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Determination of relationships between leaf area index and stand characteristics in anatolian black pine stands of kastamonu region, Turkey

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SILVICULTURE

ABSTRACT

Background: Leaf area index (LAI) is an important stand characteristic in terms of forest productivity and stand growth, and it shows significant correlations with other stand characteristics. In this study, it is aimed to reveal the relationships between LAI and some other stand characteristics, i.e. mean diameter, stand age, dominant height, site index, number of trees, stand basal area, stand density, total crown biomass and crown dimensions for Anatolian black pine (*Pinus nigra* J.F. Arnold subsp. *pallasiana* (Lamb.) Holmboe) stands in Kastamonu region, which is one of the economically important tree species in Türkiye, and to develop a regression model for LAI estimations by using these relationships.

Results: The data obtained from 119 temporary sample plots were used in the study. According to the results, stand basal area, stand density, total crown biomass, dominant height, number of trees, mean diameter, and site index positively correlated with LAI. LAI values were significantly different in terms of stand density and site classes. Among the candidate models for LAI estimations, the model containing site index and stand density as independent variables was the most successful model with the adjusted coefficient of determination (R_{adj}^2) of 0,63 and the Akaike information criterion (*AIC*) of -67,25.

Conclusion: The LAI, which is difficult to measure directly in practice, of Anatolian black pine stands in Kastamonu region of Türkiye could be estimated accurately with the help of the equation developed.

Keywords: LAI-2200C, Stand density, Site index, *Pinus nigra* subsp. *pallasiana*

HIGHLIGHTS

The LAI of an Anatolian black pine stand can be accurately estimated using site index and stand density.
Mean diameter, basal area, stand density, and site index were positively correlated with LAI.
The LAI values were statistically different for stand density and site classes.
For sustainable forest management projections, the LAI is one of the valuable stand characteristics.

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INTRODUCTION

Leaf area index (LAI) is interrelated to tree growth and forest productivity (Vose et al., 1994). It is generally used in determining biological models such as climate change, growth, and yield (Gower and Norman 1991). Furthermore, it is a successful predictor in modeling photosynthetic processes using light energy captured by forest canopy (Bonan, 1993). Accurate prediction of LAI in forestry activities will especially be important in processes such as wood production, defoliation, and snow damage (Mason et al., 2012).

LAI was defined as a dimensionless measure of the total unilateral green leaf area (m^2) per unit ground surface area (m^2) by firstly Watson (1947). To determine LAI, there are several methods based on direct or indirect approaches (Gower et al., 1999; Jonckheere et al., 2004). In direct methods, leaf area of either foliage collected from sample trees or sample leaves collected by litter traps is measured. Therefore, direct measurements give more precise results, even though they require time-consuming, labor-intensive, and expensive measurements (Gower et al., 1999). These disadvantages increase the utilization of practical and less labor-intensive indirect methods in forest inventory activities, and since the 1960s, optical measurements have been frequently applied in LAI measurements (Chianucci and Cutini, 2012). Optical measurement devices used in LAI determination are divided into two groups (Stenberg et al., 1994); fisheyes lenses (e.g., LAI-2200C plant canopy analyzer and hemispherical photographs) and line quantum sensors (e.g., SunScan plant canopy analyzer and Sunfleck ceptometer). Jelaska (2004) stated that the hemispherical photography method can be used accurately for LAI estimations of silver fir-beech forests in Croatia. Jonckheere et al. (2004) suggested also hemispherical photographs for LAI predictions. On the other hand, LAI-2000 plant canopy analyzer device was found successful for fast- growing native tree species of Costa Rica by Arias et al. (2007). The LAI-2200C is one other optical instrument that has a fisheye lens utilizing central zenith angles of 7, 23, 38, 53, and 68° to measure radiation (Chen et al., 1997). However, the studies, in which LAI 2200C was used to predict the LAI, on developing regression equations to predict LAI with stand characteristics are very limited (Bequet et al., 2012).

The aims of this study were (*i*) to assess the relationships between LAI and stand characteristics such as mean diameter, stand age, dominant height, site index, number of trees, stand basal area, stand density, total crown biomass and crown dimensions, (*ii*) to compare age, stand density and site classes in terms of LAI, and (*iii*) to develop regression models to predict LAI using stand characteristics for pure Anatolian black pine stands in Kastamonu region of Türkiye.

MATERIAL AND METHODS

The study area is located in Kastamonu region of Türkiye (Figure 1). The region has approximately 0,9 million ha forest area (GDF, 2019). The study area has a humid climate and receives high amounts of precipitation especially in autumn and winter seasons. The elevation of the study area above sea level ranges from 724 m to 1576 m with an average of 1147 m. A total of 119 temporary sample plots were taken from Taşköprü, Tosya, Karadere, Araç, Kastamonu, Daday, İhsangazi and Hanönü state forest enterprises of Kastamonu Regional Directorate of Forestry. To represent different stand structures in terms of stand ages, site qualities and densities, sample plots were selected carefully from the study area. Plot sizes were determined according to stand crown closures as 400, 600 and 800 m^2 for crown closures of >71%, 41–70 and 11–40, respectively. The plot sizes were reduced to 200 m^2 in the stands with excessive number of trees and increased to 1000 m^2 in the stands with deficient number of trees. In addition, attention was paid to the presence of at least 30 trees in each sample plot. All of the sampled plots are composed of even-aged pure Anatolian black pine stands.

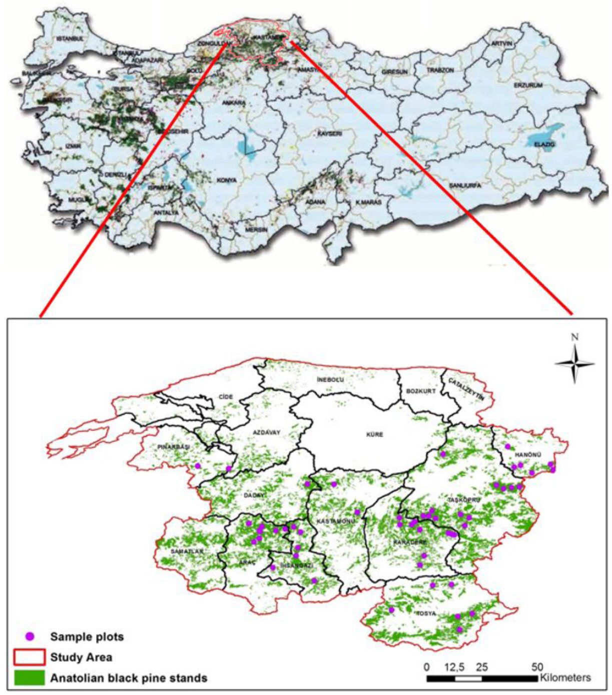

Figure 1. Geographic location of the study area.

During fieldwork, LAI values were measured using LAI-2200C instrument in sample plots, firstly. The LAI-2200C computes light levels above and below the forest canopy and returns the proportion of computing values to LAI. These measurements were carried out at five points below canopy (one of at the center of the sample plot and four of at 5 m distances from the center) within each sample plot, taking into account Selin's (2019) suggestion (Figure 2). In addition to LAI measurements, diameters at breast height (*d*) at 1.30 m above ground level were measured for all trees larger than 8 cm of *d* in each sample plot, and quadratic mean diameters (d_q) were calculated. Stand age was determined by taking the average age of trees close to the mean diameter in sample plots. To determine dominant heights (h_{100}), heights of the tallest 100-trees per hectare (i.e. 4, 6 and 8 trees for 400, 600 and 800 m^2 sized sample plots, respectively) were measured with an electronic clinometer (Haglöf EC-II) and averaged for each sample plot. Then, site indexes (*SI*) were calculated according to Kalıpsız's (1963) equation using dominant heights and stand ages, and site classes of the sample plots were identified as I (site indexes higher than 29.50 m), II (site indexes between 24.51-29.50 m), III (site indexes between 19.51-24.50 m), IV (site indexes between 14.51-19.50 m), and V (site indexes lower than 14.51 m). Stand densities (*SD*) were also calculated utilizing Eq. 1 created by Curtis et al. (1981). Where *SD* is stand density, *BA* is basal area ($m^2\ ha^{-1}$), and d_q is quadratic mean diameter (cm).

$$SD = \frac{BA}{\sqrt{d_q}} \quad [1]$$

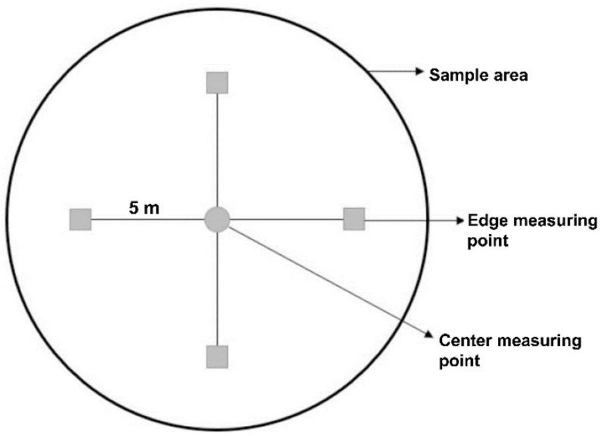

Figure 2. Arrangement of measurements within sample plots.

Total crown biomass and the mean crown dimensions were also determined using the equations developed in our previous studies for Anatolian black pine stands located in the study area. Hence, the branch and needle biomasses (M_{br} and M_{nd}, respectively) of the trees were predicted with Eq. 2 and 3 developed by Sakici et al. (2018a), firstly. Total crown biomass (M_{cr}) was then computed by summing predicted branch and needle biomasses. The crown diameters (*CD*) and crown lengths (*CL*) of sample trees were estimated using Eq. 4 and 5 generated by Sakici et al. (2018b). Then, mean crown diameter and mean crown length were calculated for all sample plots.

$$M_{br}=0.055\ d^2 \quad [2]$$

$$M_{nd}=0.021\ d^2 \quad [3]$$

$$CD=e^{2.4049-15.8050/d} \quad [4]$$

$$CL=e^{2.3418-10.2294/d} \quad [5]$$

Descriptive statistics of stand characteristics for 119 sample plots are given in Table 1. As seen in this table, sample plots represent wide ranges of diameter classes, stand ages, site indexes, number of trees and stand densities. Distributions of sample plots to age, stand density and site classes are depicted in Figure 3.

Table 1. Descriptive statistics of LAI and some stand characteristics.

Stand characteristics	Minimum	Maximum	Mean	Standard Deviation
Leaf area index ($m^2 \cdot m^{-2}$)	0.79	3.83	2.32	0.74
Mean diameter (cm)	11.4	48.9	27.9	8.6
Stand age (year)	28	137	74.9	25.1
Dominant height (m)	9.3	30.8	18.2	5.5
Site index (m)	11.2	43.9	22.5	6.2
Number of trees per hectare ($N \cdot ha^{-1}$)	190	3300	871.6	541.5
Stand basal area ($m^2\ ha^{-1}$)	14.65	88.71	44.56	17.74
Stand density	3.70	18.38	8.51	3.13
Total crown biomass ($ton \cdot ha^{-1}$)	14.18	85.88	43.13	17.17
Mean crown diameter (m)	2.50	7.87	5.78	1.18
Mean crown length (m)	3.86	8.33	6.75	0.96

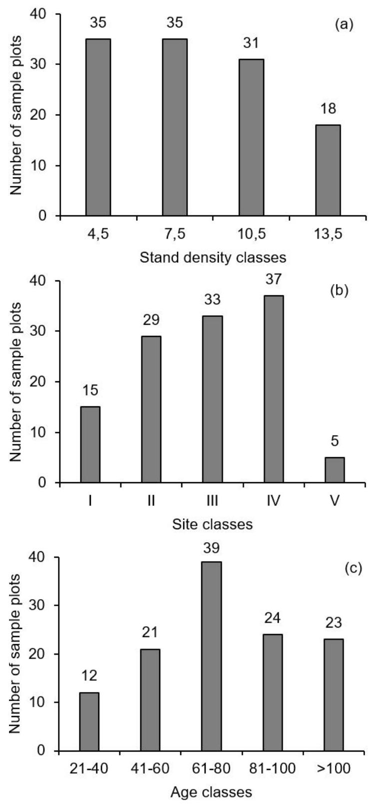

Figure 3. Distributions of sample plots by stand density (a), site (b) and age classes (c).

The Kolmogorov–Smirnov test was performed to check whether the LAI and the other stand characteristics were normally distributed. The relationships between LAI and stand characteristics were evaluated with Pearson correlation coefficients for normally distributed characteristics or Spearman's correlation coefficients for non-normal ones. LAI was also compared against age, stand density, and site classes using analysis of variance (ANOVA). In case of significant difference between groups, Duncan test was used for pairwise multiple comparisons.

Developing regression models to predict LAI was also aimed in this study. For this purpose, the data from 119 sample plots were randomly divided into two groups as model development data (89 plots, 75% of the total) and validation data (30 plots, 25% of the total). In the literature, numerous regression models with linear or non-linear form have been proposed for LAI estimations utilizing various stand characteristics as independent variables (DeRose and Seymour, 2010). Some of these models were selected to fit using regression analysis for LAI estimations of subject stands of this study. Besides, multiple linear regression analysis was also conducted to develop the equations fitting the relationships between LAI and other stand characteristics, and the ordinary least squares method was used to obtain regression models based on stepwise selection. The independent variables of these models were stand density and site index. As a result, a total of 11 regression models, seven literature-based and four study-specific were evaluated (Table 2).

The regression models were evaluated based on five goodness-of-fit statistics; Adjusted Coefficient of Determination (R_{adj}^2), Bias (*B*), Mean Absolute Error (*MAE*), Root Mean Square Error (*RMSE*), and Akaike's information criterion (AIC). Corresponding mathematical forms of these statistics are given below. Where LAI_i, $\widehat{LAI}_i$ and $\overline{LAI}_i$ represent the observed, predicted and mean LAI values, respectively. *n* is number of observations, and *p* is number of parameters within regression models.

$$R_{adj}^2 = 1 - \frac{\sum_{i=1}^{n}\left(LAI_i - \widehat{LAI}_i\right)^2 (n-1)}{\sum_{i=1}^{n}(LAI_i - \overline{LAI}_i)^2 (n-p)} \quad [6]$$

$$B = \frac{\sum\left(LAI_i - \widehat{LAI}_i\right)}{n} \quad [7]$$

$$MAE = \frac{\sum_{i=1}^{n}\left|LAI_i - \widehat{LAI}_i\right|}{n} \quad [8]$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(LAI_i - \widehat{LAI}_i\right)^2}{n}} \quad [9]$$

$$AIC = n.\ln(RMSE) + 2p \quad [10]$$

When comparing the success of evaluated models, it is desirable that the R_{adj}^2 values are high while the others have low values. For models' ranking, relative rank approach was utilized (Poudel and Cao, 2013):

$$R_i = 1 + \frac{(m-1)(S_i - S_{min})}{(S_{max} - S_{min})} \quad [11]$$

Table 2. Descriptive statistics of LAI and some stand characteristics.

Models	Form	Resource
LS-1	$LAI=b_0 BA^{b1} CL_m^{b2}$	Long and Smith, 1988
LS-2	$LAI=b_0 M_{cr}^{b1} CL_m^{b2}$	
P-1	$LAI=b_0\,(BA.CL_m)^{b1}$	Pace, 2003
P-2	$LAI=b_0\,(SD.CL_m)^{b1}$	
DS-1	$\ln LAI=b_0+b_1 \ln BA+b_2 \ln CL_m$	DeRose and Seymour, 2009
DS-2	$\ln LAI=b_0+b_1 \ln BA+b_2 \ln CD_m$	
DS-3*	$LAI=b_0 SD^{b1} SI^{b2} b_3 h_{100}^{b3-1} \exp(-((h_{100}/43)b_3))$	DeRose and Seymour, 2010
D-1	$LAI=b_0+b_1 \ln SD+b_2 \ln SI$	Regression models developed in the present study
D-2	$LAI=b_0+b_1 SD+b_2 \ln SI + b_3 SD^2$	
D-3	$\ln LAI= b_0+b_1 \ln SD + b_2 \ln SI + b_3 SD^2$	
D-4	$LAI= b_0+b_1 \ln SD + b_2 \ln SI$	

*The 43 m value is the asymptotic maximum height for Anatolian black pine in the study area. *SD*: Stand density, *BA*: Stand basal area ($m^2 \cdot ha^{-1}$), *SI*: Site index (m), h_{100}: Dominant height (m), CL_m: Mean crown length (m), CD_m: Mean crown diameter (m), M_{cr}: Total crown biomass (ton ha^{-1}), *LAI*: Leaf area index.

where R_i is the relative rank of model i (i = 1, 2, ..., m), S_i is the goodness-of-fit statistic of the model i, S_{min} and S_{max} are the minimum and maximum values of S_i, respectively.

To check the validation of developed models, observed LAI values of 30 sample plots were compared with predicted values from models using Paired Samples *t*-Test. All statistical analyses were carried out with the IBM SPSS Statistics 23 software at the 0.05 significance level.

RESULTS AND DISCUSSION

According to the Kolmogorov-Smirnov test results, mean diameter and number of trees were not normally distributed (p<0.05), while LAI and the other stand characteristics were normally distributed (p>0.05). Therefore, Pearson correlation analysis was applied to detect relationships between LAI and normally distributed stand characteristics (stand density, stand basal area, stand age, site index, dominant height, total crown biomass, mean crown diameter, and mean crown length), while Spearman correlation analysis was used for LAI and non-normal stand characteristics (mean diameter and number of trees). The results of the correlation analyzes were given in Table 3. When Table 3 is examined, stand basal area, stand density, and total crown biomass demonstrated a positively high correlation with the LAI values. The dominant height, number of trees, mean diameter and site index values were also positively correlated with LAI (p<0.05). On the other hand, significant correlations were not observed between LAI and stand age, mean crown diameter and mean crown length values (p>0.05). The linear relationships between LAI and the other stand characteristics were illustrated in Figure 4.

Table 3. Correlation analysis results between LAI and stand characteristics.

Stand characteristics	Correlation Coefficient (r)	*p*
Mean diameter (cm)	0.185^{S}	0.044*
Stand age (year)	0.165^{P}	0.073^{ns}
Dominant height (m)	0.398^{P}	<0.001*
Site index (m)	0.265^{P}	0.004*
Number of trees per ha	0.334^{S}	<0.001*
Stand basal area ($m^2 \cdot ha^{-1}$)	0.684^{P}	<0.001*
Stand density	0.687^{P}	<0.001*
Total crown biomass ($ton \cdot ha^{-1}$)	0.684^{P}	<0.001*
Mean crown diameter (m)	0.169^{P}	0.066^{ns}
Mean crown length (m)	0.158^{P}	0.086^{ns}

^{P}: Pearson correlation coefficient, ^{S}: Spearman correlation coefficient, *: significant at the 0.05 level, ^{ns}: non-significant.

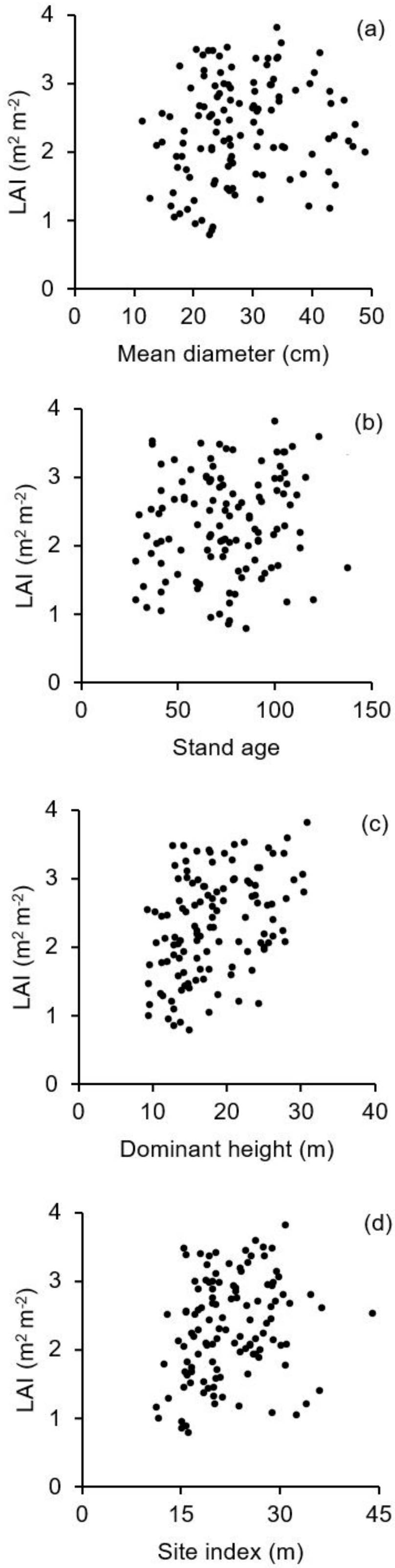

Figure 4. The relationships between LAI and stand characteristics, (a) mean diameter, (b) stand age, (c) dominant height, (d) stand age, (e) number of trees, (f) stand basal area, (g) stand density, (h) total crown biomass, (i) mean crown length, and (j) mean crown length.

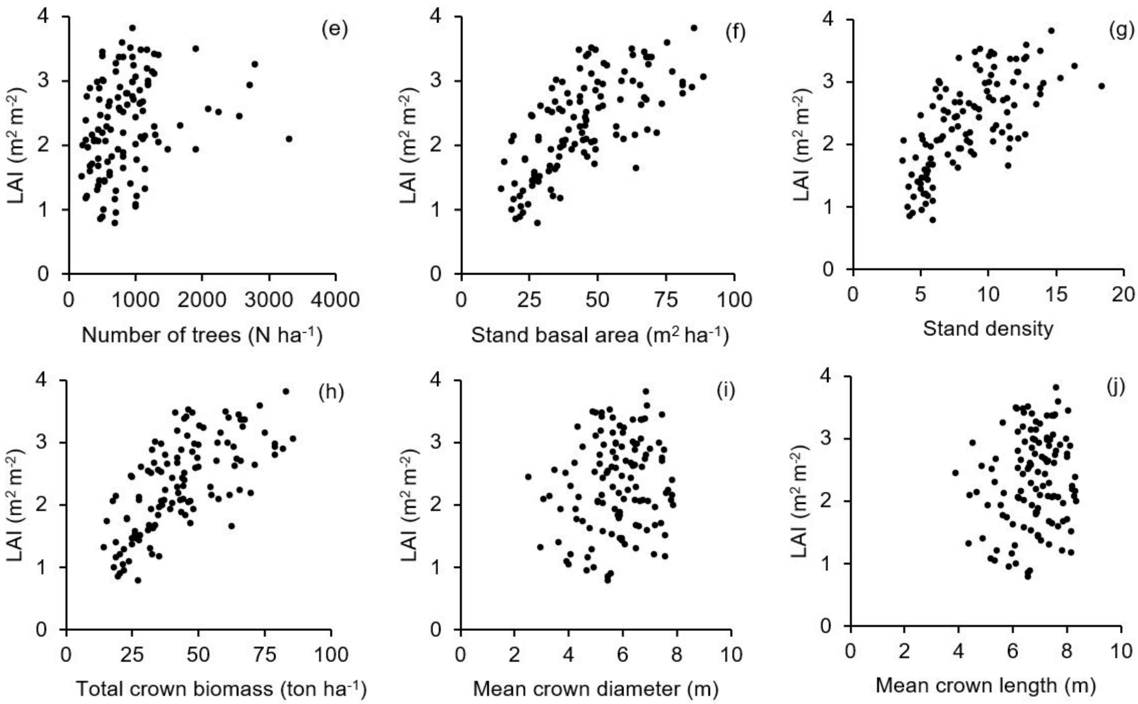

Figure 4 continuation. The relationships between LAI and stand characteristics, (a) mean diameter, (b) stand age, (c) dominant height, (d) stand age, (e) number of trees, (f) stand basal area, (g) stand density, (h) total crown biomass, (i) mean crown length, and (j) mean crown length.

According to the ANOVA results, conducted to detect the differences in LAI values for age, stand density and site classes, there were significant differences for stand density and site classes ($p<0.05$) while non-significant differences for age classes ($p>0.05$). For stand density and site classes, Duncan post-hoc test was used to determine homogenous groups. The results for stand density classes showed that each class was significantly different from the other classes, and LAI values increased depending on the increase in stand density. The LAI values of site classes formed two homogenous groups. Site class V was in the first group with 1.55 $m^2 \cdot m^{-2}$ mean LAI, while the other site classes were in the second group with larger means (Table 4).

Table 4. ANOVA results.

Stand characteristics	Homogeneity Test		Analysis of Variance		Groups	n	Mean LAI (m^2 m^{-2})	Homogeneous Groups[a]
	Levene	*p*	*F*	*p*				
Age classes	0.444	0.776	1.505	0.205[ns]	21-40	12	2.17	*a*
					41-60	21	2.24	*a*
					61-80	39	2.30	*a*
					81-100	24	2.22	*a*
					>100	23	2.65	*a*
Stand density classes	0.373	0.773	60.360	<0.001*	4.5	35	1.51	*a*
					7.5	35	2.39	*b*
					10.5	31	2.75	*c*
					13.5	18	3.06	*d*
Site classes	0.516	0.724	2.756	0.031*	I	15	2.44	*b*
					II	29	2.56	*b*
					III	33	2.37	*b*
					IV	37	2.17	*b*
					V	5	1.55	*a*

*Significant at the 0.05 level, [ns]Non-significant, [a]There is a significant difference at the 0.05 level between groups shown with different letters.

In this study, to use for LAI predictions, seven nonlinear equations from the literature and four study-specific linear models were fitted by regression analysis. When the parameter estimates and statistical criteria related to these equations were examined, multiple linear regression models ensured a better consequence based on the R_{adj}^2 than nonlinear models. The results of regression analyses were given in Table 5. There is a non-significant (p>0.05) parameter for DS-1 model, while all parameters of the other 10 models are significant. However, P-1 model showed worse fitting ability with lower R_{adj}^2 than the other models. LAI models with all parameters found as significant were ranked based on goodness-of-fit-statistics (Table 6). According to the relative ranking results, D-1 model was the most successful model.

The observed LAI values against LAI predictions by the most successful model (D-1) and the residual distribution of this model were given in Figure 5. As can be seen on the left graph, the differences between the observed and predicted LAI values have no significant tendency. When the residual distributions on the right graph are examined, D-1 model has small residuals for low and also high LAI predictions while the residuals are partially high for the LAI predictions around 2 $m^2 \cdot m^{-2}$.

Table 5. Goodness-of-fit statistics and parameter estimations of the LAI models.

Model	R^2_{adj}	*B*	*MAE*	*RMSE*	*AIC*	Parameter	Coefficient
LS-1	0.595	0.00	0.39	0.46	-63.05	b_0	0.6919**
						b_1	0.6525***
						b_2	-0.6511***
LS-2	0.595	0.00	0.39	0.46	-60.59	b_0	0.7051**
						b_1	0.6528***
						b_2	-0.6506***
P-1	0.443	0.00	0.45	0.54	-50.94	b_0	0.1892**
						b_1	0.4379***
P-2	0.536	0.00	0.41	0.49	-59.05	b_0	0.2370***
						b_1	0.5644***
DS-1	0.600	-0.04	0.38	0.47	-61.22	b_0	-0.6531*ns*
						b_1	0.7589***
						b_2	-0.7249***
DS-2	0.599	-0.04	0.38	0.47	-61.10	b_0	-1.1996***
						b_1	0.7596***
						b_2	-0.4817***
DS-3	0.620	0.00	0.36	0.45	-63.88	b_0	0.0475*
						b_1	0.5859***
						b_2	0.3448**
						b_3	1.6271***
D-1	0.631	0.00	0.36	0.44	-67.25	b_0	-2.2948***
						b_1	1.3105***
						b_2	0.6188**
D-2	0.630	0.00	0.35	0.44	-65.09	b_0	-1.9037**
						b_1	0.3955***
						b_2	0.6365**
						b_3	-0.0134*
D-3	0.635	-0.05	0.35	0.45	-63.38	b_0	-2.1683***
						b_1	0.9977***
						b_2	0.3587**
						b_3	-0.0027*
D-4	0.596	0.04	0.37	0.45	-65.66	b_0	-13.4404***
						b_1	6.0173***
						b_2	2.2401*

Significant at *** 0.001 level, ** 0.01 level, * 0.05 level, ^{ns} Non-significant.

Table 6. Relative ranks of the LAI models.

Model	R_i (R^2_{adj})	R_i (*B*)	R_i (*MAE*)	R_i (*RMSE*)	R_i (*AIC*)	Total R_i	Overall Rank
LS-1	2.88	1.00	4.60	2.80	3.32	14.59	3.19
LS-2	2.88	1.00	4.60	2.80	4,68	15.95	3.54
P-1	10.00	1.00	10.00	10.00	10.00	41.00	10.00
P-2	5.64	1.00	6.40	5.50	5.48	24.02	5.62
DS-2	2.69	8.20	3.70	3.70	4.39	22.68	5.28
DS-3	1.70	1.00	1.90	1.90	2.86	9.36	1.84
D-1	1.19	1.00	1.90	1.00	1.00	6.09	1.00
D-2	1.23	1.00	1.00	1.00	2.19	6.43	1.09
D-3	1.00	10.00	1.00	1.90	3.14	17.04	3.82
D-4	2.83	8.20	2.80	1.90	1.88	17.61	3.97

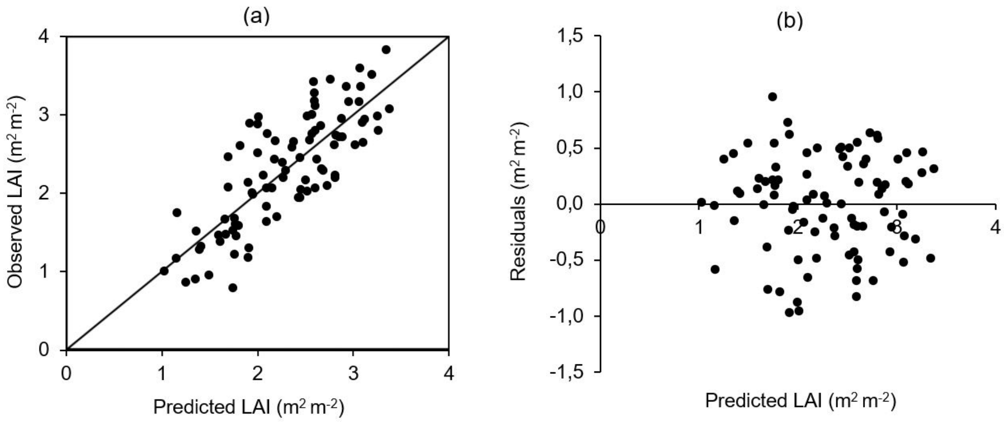

Figure 5. Observed vs. predicted LAIs (a) and residual distribution (b) of the best model.

The validity of the D-1 model was tested with Paired Samples *t*-Test using an independent dataset obtained from 30 sample plots. According to the test results, there were non-significant differences between observed and predicted values ($p>0.05$). Therefore, it was decided that the D-1 model could be used for LAI estimations in the study area.

LAI is a stand parameter that changes depending on both site and stand characteristics. In the literature, its ranges for Anatolian black pine stands are 0.61-5.57 $m^2 \cdot m^{-2}$ (Özbayram et al., 2015) and 0.49-2.92 $m^2 \cdot m^{-2}$ (Ercanlı et al., 2018) for Denizli and Çankırı regions of Türkiye, respectively. LAI values of the present study for Kastamonu region (from 0.79 to 3.83 $m^2 \cdot m^{-2}$) are similar to previous studies.

It was determined that there was a strong correlation between LAI and stand density (Jack and Long, 1991; Ercanlı et al., 2018), and a moderate correlation between LAI and site index (DeRose and Seymour, 2010; Özbayram et al., 2015). Similar results were also obtained in our study. Hence, the most successful model to predict LAI for the study area contained stand density and site index. Both stand density and site index as independent variables has positive coefficients. This means that as stand frequency or site index increases, LAI also increases. Although silvicultural interventions to the stands will decrease LAI momentarily, LAI will increase in parallel with the increase in the growing stock of the stand with the effect of the interventions.

CONCLUSION

In this study, the relationships between LAI values provided from LAI-2200C instrument and some stand characteristics (mean diameter, stand age, dominant height, site index, number of trees, stand basal area, stand density, total crown biomass and crown dimensions) were determined for pure Anatolian black pine stands in Kastamonu region, Türkiye. Among 11 regression models, D-1 model fitted by multiple linear regression was the most successful for LAI estimations for the study area. In this model, stand density and site index are independent variables. With the help of the equation below, LAI, which is difficult to measure directly in practice, could be estimated using stand characteristics.

$$LAI = -2.2948 + 1.3105 \ln SD + 0.6188 \ln SI$$

The researches on alternative methods for LAI estimations of main forest types as well as Anatolian black pine stands have great importance. Besides, investigating the relationships between LAI and other stand or site characteristics is quite valuable for projections on sustainable forest management. Therefore, research on these issues should be continued.

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AUTHORSHIP CONTRIBUTION

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