



Estimation of Crown Closure and Tree Density Using Landsat TM Satellite Images in Mixed Forest Stands

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Abstract The objective of this study was to investigate the relationship between crown closure and tree density in mixed forest stands using Landsat Thematic Mapper (TM) reflectance values (TM 1- TM 5 and TM 7) and six vegetation indices (SR, DVI, SAVI, NDVI, TVI and NLI). In this study, multiple regression analysis was used to estimate the relationships between the crown closure and tree density (number of tree stems per hectare) using reflectance values and vegetation indices (VIs). The results demonstrated that the model that used SR and DVI had the best performances in terms of crown closure ($R^2=0.674$) and the model that used the DVI and SAVI had the best performances in terms of tree density ($R^2=0.702$). The regression model that used TM 1, TM 3 together with TM 4 showed the performances of the crown closure ($R^2=0.610$) and the regression model that used TM 1 showed the performances of the tree density (0.613). Results obtained from this research show that vegetation indices (VIs) were a better predictor of crown closure and tree density than other TM bands.

Keywords Crown closure · Tree density · Landsat TM · Mixed forest

Introduction

In Turkey, forest stands are classified by differences in species composition, crown closure and development stages. Crown closure is defined as the percentage of forest canopy projected on a horizontal plane over a unit ground area, and it becomes a very important parameter in developing forest, ecological, hydrological and climate models (Xu et al. 2003). Nevertheless, its measurement in the field is hard, time consuming and expensive (Xu et al. 2003; Pu et al. 2003). Thus, other methods of estimating forest characteristics for larger areas such as remote sensing are often used. Remote sensing data is an alternative way of taking field measurements in accurate crown closure estimation because it is considered a low-cost and large-area coverage forest information resource (Franklin et al. 2003). In other similar studies on this topic, Butera (1986) confirmed the relationship between the crown closure and the simulated Thematic Mapper (TM) spectral bands in Colorado, USA and the TM data bands predicted forest crown closure with 57–74 % accuracy. Peterson et al. (1987) analyzed the forest structure in Sequoia National Park (California, USA) using simulated TM data. Statistically significant relationships were found between the TM reflectance values and stand parameters such as crown closure and basal area. Pereira et al. (1995) used Landsat TM imagery and ground measurements to determine biomass, percent canopy cover and canopy volume in Mediterranean shrublands; the greatest results were obtained with the Normalized Difference Vegetation Index (NDVI) to estimate percent canopy cover ($R^2=0.65$). Calvão and Palmeirim (2004) collected field data on Mediterranean shrublands and developed correlations between several parameters and spectral variables (single channel reflectance value and NDVI) from Landsat TM data; the highest correlation for

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canopy cover was obtained with TM 3 ($r=-0.91$) and NDVI ($r=0.91$). Sivanpillai et al. (2006) evaluated the relationship between Landsat ETM+reflectance values and the stand characteristics of commercially managed loblolly pine (*Pinus taeda* L.) in east Texas. The models for stand age and tree density respectively were obtained with an adjusted R^2 (78 % and 60 %). Mohammadi et al. (2010) modeled forest stand volume and tree density using Landsat ETM+data in the Hyrcanian forests, northern Iran. The models for stand volume and tree density respectively were obtained with an adjusted R^2 (43 % and 73.4 %). The aim of this study was to investigate the relationship between spectral reflectance values and VIs calculated by Landsat TM sensor to estimate crown closure and tree density in the mixed forest areas.

Materials and Methods

Study Area and Data

The study area covers the provinces of Almus, Niksar, Erbaa, Bafra, Vezirköprü, Merzifon, Kargı, Boyabat, Arac, Samatlar, Ilgaz, Dirgine, Karabük and Mengen in the Black Sea Region, in the north of Turkey. This study area ranges in latitude (North) from 40°15'28" to 41°46'15" and in longitude (East) from 32°28'02" to 37°32'56" (Fig. 1). These sampled mixed stands were naturally regenerated and uniformly stocked stands (55–97 % tree layer cover), without any evidence of historical damage such as fire or storms. Located between 750 m and 1750 m altitude, the study area is characterized geomorphologically by high mountainous land, with moderate to steep slopes ranging between 5 % and 60 % (30 % of the whole area). The mean annual temperature is between -5.8 °C and 14.6 °C, and minimum and maximum temperatures are -8.4 °C and 22.67 °C, respectively. The climatic regime is of typical Black Sea climate characterized by a mild winter, a cool summer and relatively homogeneous precipitation as high as 1000 and 1250 mm.

In this study, the data were obtained from 156 temporary sample plots with ranging stand age, site index, density and mixture percentage in mixed stands Scots pine (*Pinus sylvestris* L.) and Oriental beech (*Fagus orientalis* Lipsky). The size of circular plots ranged from 600 to 1200 m², depending on stand density, to accomplish a minimum of 50–60 trees per plot. The diameters at breast height, total height, age, crown height, crown diameter, and spatial coordinate were measured in each tree of sample plots. In each plot altitude, aspect and slope were also measured. The spatial coordinates were measured in all trees (alive and dead). Diameter at breast height (dbh) was measured to the nearest 0.1 cm with calipers for every living tree with dbh > 8.0 cm. Tree height and crown height were measured to the nearest 0.1 m by digital

hypsoneter in a randomized sub-sample of 30–40 trees representing various dbh classes in the sample plots. Crown diameter was measured to the nearest 0.1 cm by tape meter in a randomized sub-sample of 30–40 trees representing various dbh classes in the sample plots.

The tree density per hectare was obtained by multiplying the tree number per plot by the hectare conversion coefficient. Crown area and stand canopy were calculated. Also, two different Landsat TM satellite images were used in this study. The Landsat TM was acquired on 24th October 2005 and 21st July 2006.

Digital Processing of Landsat TM

Data processing, interpreting and analysis were performed using Erdas Imagine 9.1TM image processing software (Erdas 2002). The Landsat TM satellite image was orthorectified and its accuracy was checked using Global Position System (GPS) data collected from the study area. A subset of Landsat TM was rectified using 1/25,000 scale topographical maps with UTM projection (ED 50 DATUM, Zone 36) using first order nearest neighbor rules. In total 40 ground points were used to register the TM image subset with a rectification error less than 1 pixel image. Solar zenith angle and atmosphere influence the spectral value of a satellite image. Thus, radiometric correction must be done to convert the digital number to the reflectance value. In the process of radiometric correction, the digital number of Landsat TM must be converted to the radiance value, and then to reflectance. The information for the radiometric correction (solar zenith angle, acquisition date, and so on) can be obtained from Landsat TM ancillary data.

Determining Crown Canopy Ratio

To determine the crown canopy ratio of each sample plot, firstly the center coordinates of each sample plot was entered into an Excel file and that file was added to a GIS (Geographic Information System) environment and converted to a point layer file using Arc GIS 10.0TM functions. Then, a buffer layer including all plots was created according to sample plot size ranges from 600 to 1200 m². After that, all tree x, y coordinates were also entered into an Excel file and buffers were created using crown diameters for each tree using the same method explained above (Fig. 2).

Finally, the two layers, the sample plot area layer and the tree area layer, were intersected using GIS analysis tools to obtain a sample plot crown closure (Fig. 3). Subsequently, crown canopy and crown canopy ratio values were calculated using GIS area calculation procedures using “statistics” and “field calculator” commands.

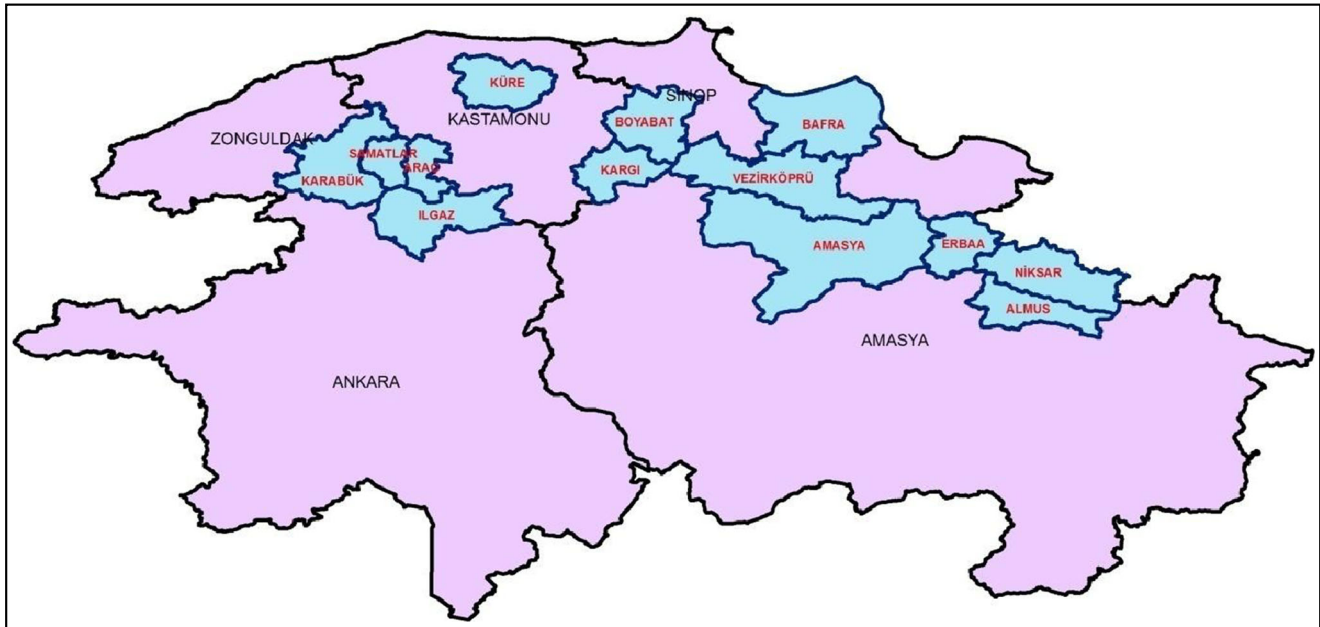


Fig. 1 Map showing the locations of the mixed Scots pine-Oriental beech studied in northern of Turkey

Calculating Vegetation Indices

In this study, Landsat TM satellite images were used to produce six VIs such as SR, DVI, SAVI, NDVI, TVI and NLI. The VIs formulas and references for these indices are shown in Table 1.

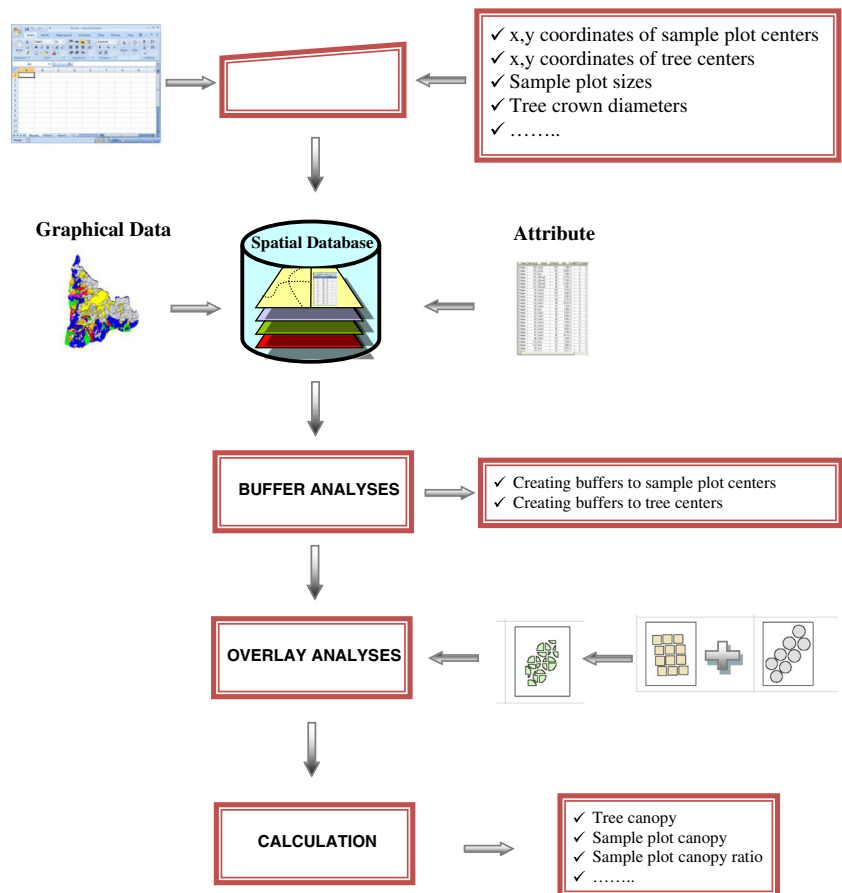
SR, Simple Ratio; DVI, Difference Vegetation Index; SAVI, Soil Adjusted Vegetation Index; NDVI, Normalized Difference Vegetation Index; TVI, Transformed Vegetation Index; NLI, Nonlinear Vegetation Index; VIS, Visible wavelengths (TM1, TM2, TM3); NIR, near infrared wavelengths (TM4), MID, middle infrared wavelengths (TM 5, TM 7). L is equal to 0.5 in this study.

Statistical Analysis

The digital number of pixels within a 3×3 pixel window was extracted from all Landsat TM bands and VIs. To examine and model the relationships between remote sensing data based on the spectral reflectance values, TM 1–5 and 7, and six VIs, and stand parameters, e.g., tree density and crown closure, the

correlation analysis and multiple linear regression analysis were used in the studied species and stands. These multiple regression models were developed to estimate the models for crown closure and tree density using remote sensing data, reflectance values and VIs, their combination as an independent variable and which dependent variables were stand attributes, e.g. tree density and crown closure. Also, the regression models were developed to estimate the stand parameters as a function of the suite of remote sensing data variables gathered in the studied forest site. Multiple linear regression technique was used to model the variation in some stand parameters based on a stepwise variable selection method. In a stepwise variable selection method, the process starts out just as in forwards selection, but at each step a variable that is already in the model is first evaluated for removal, and if any are eligible for removal, the one whose removal would least lower the R^2 is removed. The multiple stepwise regressions and partial correlation analysis were performed using SPSS version 15.0 (SPSS Institute Inc. 2007). The stepwise regression technique was used to select the best site variables that are

Fig. 2 General framework of sample plot crown closure ratio calculation



significant ($p < 0.05$) with the determination of the highest value of the coefficient adjusted by the number of parameters (R_{adj}^2), also called adjusted by the coefficient of determination. In this study, the following linear relationship was assumed:

$$SP = \beta_0 + \beta_1 \cdot X_1 + \beta_2 \cdot X_2 + \dots + \beta_n \cdot X_n + \varepsilon \quad (1)$$

where SP is the forest stand parameter, e.g. tree density and crown closure, $X_1 \dots X_n$ are variable vectors corresponding to remote sensing data, e.g. the reflectance values, TM 1–5 and TM 7, and 6 VIs variables, $\beta_1 \dots \beta_n$ represent model coefficients and ε is the additive error term (Corona et al. 1998; Fontes et al. 2003).

To compare the predictive power of the spectral reflectance values, e.g. TM 1–5 and 7, and VIs, separate regression analysis was performed using relevant remote sensing data. Hence, four regression models were developed (two forest stand parameters and two remote sensing data selection models, e.g. band reflectance values and VIs). For example; there was a model predicting tree density using the spectral band reflectance values, another model using VIs and predicting tree density by using the band reflectance values and another model using VIs. In each sub-group, the related forest stand parameters were predicted using the spectral reflectance values, e.g. TM 1–5 and 7, and VIs.

The estimate of each parameter for the variables of these regression models should be statistically significant at a 95 % probability level. The null hypothesis $H_0 = \beta_0 = \beta_1 = \dots = \beta_n = 0$ was tested and parameters that were not significantly different from zero were rejected (Fontes et al. 2003).

The regression models were evaluated based on the accuracy statistics. The accuracy statistics covered the absolute and relative biases and the root mean square error (RMSE and RMSE %). These statistics were calculated for the models as follows:

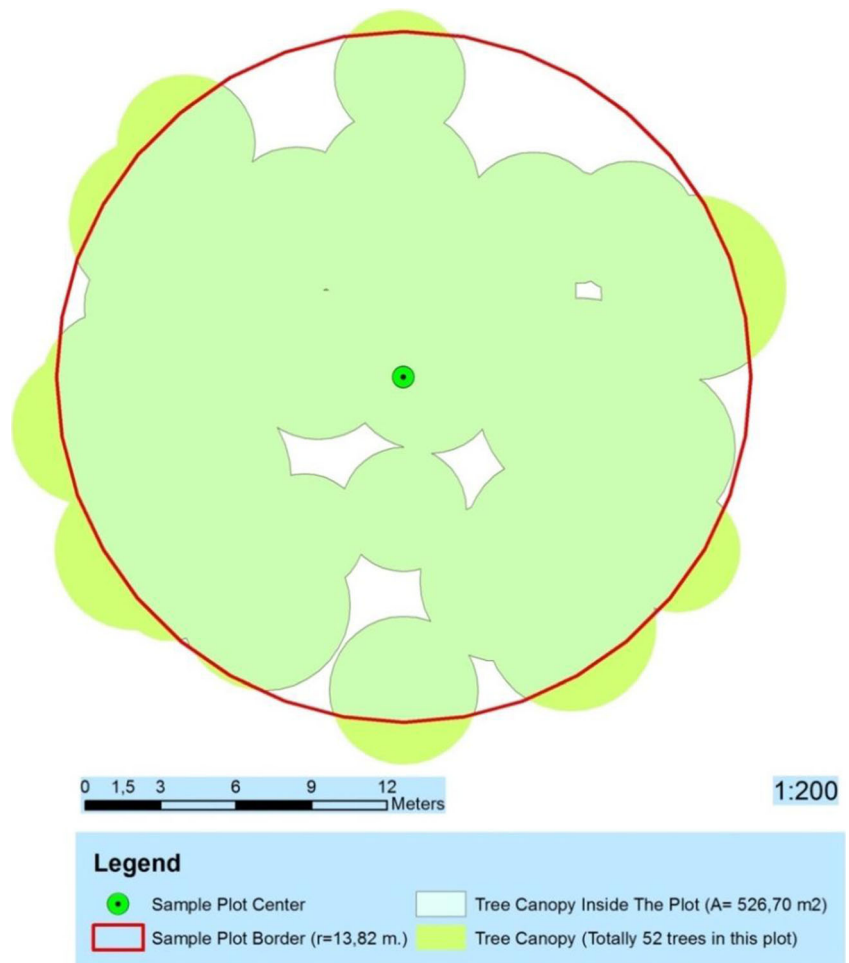
$$bias = \frac{\sum (y_i - \hat{y}_i)}{n} \quad (2)$$

$$bias\% = 100 \frac{\sum (y_i - \hat{y}_i) / n}{\sum \hat{y}_i / n} \quad (3)$$

$$RMSE = \sqrt{\frac{\sum (y_i - \hat{y}_i)^2}{n-1}} \quad (4)$$

$$RMSE\% = 100 \frac{\sqrt{\sum (y_i - \hat{y}_i)^2 / (n-1)}}{\sum \hat{y}_i / n} \quad (5)$$

Fig. 3 Calculation of a sample plot crown closure



Where n is the number of observations, and y_i and \hat{y}_i are the observed and predicted values of stand parameters e.g. tree density and crown closure from the developed models.

Descriptive statistics including mean, minimum, maximum, standard deviation and the coefficient of variation of the plot characteristics, reflectance values and VIs are listed below (Table 2).

Table 1 Definition of vegetation indices used in the study area

Vegetation indices	Formula	Reference
SR	$(TM4)/(TM3)$	Jordan (1969)
DVI	$(TM4)-(TM3)$	Clevers (1988)
SAVI	$(TM4-TM3) * (1+L) / (TM4 + TM3 + L)$	Huete (1988)
NDVI	$(TM4-TM3) / (TM4+TM3)$	Rouse et al. (1974)
TVI	$((TM4-TM3) / (TM4+TM3)) + 0.5$	Deering et al. (1975)
NLI	$((TM4)^2 - TM3) / ((TM4)^2 + TM3)$	Gong et al. (2003)

Results and Discussion

Relationships Between Crown Closure, Tree Density, Reflectance Values and Vegetation Indices

Table 3 shows the Pearson correlations between the crown closure, tree density, reflectance values (TM 1–5 and TM 7) and VIs (SR, DVI, SAVI, NDVI, TVI and NLI) representing the ecological variation in the study area. Not all VIs and reflectance values were significantly related to the crown closure and tree density. TM 1, TM 2, TM 5 and SR were significantly correlated with stand crown closure at a 95 % probability level. In addition, all spectral bands and VIs (except for DVI and NLI) were significantly correlated with stand tree density at a 95 % probability level. The independent variables TM 1 and TM 2 and TM 5 were positively correlated with the dependent variable stand crown closure, whereas the other variable SR was negatively correlated. Moreover, the predictor variables spectral reflectance values TM 1–5 and TM 7 were positively correlated with the dependent variable stand tree density,

Table 2 Summary statistics for sample data in the study area

Variables	Minimum	Maximum	Mean	Std. Deviation	Coeffication of variation
Crown closure	0.55	0.97	0.82	0.08	9.69
Tree density	180.00	1520.00	660.24	239.33	36.25
TM 1	29.00	98.00	46.37	20.58	44.38
TM 2	20.00	99.00	36.92	18.97	51.39
TM 3	16.00	126.00	35.13	22.48	63.97
TM 4	29.00	135.00	64.90	19.28	29.72
TM 5	12.00	169.00	51.83	38.25	73.80
TM 7	9.00	109.00	30.89	24.42	79.04
NDVI	-0.17	0.58	0.34	0.17	50.57
SR	0.71	3.72	2.17	0.67	30.92
DVI	-33.00	76.00	29.76	19.30	64.85
TVI	0.33	1.08	0.84	0.17	20.31
NLI	0.96	0.99	0.98	0.01	0.75
SAVI	-0.26	0.85	0.49	0.25	50.64

whereas the other variables vegetation indices NDVI, SR, TVI and SAVI were negatively correlated. The stand crown closure showed a moderate correlation with TM 1 ($r=0.34$) and SR ($r=-0.31$). Furthermore, stand tree density showed a moderate correlation with TM 2 ($r=0.47$), TM 2 ($r=0.49$), TM 2 ($r=0.47$), TM 3 ($r=0.42$), TM 4 ($r=0.40$), NDVI ($r=0.36$), TVI ($r=0.36$) and SAVI 2 ($r=0.36$).

Estimating Tree Density and Crown Closure Using Landsat TM

A linear combination of VIs (DVI and SAVI) was a better estimation of tree density ($R^2=0.702$) than other VIs and band

reflectance values. An inverse relationship was observed between DVI and SAVI, whereas a direct relationship was observed between TM 1 and tree density. Linear combinations of VIs (SR and DVI) were better predictors of crown closure than other VIs and band reflectance values. Inverse relationships were observed between SR and DVI, and TM 1 with TM 3 and TM 4 (Tables 4 and 5).

A linear combination of SAVI and DVI explained more variance in tree density than other combinations of bands and VIs. There was a significant relationship at the 95 % probability level, normality of the residuals, 70.2 % adjusted R^2 , and RMSE of 83.208 n ha^{-1} . Tree density values compared favorably to RMSE and R^2 values obtained by Sivanpillai et al.

Table 3 Pearson correlations between crown closure, tree density, reflectance values and vegetation indices

Variable	Crown closure	Tree density	TM 1	TM 2	TM 3	TM 4	TM 5	TM 7	NDVI	SR	DVI	TVI	NLI	SAVI
Crown closure	1.00													
Tree density	0.54**	1.00												
TM 1	0.34**	0.49**	1.00											
TM 2	0.19*	0.47**	0.98**	1.00										
TM 3	0.11	0.42**	0.91**	0.96**	1.00									
TM 4	0.12	0.40**	0.73**	0.71**	0.58**	1.00								
TM 5	0.17*	0.46**	0.96**	0.98**	0.93**	0.77**	1.00							
TM 7	0.14	0.44**	0.93**	0.97**	0.97**	0.65**	0.98**	1.00						
NDVI	-0.15	-0.36**	-0.72**	-0.76**	-0.87**	-0.16*	-0.72**	-0.82**	1.00					
SR	-0.31**	-0.34**	-0.65**	-0.69**	-0.77**	-0.08	-0.64**	-0.73**	0.97**	1.00				
DVI	-0.02	-0.15	-0.33**	-0.40**	-0.58**	0.32**	-0.32**	-0.48**	0.85**	0.81**	1.00			
TVI	-0.15	-0.36**	-0.72**	-0.76**	-0.87**	-0.16**	-0.72**	-0.82**	0.99**	0.97**	0.85**	1.00		
NLI	-0.10	-0.12	-0.21**	-0.25**	-0.39**	0.44**	-0.17*	-0.31**	0.77**	0.79**	0.89**	0.77**	1.00	
SAVI	-0.15	-0.36**	-0.72**	-0.77**	-0.86**	-0.15	-0.71**	-0.82**	0.99**	0.97**	0.86**	0.99**	0.77**	1.00

Only significant correlations ($p<0.05$) are listed: ** $p<0.01$, * $p<0.05$, the other ns

Table 4 Parameters of the ‘best fit’ regression models of stand attributes based on the spectral reflectance values, TM 1–5 and TM 7

Model description			Coefficients of independent variables	Standard error of variables	<i>t</i> statistics	<i>p</i> -value	VIF
Model group	Dependent variables	Independent variables					
Stand crown closure	CC	Constant	0.7862	0.0104	75.862	0.000	
		TM 1	0.0042	0.0004	10.685	0.000	7.993
		TM 3	−0.0024	0.0003	−8.287	0.000	5.607
		TM 4	−0.0011	0.0002	−5.077	0.000	2.338
$R_a^2=0.610$	$S_{y.x}=0.027$	D. W.=2.21	Bias=−2.263e−17	Bias%=−3.336e−17	RMSE=0.026	RMSE%=0.031	
Stand tree density	N	Constant	343.5067	24.6114	13.957	0.000	
		TM 1	6.2050	0.4747	13.070	0.000	1.000
		D. W.=1.49	Bias=−3.180e−13	Bias%=−4.982e−16	RMSE=102.079	RMSE%=0.160	

R_a^2 adjusted coefficient of determination, *S.E.* standard error, *D. W.* Durbin-Watson value, *t statistics* is probability values, *RMSE* the root mean square error

(2006) (RMSE=312.5 n ha^{−1}; R²=60.4 %) and Freitas et al. (2005) (R²=66.6 %). The R² value obtained from this study was lower than the one that was obtained through direct estimation to predict tree density (R²=0.73, Mohammadi et al. 2010). In addition, the regression model with ETM4 and ETM5 as independent variables could predict tree density (R²=73.4 %; RMSE=170.13 ha^{−1}) better compared with other combinations of ETM+bands and vegetation indices. In this study, the regression model with only TM 1 as an independent variable could estimate tree density (R²=61.3 %; RMSE=102.08 n ha^{−1}) and the other TM bands did not show relationships.

A linear combination of SR and DVI explained more variance in crown closure than other combinations of original bands and VIs. There was a significant relationship at the 95 % probability level, normality of the residuals, 67.4 % adjusted R², and RMSE of 0.02103. Falkowski et al. (2005)

compared the regression models for each response variable (crown closure). Red and green band reflectance values had a strong relationship to crown closure with scores of (R²=0.71) and (R²=0.75), respectively. The relationship between NIR band reflectance values and crown closure was poor (R²=0.08). In the same study, the model including both the NDVI and GRVI vegetation indices as predictors of crown closure obtained the highest relationship (R²=0.77). Xu et al. (2003) found that the regression model with TM 4, TM3 and TM2 as independent variables could better predict stand crown closure (R²=0.802). Berberoglu et al. (2009) found that Envisat MERIS data (as 13 independent waveband variables) can be used to predicted crown closure (R²=0.433) with considerable spatial detail. Franklin et al. (2003) found that for jack pine, the relationship was positive and its value was moderate to strong (significant R ranged from 0.40 to 0.81). For white spruce, the relationship was negative and weak to moderate

Table 5 Parameters of the ‘best fit’ regression models of stand attributes based on vegetation indices

Model description			Coefficients of independent variables	Standard error of variables	<i>t</i> statistics	<i>p</i> -value	VIF
Model group	Dependent variables	Independent variables					
Stand crown closure	CC	Constant	0.9257	0.0097	95.086	0.000	
		SR	−0.0723	0.0065	−11.107	0.000	3.172
		DVI	0.0018	0.0002	7.961	0.000	3.172
		D. W.=2.024	Bias=−6.824e−17	Bias%=−8.303e−17	RMSE=0.02103	RMSE%=0.0258	
$R_a^2=0.674$	$S_{y.x}=0.021$						
Stand tree density	N	Constant	861.2667	19.0630	45.180	0.000	
		DVI	7.0350	0.9353	7.521	0.000	4.278
		SAVI	−853.2695	69.5029	−12.277	0.000	4.278
		D. W.=1.794	Bias=−1.164e−13	Bias%=−1.794e−16	RMSE=83.208	RMSE%=0.128	
$R_a^2=0.702$	$S_{y.x}=84.24$						

R_a^2 adjusted coefficient of determination, *S.E.* standard error, *D. W.* Durbin-Watson value, *t statistics* is probability values, *RMSE* the root mean square error

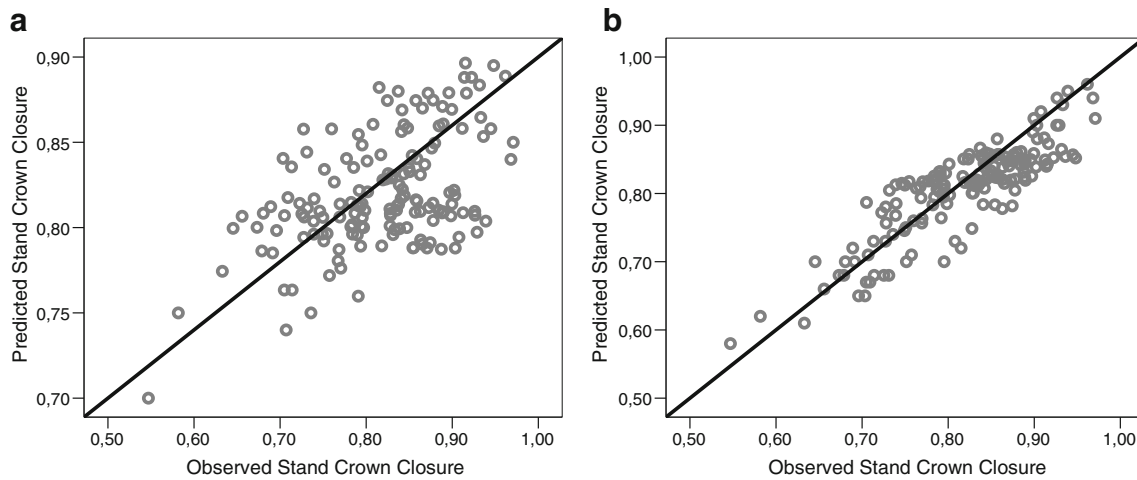


Fig. 4 Comparison between observed and predicted stand crown closure by regression models based on the spectral reflectance values, TM 1–5 and TM 7 (a) and VIs (b)

(significant R ranged from -0.20 to -0.57). In this study, the regression model with TM 1, TM 3 and together with the TM 4 as independent variables could estimate tree density ($R^2=61.0\%$; $RMSE=0.02604\%$) and the other TM bands did not show relationships. Stand crown closure and stand tree density estimations by both Landsat TM reflectance values and VIs using the models are plotted against these observed forest variable values (Figs. 4 and 5).

Conclusions

In this study, the relationship between reflectance values and some VIs obtained from Landsat TM recorded with tree density and crown closure were analyzed through

multiple linear regression analysis in mixed forest stands. Statistically significant relationships were found between corresponding reflectance values and VIs recorded by the TM satellite image with tree density and crown closure. A linear combination of SAVI and DVI explained more variance in tree density than other combinations of bands and VIs. The model for tree density resulted in adjusted $R^2=70.2\%$; $RMSE=83.208\text{ n ha}^{-1}$. Similarly, a linear combination of SR and DVI explained more variance in crown closure than other combinations of bands and VIs. The model for crown closure resulted in adjusted $R^2=67.4\%$; $RMSE=0.02103\%$. Based on the results of this study, the Landsat TM satellite image data are useful to estimate tree density and crown closure in mixed forest stands.

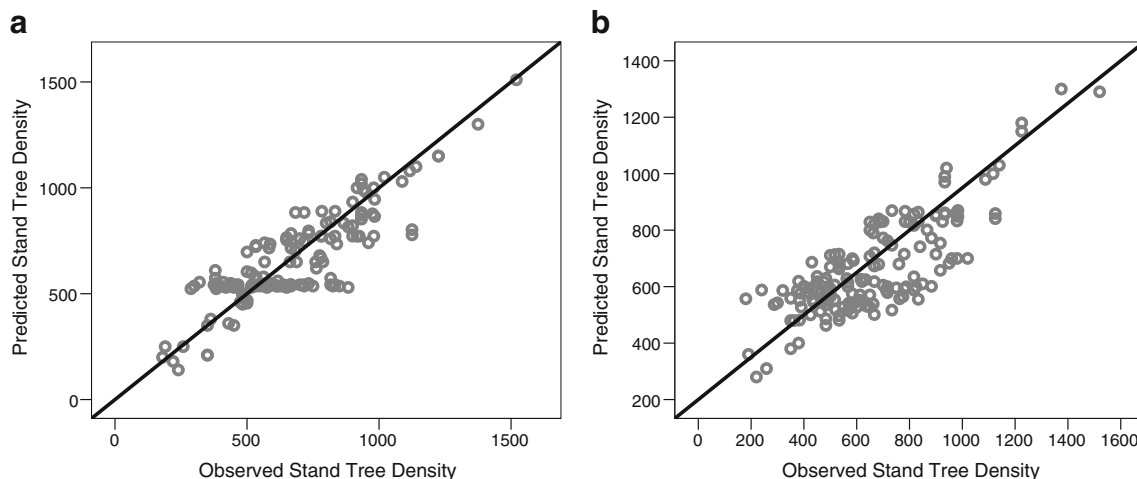


Fig. 5 Comparison between observed and predicted stand tree density by regression models based on the spectral reflectance values, TM 1–5 and TM 7 (a) and VIs (b)

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References

- Berberoglu, S., Satir, O., & Atkinson, P. M. (2009). Mapping percentage tree cover from Envisat MERIS data using linear and nonlinear techniques. *International Journal of Remote Sensing*, 30, 4747–4766.
- Butera, M. K. (1986). A correlation and regression analysis of percent canopy closure versus TMS spectral response for selected forest sites in the San Juan National Forest, Colorado. *IEEE Transactions on Geoscience and Remote Sensing*, 24(1), 122–129.
- Calvão, T., & Palmeirim, J. M. (2004). Mapping Mediterranean scrub with satellite imagery: biomass estimation and spectral behaviour. *Int. J. Remote Sens.*, 25(16), 3113–3126.
- Clevers, J. G. P. W. (1988). The derivation of a simplified reflectance model for the estimation of leaf area index. *Remote Sensing of Environment*, 25, 53–70.
- Corona, P., Scotti, R., & Tarchiani, N. (1998). Relationship between environmental factors and site index in Douglas-fir plantations in central Italy. *Forest Ecology and Management*, 101, 195–207.
- Deering, D. W., Rouse, J. J. W., Haas, R. H., & Schell, J. S. (1975). *Measuring forage production of grazing units from Landsat MSS data*, Proceedings 10th International Symposium Remote Sensing Environment (pp. 1169–1178). Ann Arbor, Michigan: Environmental Research Institute of Michigan.
- Erdas. (2002). *Erdas Field Guide Sixth edition*. Atlanta, Georgia: Erdas LLC.
- Falkowski, M. J., Gessler, P. E., Morgan, P., Hudak, A. T., & Smith, A. M. S. (2005). Characterizing and mapping forest fire fuels using ASTER imagery and gradient modeling. *Forest Ecology and Management*, 217, 129–146.
- Fontes, L., Margarida, T., Thompson, F., Yeomans, A., Luis, J. S., & Savill, P. (2003). Modelling the Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) site index from site factors in Portugal. *Forestry*, 76, 491–507.
- Franklin, S. E., Hall, R. J., Smith, L., & Gerylo, G. R. (2003). Discrimination of conifer height, age and crown closure classes using Landsat-5 TM imagery in the Canadian Northwest Territories. *International Journal of Remote Sensing*, 24, 1823–1834.
- Freitas, S. R., Mello, M. C. S., & Cruz, C. B. M. (2005). Relationships between forest structure and vegetation indices in Atlantic Rainforest. *Forest Ecology and Management*, 218, 353–362.
- Gong, P., Pu, R., Biging, G. S., & Larrieu, M. R. (2003). Estimation of forest leaf area index using vegetation indices derived from hyperion hyperspectral data. *IEEE Transaction on Geoscience and Remote Sensing*, 41, 1355–1363.
- Huete, A. R. (1988). A soil adjusted vegetation index (SAVI). *Remote Sensing of Environment*, 25, 295–309.
- Jordan, C. F. (1969). Derivation of leaf area index from quality of light on the forest floor. *Ecology*, 50, 663–666.
- Mohammadi, J., Joibary, S. S., Yaghmaee, F., & Mahiny, A. S. (2010). Modelling forest stand volume and tree density using Landsat ETM+ data. *International Journal of Remote Sensing*, 31(11), 2959–2975.
- Pereira, J. M. C., Oliveira, T. M., & Paul, J. C. P. (1995). Satellite-based estimation of Mediterranean shrubland structural parameters. *EARSeL Advanced Remote Sensing*, 4(3), 14–20.
- Peterson, D. L., Spanner, M. A., Running, S. W., & Teuber, K. B. (1987). Relationship of thematic mapper simulator data to leaf area index of temperate coniferous forests. *Remote Sens. Environ.*, 22, 323–341.
- Pu, R., Xu, B., & Gong, P. (2003). Oakwood crown closure estimation by unmixing Landsat TM data. *International Journal of Remote Sensing*, 24, 4433–4445.
- Rouse, J. W., Haas, R. H., Deering, D. W., Schell, J. A., & Harlan, J. C. (1974). *Monitoring the vernal advancement and retrogradation (green wave effect) of natural vegetation*. Greenbelt, MD: NASA/GSFC Type III, Final Report.
- Sivanpillai, R., Smith, C. T., Srinivasan, R., Messina, M. G., & Benwu, X. (2006). Estimation of managed loblolly pine stands age and density with Landsat ETM data. *Forest Ecology and Management*, 223, 247–254.
- SPSS Institute Inc. (2007) SPSS Base 15.0 user's guide, SPSS Programming and Data Management, 4th Edition A Guide for SPSS and SAS Users, USA, 522p
- Xu, B., Gong, P., & Pu, R. (2003). Crown closure estimation of oak savannah in a dry season with Landsat TM imagery: comparison of various indices through correlation analysis. *International Journal of Remote Sensing*, 24, 1811–1822.