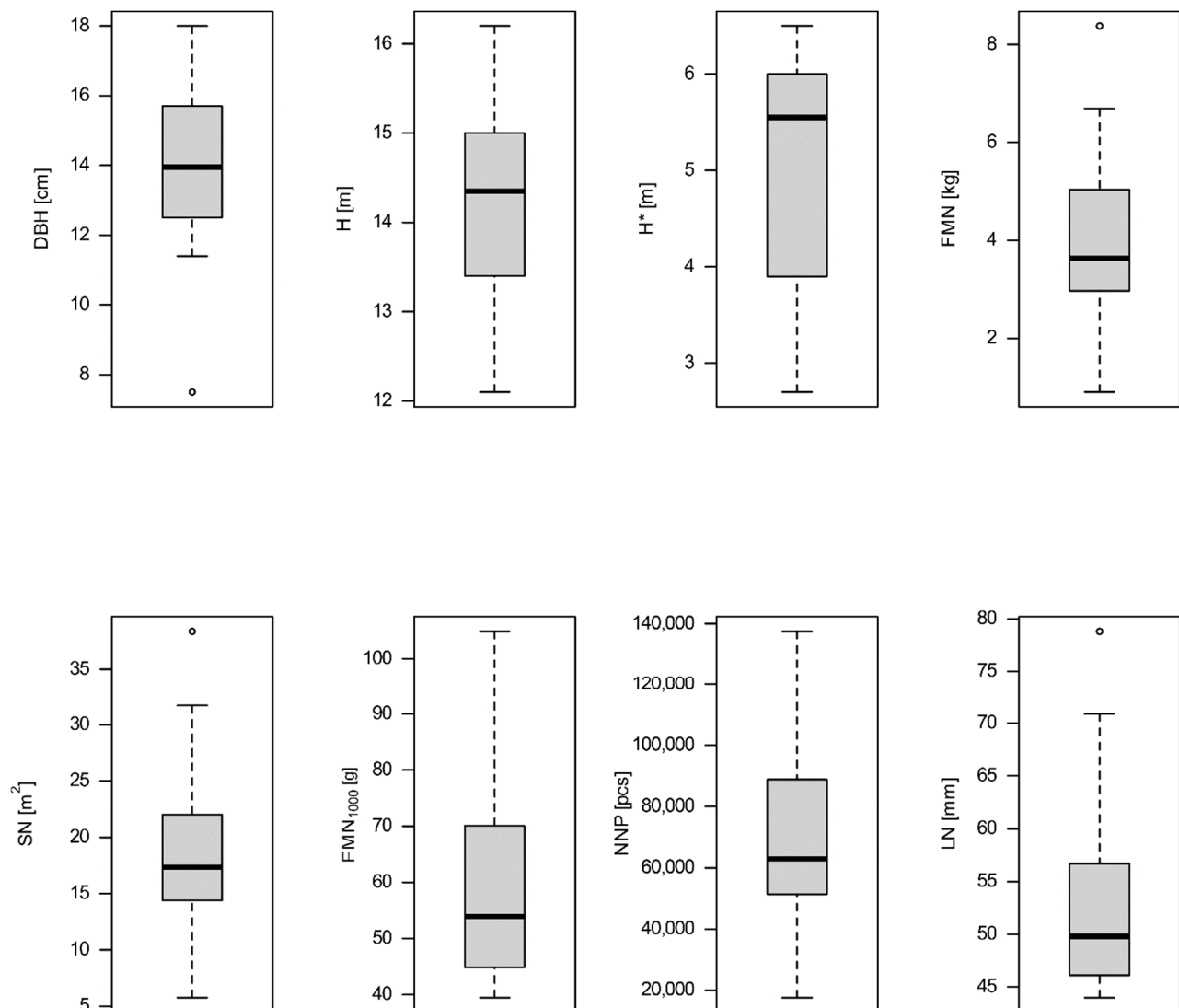


Figure 1. Median (horizontal line in box), the 25th percentile to the 75th percentile (box spans) and a ‘whisker’ ranging to maximum and minimum but no more than 1.5 times of the interquartile range (IQR) from the box top and bottom, respectively, (DBH—diameter breast height; H—tree height; H*—crown length; FMN—fresh mass of needles (Dry mass of needles = $FMN \cdot 0.468$); SN—surface of the needles; FMN_{1000} —fresh mass 1000 pairs of needles; NNP—number of needle pairs in a sample tree; LN—mean length of needles).

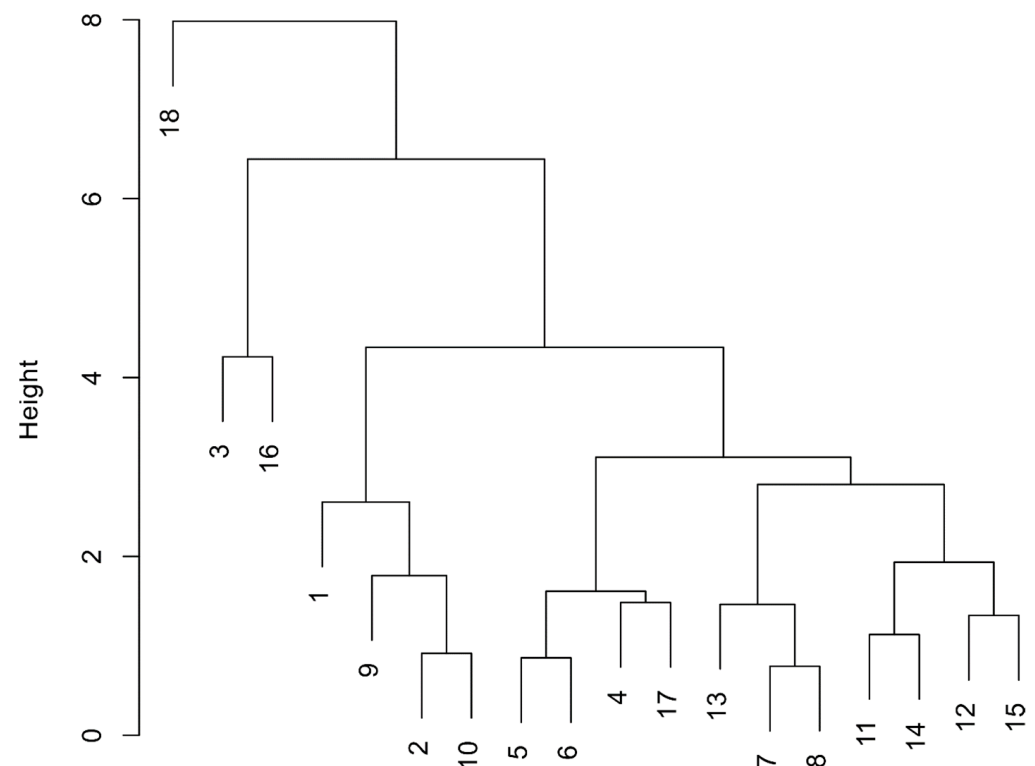
Based on the mass of needles in the whole crown, the mass of 1000 needle pairs, and the number and length structure of needles, we calculated the assimilation surface (surface area) for each sample tree. The calculated surface area of the needles was 5.8–38.4 m² (Figure 1), making the difference between the extreme values as high as seven-fold. In one-half of the individuals, the surface area of the needles was below 17 m². The highest correlation coefficients were found for DBH and FMN ($r = 0.848$; $p < 0.0001$) and SN ($r = 0.727$; $p < 0.001$) (Table 1).

Table 1. Pearson's correlation matrix between needle weight results and needle area and biometric features of 18 sample trees. Significant results ($p < 0.05$) in bold.

		FMN (kg)	SN (m ²)	DBH (cm)	H (m)	H* (m)
SN (m ²)	Pearson's r	0.9384	-			
	<i>p</i> -value	<0.0001	-			
DBH (cm)	Pearson's r	0.8481	0.7267	-		
	<i>p</i> -value	<0.000	<0.001	-		
H (m)	Pearson's r	0.5870	0.4808	0.6276	-	
	<i>p</i> -value	<0.010	<0.043	<0.005	-	
H* (m)	Pearson's r	0.6956	0.6774	0.7002	0.2012	-
	<i>p</i> -value	<0.001	<0.002	<0.001	<0.423	-

DBH—diameter breast height; H—tree height; H*—crown length; FMN—fresh mass of needles; SN—surface of the needles.

A multidimensional analysis of variables, shown in the form of a dendrogram (Figure 2), showed that trees No. 3, 16, and 18 diverged from the other ones because of their biometric parameters. The group comprised of extreme trees, namely, a dominant tree (No. 18) with maximum biometric parameters (DBH, H, H*), and a suppressed tree (No. 16), which was self-thinning from the tree stand and had the lowest values of the parameters. The third tree in this group (No. 3) had a much-shortened crown and a low mass of needles. On the other hand, it had the highest mass of 1000 needle pairs (FMN₁₀₀₀) in the whole test group, which most probably was accounted for by its higher-than-average length.

**Figure 2.** The dendrogram illustrating structures composed of the points with coordinates defined by the scaled sample tree parameters (DBH, H, H*, FMN, FMN₁₀₀₀, LN).

PCA indicated that the first three principal components (PC1-3) explained 92.6% of the total variance. Figure 3 shows the points representing data in PC1 and PC2 coordinates. The length of the arrow projection on the axes illustrates the contribution of the variable to PC1 and PC2. Similar directions of the arrows representing FMN and DBH variables indicate co-variability of the parameters. Similarly, FMN₁₀₀₀ and LN shared the trend of

the changes. This observation was confirmed by the correlation coefficients presented in the section above (Table 1).

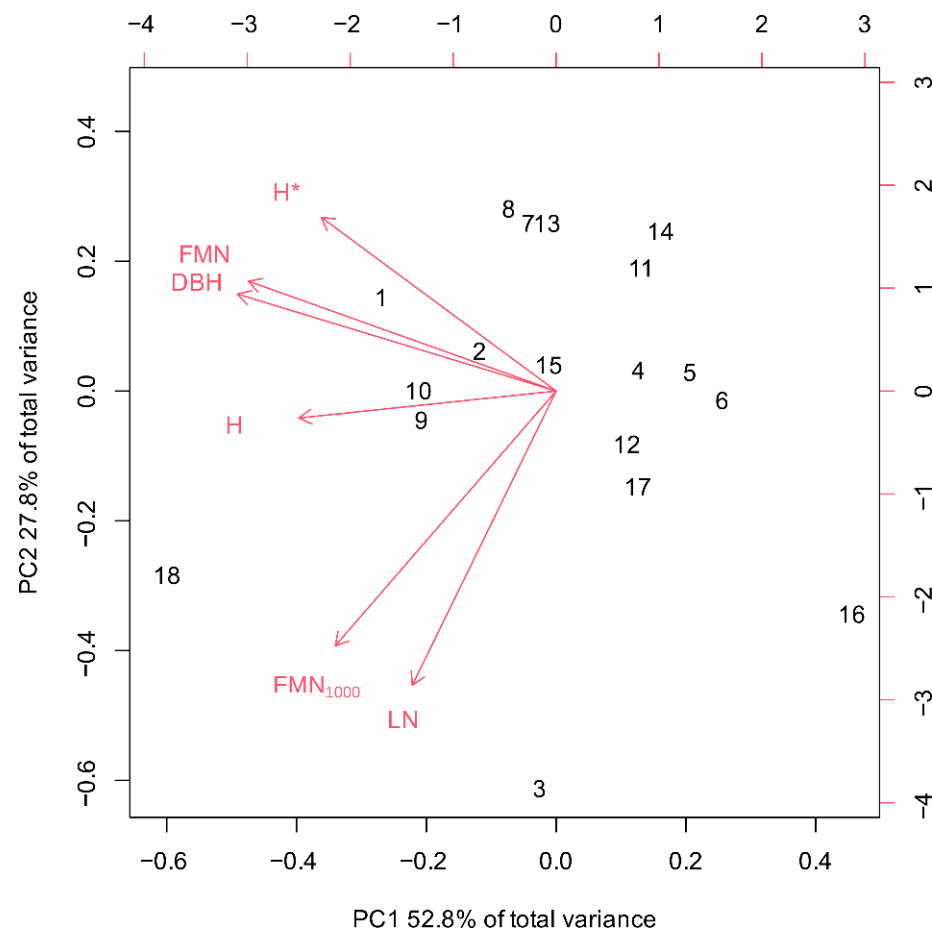


Figure 3. Biplot illustrating PCA-derived relationships between the scaled sample tree parameters (DBH, H, H*, FMN, FMN₁₀₀₀, LN).

The data, obtained from actual measurements of the sample trees, were used for deriving linear allometric equations, enabling the calculation of the mass and surface area of needles if the DBH of the given tree is known. Structural parameters β of the relationship $FMN = \beta_{0FMN} + \beta_{1FMN} \cdot DBH$ (Figure 4a) and $SN = \beta_{0SN} + \beta_{1SN} \cdot DBH$ (Figure 4b). Their standard errors (FMN) and p -values (p) for $H_0: \beta_i = 0 \{i = 0,1\}$ were calculated [59]. For normality assessment of the model residuals distribution, the Anderson–Darling and the Kolmogorov–Smirnov tests were used. To test heteroskedasticity, the Breusch–Pagan and the Goldfeld–Quandt tests were applied.

Table 2 presents the estimated parameters of the models. It shows the values of intercepts (β_0) and slopes (β_1) with their standard errors (SE_{β_0} , SE_{β_1} respectively) and p -values for $H_0: \beta_i = 0 \{i = 0,1\}$. Additionally, the limits of the parameter's 95% confidence interval ($CI_{\beta_i} \{i = 0,1\}$) and coefficient of determination (R^2) were calculated.

Taking into account the calculated p -values concerning structural parameters in the models, the null hypotheses can be rejected. The soundness of this conclusion is weaker for β_{0SN} since within the CI range, the 0 value is included. To verify the normal distribution of the model, residual Anderson–Darling and Kolmogorov–Smirnov tests were used. The results obtained for both models (p -value > 0.05) indicate retaining the null hypotheses. For heteroskedasticity tests, similar conclusions were drawn, the null hypothesis concerning homogeneity of the model variance cannot be rejected.

The equations were derived based on data for the studied population; therefore, they can be successfully used in calculating the FMN and SN of all the trees in the research plots.

They can also be used for calculating the FMN and SN for other tree stands of a similar age that grow in comparable habitat conditions.

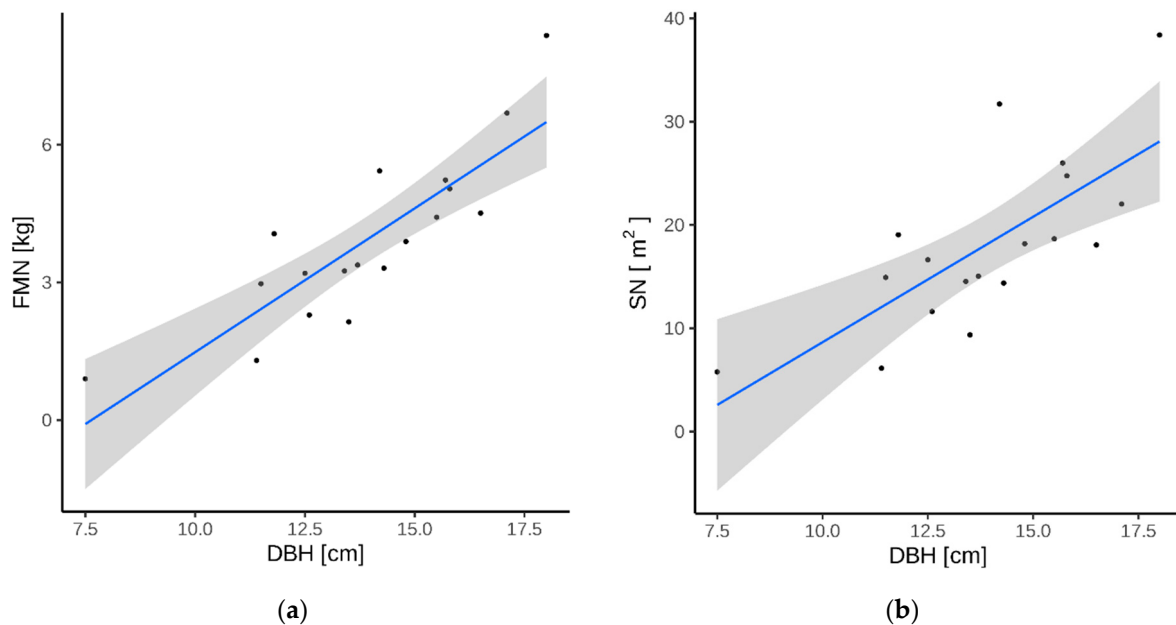


Figure 4. The relationship between: (a) the breast height diameter (DBH) and the fresh mass of the needles (FMN), (b) the breast height (DBH) and the surface area of the needles (SN).

Table 2. Allometric equations for the mass of needles (FMN) and needle surface (SN) determination in Scots pine stands from DBH values.

Model Formula	β_0	SE_{β_0}	p -Value	CI_{β_0}	β_1	SE_{β_1}	p -Value	CI_{β_1}	R_d
$SN = \beta_{0SN} + \beta_{1SN} \cdot DBH$	−15.6	8.1	0.003	−32.8–1.5	2.43	0.57	<0.001	1.2–3.7	0.53
$FMN = \beta_{0FMN} + \beta_{1FMN} \cdot DBH$	−4.8	1.4	0.003	−7.7–1.9	0.627	0.098	<0.001	0.42–0.83	0.72

3.2. Mass of Needles and the LAI of the Tree Stand

The values of FMN and SN, calculated from the allometric equations for the 25 research plots covered with the 33-year-old Scots pine stand, are shown in Table 3. The FMN varied between $6458 \text{ kg} \cdot \text{ha}^{-1}$ and $11,102 \text{ kg} \cdot \text{ha}^{-1}$. The difference in the mass of needles between the extreme values was nearly two-fold.

The mean value of the LAI for the Scots pine stand was $4.04 \text{ m}^2 \cdot \text{m}^{-2}$. In the respective research plots, the LAI was in the range of 3.2 to $5.4 \text{ m}^2 \cdot \text{m}^{-2}$ at a stock density of 2500 and 3900 trees $\cdot \text{ha}^{-1}$ (Table 3). Based merely on the two research plots, it could be concluded that a higher number of trees results in a higher value of the LAI, but this simple relationship is not true in this case. Individuals growing close to each other have relatively shorter crowns, which results in lower masses of needles and smaller surface areas. On the other hand, in the total area per unit of land, a small assimilation area of a single individual may, to some extent, be compensated by the number of individuals, giving, ultimately, the same or similar value of the LAI. For example, the same LAI of $3.5 \text{ m}^2 \cdot \text{m}^{-2}$ was obtained for different tree densities of 1800, 2000, 2200, and 2400 trees $\cdot \text{ha}^{-1}$.

Presumably, the total surface area of needles also depends on the distance between the trees. For the same stock density of 2800 trees $\cdot \text{ha}^{-1}$, the value of the LAI was 4.2 or $5.1 \text{ m}^2 \cdot \text{m}^{-2}$. This is justified: densely growing trees prevent access of sunlight to each other, which leads to an early needle drop. Such differentiation results in different biocenotic relationships associated with photosynthesis, carbon fixation, and growth rings.

Table 3. Differences in needle surface area in 33 years old Scots pine stand (data sorted in ascending order by LAI).

Number of Plots	LAI ($\text{m}^2 \cdot \text{m}^{-2}$)	SN ($\text{m}^2 \cdot \text{ha}^{-1}$)	FMN ($\text{kg} \cdot \text{ha}^{-1}$)	Stand Density ($\text{pcs} \cdot \text{ha}^{-1}$)
4	3.2	32,310	6458	2500
12	3.4	33,570	7160	2000
23	3.5	34,760	7617	1800
6	3.5	35,760	7724	2000
21	3.5	35,060	7393	2200
16	3.5	35,090	7250	2400
7	3.6	36,110	7890	1900
3	3.6	36,380	7308	2100
24	3.7	36,970	8038	2000
8	3.7	37,350	8060	2100
15	3.7	37,250	7957	2200
18	3.7	36,580	7484	2600
1	3.8	37,660	7837	2500
22	3.9	39,080	8356	2300
9	4.0	39,800	8013	3000
10	4.0	39,850	7727	3400
5	4.2	42,160	8925	2600
2	4.2	41,950	8720	2800
25	4.4	44,240	9387	2700
19	4.6	46,020	10,071	2400
13	4.8	47,810	10,082	3000
20	4.9	48,860	9638	2700
17	4.9	48,920	10,480	3100
14	5.1	51,180	11,102	2800
11	5.4	54,140	11,037	3900

4. Discussion

The importance of the assimilation surface results from the fact that the amount of generated biomass depends on the surface area of the needles (an allometric relationship). The usefulness of the biometric features of trees, for instance, DBH, tree height, or length of the crown, for the estimation of the surface area of leaves at the tree level was demonstrated in several studies [26,27,60–62]. In comparison with other features of a single tree, the DBH was a better predictor of the surface area of needles than the tree height or length of the crown. For the quantification of total needle area in the field, DBH is a reliable and easy-to-measure scalar, and the relationships of the needle area with DBH are highly significant, confirming similar findings for the needle biomass [9]. In addition, in our studies, DBH proved to be the best parameter for the calculation of the mass of the needles and their surface area.

Generally, a growing crown seeks to develop as high an assimilation surface as possible in given habitat conditions and stock density. The stock density combined with other abiotic and biotic factors results in pronounced differences in the surface area of needles for the respective individuals, regardless of their age. Incomparable habitat conditions prevailing in a fresh mixed coniferous forest, the surface area of needles in Scots pine trees varied from 0.49 to 73.16 m^2 for 9-year-old trees and from 10.9 to 94.3 m^2 for 70-year-old ones [3]. Significant differences can be seen in the surface area of needles, depending on the biosocial position of a given tree. This is probably connected with stock density in a community and the resulting varied access to sunlight—one of the key factors preventing needle drop. Scots pine is a heliophytic species that does not tolerate shade. Its needle longevity reaches 2 to 6 years, so the trees do not develop such large canopies as spruces, in which the needle longevity is 7 to 15 years [63]. Thus, the leaf longevity and canopy structure influence the potential maximum LAI [64].

Jack and Long [65] analyzed the impact of stock density on the LAI in *Pinus contorta* var. *latifolia*. The mean surface area of needles per tree varied from 7 to 190 m² at a stock density from 6300 to 208 trees·ha⁻¹, and the LAI was increasing with the stock density. The same relationship was observed for the stand described in this paper. On the other hand, we also demonstrated that the same or similar values of the LAI can be obtained for different stock densities.

In a study performed on a 50-year-old tree stand in Sweden [66], the fresh mass of needles and the corresponding surface area of the needles for five Scots pine trees were: 8.81 kg–62.7 m²; 6.35 kg–47.4 m²; 6.60 kg–48.9 m²; 5.86 kg–44.3 m²; and 2.48 kg–23.5 m². The coefficient of correlation between the mass and the surface area of the needles in that study was very high ($r = 0.99$), similar to our study ($r = 0.94$; $p < 0.0001$). Nonetheless, it should be observed that, for similar masses of needles, we obtained assimilation surfaces nearly 50% lower (8.38 kg–38.4 m², 6.69 kg–22.0 m², 5.43 kg–31.7 m², 2.14 kg–9.36 m²; Figure 1) than those obtained in the Swedish study. This may have resulted from the structure of needles, i.e., their length and width. The surface area of 1 g of shorter needles is larger than that of longer needles [3]. On the sunlit side of the crown, 1 g of the needles has a surface area of 70 cm², and in the shade, 107 cm² [67]. This large surface area of needles in the shade may be caused by their smaller size, consequently resulting in a large surface area per 1 g. The volume of wood production during the vegetation season is a function of the surface area of needles and the amount of transpiration. If a variation of surface area amounting to 46% is obtained for 1 g of the fresh mass of needles from a Scots pine tree located in the same site of a mixed fresh coniferous forest, then such a variation is to be expected for the increase in the wood mass.

Older literature on the subject contains the results of measurements carried out by Tirén in Swedish Scots pine forests [4]. According to the author, the surface area of needles in a 35-year-old stand was 71,400 m²·ha⁻¹ as compared with 66,200 m²·ha⁻¹ for a 105-year-old stand. These results are higher than those reported in this paper, roughly 43%. The lower assimilation surface for the stand analyzed in this study must have partly resulted from the gradation of *Acantholyda nemoralis* Thoms [51]. Measurements performed on 18 sample trees indicated the reduction of the mass of needles per individual crowns by as much as 89%, and that of the surface area of needles by 85%. In a study conducted in Finland in a 34-year-old pine stand, the weight of the pine needles was 5100 kg·ha⁻¹ with a dominant share of two the youngest age classes of needles. The LAI for this stand was 3.9 m²·m⁻² [68]. These values are lower than in our work (Table 3), which can be explained by the fact that the needles of Scots pines we investigated belonged to four age classes.

When developing and using climate and carbon balance models, it is crucial to obtain accurate information about leaf area in forests, since they cover such a large part of the world's land area and biomass [69]. The method we used to determine the weight of the needles from the entire crown, to calculate the number of needles in the crown, and to work out the structure of the needles, provided solid foundations for an accurate calculation of the needle surface.

5. Conclusions

The problem to be investigated involved the determination of the variation in the mass and surface area of needles of a Scots pine stand depending on the biometric features of the individual trees. The starting point for calculating the pine needle surface was to remove and weigh all the needles from the crowns of the sample trees.

This work aimed to derive equations enabling us to calculate the mass ($FMN = \beta_{0FMN} + \beta_{1FMN} \cdot DBH$) and surface area ($SN = \beta_{0SN} + \beta_{1SN} \cdot DBH$) of the needles for the Scots pine stand. The quantitative determination of the total mass and surface area of the needles per unit area of land may successfully be carried out with the use of diameter at breast height (DBH), which is an easily measured parameter. Higher values of R^2 were recorded for allometric equations in which DBH was the independent variable. Significant results on

the mass and surface area of needles were obtained. No simple relationship between the number of individual trees per unit of land and the value of the LAI was found.

The limitations of this study were the range and size of the data set. Due to the labor involvement required in our methodology, needles were collected from 18 sample trees. This sample size might have affected the derived allometric equations. If the use of the LAI in forestry is to increase, further studies are required and more algorithms need to be developed for the quantitative assessment of the LAI in Scots pine trees, using a larger number of sample trees with more varied biometric features.

Author Contributions: Conceptualization, M.S. and K.S.; Methodology, M.S. and K.S.; Formal Analysis M.S., K.S. and J.S.; Investigation M.S. and K.S.; Resources M.S., K.S. and M.K.; Writing—Original Draft Preparation, M.S. and K.S.; Writing—Review and Editing, M.S., K.S., J.S. and M.K.; Visualization, M.S., K.S., J.S., M.A.R.L., M.K. and R.K.; Supervision, M.S., K.S. and M.A.R.L.; Project Administration, M.S. and K.S.; Funding Acquisition, J.S., M.K. and R.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Cultural and Educational Grant Agency of the Ministry of Education, Science, Research and Sport of the Slovak Republic under contract No. KEGA 026UMB-4/2021 and by the grant agency VEGA under project No. 1/0324/21 and project No. 1/0629/20.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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