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Modeling forest stand attributes using Landsat ETM+ and QuickBird satellite images in western Turkey

Modelado de atributos de rodales forestales utilizando imágenes de satélite Landsat ETM+ y QuickBird en el oeste de Turquía

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SUMMARY

This study assessed the suitability of Landsat ETM+ and QuickBird digital number values and various vegetation indices for predicting some structural parameters of forests in western Turkey. The empirical relationships between the structural parameters such as stand volume, basal area, tree density and quadratic mean diameter, and Landsat ETM+ and QuickBird satellite images were estimated using stepwise multiple regression analysis. Results indicated weak relationships between forest structural parameters and Landsat ETM+ images. The adjusted R^2 values of the regression analysis using the spectral digital number values for stand volume, basal area, tree density and quadratic mean diameter were found to be 0.37, 0.32, 0.44 and 0.25, respectively. Based on the vegetation indices, the adjusted R^2 values of the regression analysis were attained as 0.36, 0.34, 0.28 and 0.17, respectively. However, the results demonstrated moderate relationships between the forest structural parameters and the QuickBird satellite image. The adjusted R^2 values from the regression analysis using the digital number values for stand volume, basal area, tree density and quadratic mean diameter were found as 0.57, 0.45, 0.29 and 0.30, respectively. Depending on the vegetation indices, the adjusted R^2 values from the regression analysis were obtained as 0.54, 0.41, 0.41 and 0.44, respectively. When the results from Landsat ETM+ and QuickBird satellite images are compared with each other, it could be stated that the QuickBird satellite images provide better representation of structural parameters of forests.

Key words: forest structural parameters, Landsat ETM+ and QuickBird Satellite Images, vegetation indices, western Turkey.

RESUMEN

Este estudio evaluó la idoneidad de los valores de número digital Landsat ETM+ y QuickBird y varios índices de vegetación para predecir parámetros estructurales de bosques en el oeste de Turquía. Las relaciones empíricas entre los parámetros estructurales tales como volumen del rodal, área basal, densidad y DMC, y las imágenes satelitales Landsat ETM+ y QuickBird se estimaron mediante análisis de regresión múltiple por pasos. Los resultados indicaron relaciones débiles entre los parámetros estructurales del bosque y las imágenes Landsat ETM+. Los valores ajustados de R^2 del análisis de regression, utilizando los valores numéricos digitales espectrales para el volumen del rodal, área basal, densidad y DMC fueron 0,37, 0,32, 0,44 y 0,25, respectivamente. Con base en los índices de vegetación, los valores R^2 ajustados alcanzaron a 0,36, 0,34, 0,28 y 0,17, respectivamente. Los resultados demostraron relaciones moderadas entre parámetros estructurales del bosque y la imagen del satélite QuickBird. Los valores ajustados de R^2 del análisis de regresión usando los valores numéricos digitales para volumen, área basal, densidad y DMC fueron 0,57, 0,45, 0,29 y 0,30, respectivamente. Según los índices de vegetación, los valores ajustados de R^2 fueron 0,54, 0,41, 0,41 y 0,44, respectivamente. Al comparar resultados de imágenes Landsat ETM+ y QuickBird, podría decirse que este último proporcionan mejor representación de parámetros estructurales de los bosques.

Palabras clave: parámetros estructurales del bosque, Landsat ETM+, QuickBird, índice de vegetación, Turquía.

INTRODUCTION

Forest structural parameters such as stand volume, basal area, tree density and quadratic mean diameter are important indicators for forest management and are essential elements for effective and successful resource management (Zimble *et al.* 2003). Traditionally, these forest structural parameters have been gathered through national forest inventories using temporary sample plots. Although this method offers highly accurate measurements of forest structural parameters, it is very costly and time-consuming (Trotter *et al.* 1997). Many investigators have recommended that remotely sensed data be investigated as an alternative method of obtaining information about forest structural parameters (Lu *et al.* 2004).

Recently, remote sensing studies have demonstrated that estimation of forest structural parameters using satellite images depends on empirical relationships established between field data and satellite image data such as band reflectance values and vegetation indices (Rouse *et al.* 1974). Landsat images and other moderate resolution sensors are crucial for a wide range of forest applications with the estimation of forest structural parameters. Landsat images have several prevailing characteristics, including free availability and a long period of observation. Furthermore, multiple regression models derived from Landsat imagery are useful for deriving forest structural parameters (Cohen and Goward 2004). Applications of these models at landscape level are cost efficient with continuous temporal observations, permitting to evaluate the past and the present patterns of changes.

In many studies, efforts combining remote sensing data with field measured data focus on the estimation of forest structural parameters through the multiple regression analysis. The possibility of predicting forest structural parameters using satellite data has been examined in several studies (Lu *et al.* 2004, Hall *et al.* 2006, Mohammadi *et al*. 2010). For example, Zheng *et al.* (2004) found that diameter at breast height for hardwood forests was strongly related to stand age and near-infrared reflectance ($R^2 = 0.77$), whereas for softwood forests the similar estimation was strongly related to Normalized Difference Vegetation Index (NDVI) ($R^2 = 0.79$). Hall *et al.* (2006) modelled forest stand structure attributes using Landsat ETM+ data. The model for forest stand volume using the Biostruct method was developed with an $R^2 = 0.71$. Mohammadi *et al.* (2010) investigated the relationships between forest structural parameters (stand volume and tree density) with Landsat ETM+ data. They found that ETM 4 and ETM 5 indicated the best performance with tree density ($R^2 = 0.734$) and the weak performance with stand volume ($R^2 = 0.43$). Kahriman *et al.* (2014) showed the relationships between Landsat TM reflectance and vegetation indices values with crown closure and tree density in mixed stands. Crown closure and tree density could be estimated with Landsat data with $R^2 = 0.674$ and $R^2 = 0.702$; $R^2 = 0.610$ and $R^2 = 0.613$, respectively. Noorian *et al.* (2016) indicated the relationship between different satellite images and forest structural attributes in Hyrcanian forests. In recent years, new high-resolution satellite images such as QuickBird and WorldView have been used in estimating forest structural parameters (Özdemir and Karnieli 2011, Noorian *et al*. 2016, Günlü *et al.* 2017).

This study primarily aims both at determining the relationships between forest structural parameters with band digital number values and some vegetation indices using the multiple regression analysis and at comparing the model results from Landsat ETM+ and QuickBird images with the results of the related previous studies in literature. Based on the objectives, the hypothesis of the research is that QuickBird images would be able to present better estimation of forest structural parameters as compared with Landsat ETM+ images. The objectives, along with the hypothesis, are tested with the measurements of the forest structural parameters (stand volume, basal area, tree density and quadratic mean diameter) from sample plots and the interpretation of the band digital number and some vegetation indices values generated from Landsat ETM+ and QuickBird satellite images of each sample plot.

METHODS

The study area, with 18639.75 ha, is located in the Honaz Planning Unit in the western region of Turkey (702171-712252 E 4165992-4184358 N, UTM ED 50 datum Zone 35) (figure 1). Forests cover nearly 41.4 % of the study area. The elevation ranges from 360 to 2113 m above sea level with an average slope of 39 %. The study area, characterized by several types of conifer forests, is composed mostly by Turkish red pine (*Pinus brutia* Ten.) and black pine (*Pinus nigra* Arnold. subsp. *pallasiana* (Lamb.) Holmboe). Mean annual temperature of the study area is about 16.1 °C and the mean annual precipitation is 557.1 mm.

In this study, field data were collected from 488 sample plots. Their locations were obtained from forest inventory data based on the spatial distribution of 300 x 300 m grids of plots in August 2009. The size of sample plots ranged from 400 m^2 to 800 m^2. The geographical locations of sample plots were positioned and registered using ground control points and a Global Positioning System (GPS) device. In each sample plot, dendrometric details of all trees possessing a diameter superior to 7.9 cm at breast height were measured and recorded in inventory sheets. For example, stand height was measured with the nearest 0.1 m with digital hypsometer in randomized sub-sample and diameter at breast height (DBH) was measured with the nearest 0.5 cm. The stand volume in each sample plot was calculated by using a local volume table including DBH, developed to estimate the volume of different species (*P. brutia* and *P. nigra*) in plots. Eventually, the stand volume (m^3 ha^{-1}) was predicted by using a sum of the volumes of whole trees in each sample plot. Furthermore, tree density was calculated by counting the trees in each sample plot. Basal area (BA) (m^2 ha^{-1}) and the quadratic mean diameter (dg) (m) were calculated using equations 1 and 2, respectively:

$$BA = \frac{10000}{a} \cdot \frac{\pi}{4} \sum d_i^2 \qquad [1]$$

Where, d_i = stem diameter taken at 1.30 m from the ground, a = sampling plot area (m^2) and n = number of trees in the sampling plot.

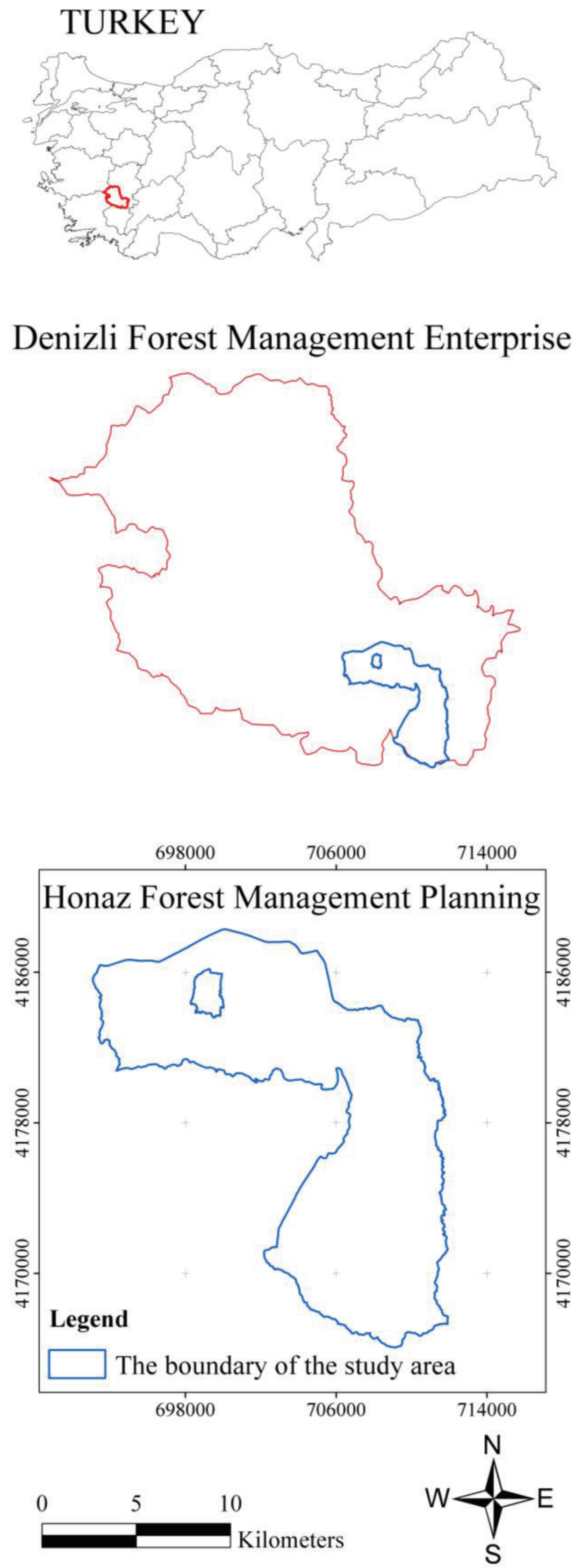

Figure 1. The geographical location of the study area.

Localización geográfica del área de estudio.

$$dg = \sqrt{\frac{\sum di^2}{N}} \quad [2]$$

Where, di = diameter at breast height of an individual tree, and N = total number of trees.

Descriptive statistical values for the forest structural parameters are given in table 1.

Two satellite images were used as remote sensing data resources; one was the medium spatial resolution Landsat ETM+ image acquired on July 12, 2009 and the other was the high-resolution QuickBird image acquired on April 23, 2007. The first six bands (visible, NIR and MIR) of the Landsat ETM+ satellite image with a spatial resolution of 30 m were used, the QuickBird data consisted of four spectral bands with 2.4 m spatial resolution and one panchromatic band with 0.60 m spatial resolution. A panchromatic band with four spectral bands was fused through IHS transformation using Erdas Imagine 2014 (Erdas 2014). Fused pan-sharpened satellite data were used in this study. Geometric rectification of remote sensing data is essential for many applications. The significance of correct geometric rectification is clear because the satellite image is frequently related to the ground truth data. The research area was subtracted from the satellite images using "subset" tools. The subset satellite images were georeferenced with a 1:25,000 scaled topographic map. Later, the satellite images were re-projected with UTM projection (ED 50 Datum, Zone 35) using 25 ground control points taken from topographic maps. A nearest neighbor resampling technique was used and the root mean square error (RMSE) was less than 0.5 pixels for Landsat ETM+ and average positional RMSE of ± 4 m for QuickBird obtained from the rectified satellite images. The software package Erdas Imagine (2014) was used for satellite image preprocessing. The geometric accuracy of the Landsat ETM+ satellite data and the positional accuracy of sample plots are connected to the spatial approximation of spectral and field measured data. In this study, the positional RMSE of the field measurement data was less than 4 m (determined by GPS device), whereas the geometric RMSE of the satellite image was 0.5 pixels (*i.e.* 15 m) and total spatial appropriate RMSE between the two was less than 19 m. Nevertheless, it was well enough for the spatial approximation of the current satellite image and field measurement data. The satellite image was spatially graded by two times using a nearest neighbor resampling technique. This resampling resulted in scaling up spectral data to the sample plot size (400 m^2, 600 m^2 and 800 m^2), thus guaranteeing a better spatial approximation of the satellite image and field measurement datasets.

After geometric corrections, some vegetation indices (VIs) were calculated for the study area (table 2). All sample plots have correct coordinates obtained from GPS devices and located on rectified satellite images over the study

Table 1. Descriptive statistics of the forest structural parameters (488 plots).
Estadística descriptiva de los parámetros estructurales de los bosques (448 parcelas).

Forest structural parameter	Minimum	Maximum	Mean	Standard deviation
dg (cm)	8.3	61.5	25.3	8.8
V (m^3 ha^{-1})	3.0	1.073.4	151.6	144.9
N (trees ha^{-1})	0	7,650	651.9	1,017.6
BA (m^2 ha^{-1})	0.30	57.4	19.62	10.05

Table 2. Definition of vegetation indices used in the study area.
Definición de índices de vegetación utilizados en el área de estudio.

Vegetation indices	Formula	Reference
SR	(ETM4)/(ETM3)	Jordan (1969)
NDVI	(ETM4-ETM3)/(TM4+TM3)	Rouse *et al.(*1974)
TVI	((ETM4-ETM3)/(ETM4+ETM3))+0.5	Deering *et al.* (1975)
DVI	(ETM4)-(ETM3)	Clevers (1988)
SAVI	(ETM4-ETM3)*(1+L)/(ETM4+ETM3+L)	Huete (1988)
NLI	$((ETM4)^2$-ETM3))/(($ETM4^2$)+ETM3))	Gong *et al.* (2003)

NDVI, Normalized Difference Vegetation Index; SR, Simple ratio; SAVI, Soil Adjusted Vegetation Index; DVI, Difference Vegetation Index; TVI, Transformed Vegetation Index; NLI, Vegetation Index; VIS, visible wavelengths (ETM1, ETM2, ETM3 for Landsat ETM+ satellite image; Band 1, Band 2, Band 3 for QuickBird satellite image); NIR, near infrared wavelengths (ETM4 for Landsat ETM+ satellite image; Band 4 for QuickBird satellite image), L:1.0

area. A sample plot level average digital number value was obtained from the corresponding satellite images for each sample plot following calculation vegetation indices. The spectral response of pixels within a 1x1 pixel window corresponding to each sample plot was extracted after overlapping the sample plots on the resampled Landsat ETM+ satellite image. In QuickBird satellite image, to analyze spectral values in sample plots, the average digital number of pixels within a 35×35 pixel window (for the size of 400 m^2), 41x41 pixel window (for the size of 600 m^2) and 48x48 pixel window (for the size of 800 m^2) centered on the GPS location of each field plot was extracted from the QuickBird spectral band values (Günlü *et al.* 2017).

Descriptive statistical values for the band digital number values and some vegetation indices of the Landsat ETM+ and QuickBird satellite image are given in tables 3 and 4, respectively.

A stepwise multiple linear regression analysis was used to model and examine the relationships between ETM 1-5 and 7 digital number values and six VIs for Landsat ETM+ satellite image, and Band 1, Band 2, Band 3 and Band 4 values and six VIs for QuickBird image with forest structural parameters such as stand volume, basal area, tree density and quadratic mean diameter. The models were used to estimate the forest structural parameters using remote sensing data, band digital number values and VIs, and their combination as independent variable. The dependent variables were forest structural parameters such as stand volume, tree density, basal area and quadratic mean diameter, measured from the case study area.

The modeling process starts out just as in forward selection, nonetheless, at each step the variable that is already in the model is first evaluated for removal. If variables are found eligible for removal, then the one whose values show the least low R^2 is removed. The analysis was performed using SPSS version 15.0 (SPSS 2007). The stepwise regression technique was used to select the best site variables that are significant ($P < 0.05$) with the highest value of the determination of coefficient adjusted by number of parameters (), also called adjusted coefficient of determination. In this study, the following linear relationship was assumed [3]:

$$SP = \beta_0 + \beta_1.X_1 + \beta_2.X_2 + \dots \beta_n.X_n + \varepsilon \quad [3]$$

Where: SP = forest structural parameter (stand volume, basal area, tree density and quadratic mean diameter), X1…Xn = variable vectors corresponding to remote sensing data, *e.g.* the digital number values, ETM 1-5 and TM 7 for Landsat ETM+ satellite image, Band 1, Band 2, Band 3 and Band 4 for QuickBird, and six VIs variables, β1… βn = model coefficients and Ɛ = additive error term (Corona *et al.* 1998).

A separate regression analysis was performed using the relevant remote sensing data to compare the predictive power of the digital number values, *e.g.* ETM 1-5 and 7 for Landsat ETM+ image, Band 1, Band 2, Band 3 and Band 4 for QuickBird satellite image and VIs. Therefore, sixteen regression models were developed (four forest structural parameters and Landsat ETM+ and QuickBird images, *e.g.*, band digital number values and VIs).

For example, one model predicting basal area uses digital number values, and another model uses VIs and predicts tree density using the band digital number values, and another model using VIs. In each sub-group, the rela-

Table 3. Descriptive statistics on the band digital number values and some vegetation indices of the Landsat ETM+ satellite image (488 plots).

Estadística descriptiva de los valores numéricos digitales de banda y algunos índices de vegetación de la imagen del satélite Landsat ETM+ (488 parcelas).

Image	Minimum	Maximum	Mean	Standard deviation
ETM 1	64.00	154.00	81.26	12.43
ETM 2	46.00	163.00	70.27	16.21
ETM 3	40.00	208.00	74.09	25.02
ETM 4	40.00	112.00	64.99	10.93
ETM 5	40.00	191.00	87.28	28.64
ETM 7	23.00	146.00	59.44	23.53
NDVI	-0.35	0.24	-0.05	0.101
SR	0.48	1.62	0.93	0.18
DVI	-96.00	34.00	-9.10	17.99
TVI	0.15	0.74	0.45	0.10
NLI	0.93	0.99	0.97	0.01
SAVI	-0.53	0.35	-0.07	0.15

Table 4. Descriptive statistics on the band digital number values and some vegetation indices of the QuickBird satellite image (488 plots).

Estadística descriptiva de los valores numéricos digitales de banda y algunos índices de vegetación de la imagen del satélite QuickBird (488 parcelas).

Image	Minimum	Maximum	Mean	Standard deviation
Band 1	197	478	252.2	43.17
Band 2	260	824	369.3	86.07
Band 3	144	704	257.2	88.32
Band 4	336	1058	509.8	77.23
NDVI	0.00	0.72	0.34	0.11
SR	1.00	6.05	2.11	0.50
DVI	-1.00	883.00	252.61	71.42
TVI	0.00	0.72	0.34	0.11
NLI	0.99	1.00	0.99	0.00
SAVI	0.00	1.07	0.51	0.16

ted forest structural parameters were predicted by using the digital number values of ETM 1-5 and 7 for Landsat ETM+ image, Band 1, Band 2, Band 3 and Band 4 for QuickBird image and VIs.

The regression models were evaluated based on the accuracy statistics, covering the absolute and relative biases and the root mean square error (RMSE and RMSE %). These statistics were calculated for the models as follows: [4-7].

$$bias = \frac{\sum(y_i - \hat{y}_i)}{n} \quad [4]$$

$$bias\% = 100\frac{\sum(y_i - \hat{y}_i)/n}{\sum \hat{y}_i / n} \quad [5]$$

$$RMSE = \sqrt{\frac{\sum(y_i - \hat{y}_i)^2}{n-1}} \quad [6]$$

$$RMSE\% = 100\frac{\sqrt{\sum(y_i - \hat{y}_i)^2 \,(\, n-1)}}{\sum \hat{y}_i / n} \quad [7]$$

Where, n = number of observations, and y_i and $\hat{y}_i$ = observed and predicted values of stand parameters *e.g.* stand volume, basal area, tree density and quadratic mean diameter from developed models.

RESULTS

The selected best regression models provided accuracy statistics such as coefficients of determination (R^2_{adj}), standard error of the model (S*y.x*), bias, bias%, RMSE and RMSE% values. Tables 5 and 6 summarize the best regression models for the forest structural parameters based on individual band reflectance values and VIs obtained from the Landsat ETM+ satellite image. In these selected regression models for the forest structural parameters, the F statistics and coefficients were significant at a probability level of 95 %. The quadratic mean diameter model that used ETM 1 and ETM 5 as independent variables had an R^2 of 0.25 and RMSE of 1.702 cm (table 5). The quadratic mean diameter with VIs was developed by NDVI, DVI and SAVI as independent variables. The model performance was calculated with adjusted R^2 = 0.17 and RMSE = 1.61 cm (table 6). The tree density model that used ETM 5 and ETM 7 as independent variables had an R^2 of 0.44 and RMSE of 139.931 n ha^{-1} (table 5). The tree density with VIs was developed by DVI, NLI and SAVI as independent variables, and the model performance was calculated with R^2 = 0.28 and RMSE = 126.86 n ha^{-1} (table 6). The basal area model that used ETM 1 and ETM 2 as independent variables had an R^2 of 0.32 and RMSE of 2.22 m^2 ha^{-1} (table 5). The basal area with VIs was developed by NLI, DVI, SAVI and NDVI as independent variables, and the model performance was calculated with R^2 = 0.34 and RMSE = 2.22 m^2 ha^{-1} (table 6). The stand volume model that used ETM 5 and ETM 7 as independent variables had an R^2 of 0.37 and RMSE of 29.13 m^3 ha^{-1} (table 5). The stand volume with VIs was developed by DVI and NLI as independent variables, and the model performance was calculated with R^2 = 0.36 and RMSE = 36.43 m^3 ha^{-1} (table 6). Table 7 and Table 8 summarize the best regression models for the forest structural parameters based on individual band reflectance values and VIs obtained from the QuickBird satellite image. The quadratic mean diameter model that used Band4 as independent variables had an R^2 of 0.30 and RMSE of 1.64 cm (table 7). The quadratic mean diameter with VIs was developed by NLI, SR and DVI as independent variables, and the model performance was calculated with adjusted R^2 = 0.44 and RMSE = 1.34 cm (table 8). The tree density model that used Band4 as independent variables had an R^2 of 0.29 and RMSE of 116.63 n ha^{-1} (table 7). The tree density with VIs was developed by SR, TVI, NLI and SAVI as independent variables, and the model performance was calculated with R^2 = 0.41 and RMSE = 114.15 n ha^{-1} (table 8). The basal area model that used Band1, Band2 and Band4 as independent variables had an R^2 of 0.45 and RMSE of 1.79 m^2 ha^{-1} (table 7). The basal area with VIs was developed by DVI, TVI, NLI and SAVI as independent variables, and the model performance was calculated with R^2 = 0.41 and RMSE = 1.74 m^2 ha^{-1} (table 8). The stand volume model that used Band1, Band2 and Band3 as independent variables had an R^2 of 0.57 and RMSE of 25.37 m^3 ha^{-1} (table 7). The stand volume with VIs was developed by SR, DVI and NLI as independent variables, and the model performance was calculated with R^2 = 0.54 and RMSE = 22.85 m^3 ha^{-1} (table 8).

DISCUSSION

Both Landsat ETM+ and QuickBird images were used and evaluated for estimation of stand volume, basal area, tree density and quadratic mean diameter. First, the regression models were employed for establishing models between the forest structural parameters and the digital number values and VIs from Landsat ETM+ image. The results of the regression models from Landsat ETM+ band values and VIs indicated that 25 % to 44 % and 17 % to 36 % of forest structural parameters variability could be explained, respectively (table 5 and 6). All models were statistically significant. However, the models estimating the stand volume, basal area, tree density and quadratic mean diameter provided low R^2 values. Therefore, the results obtained from this study seem to be unsuitable for forest management practices. When literature is examined, it seems that there are numerous studies on this topic. Related to these studies; Landsat TM reflectance bands were found to

Table 5. Parameters of the 'best fit' regression models of forest structural parameters based on the digital number values, ETM 1-5 and 7 (Landsat ETM+ satellite image).

Parámetros de los modelos de regresión de "mejor ajuste" de los parámetros estructurales de los bosques basados en los valores numéricos digitales, ETM 1-5 y 7 (imagen satelital Landsat ETM+).

Model description			Coefficients of independent variables	S.E. of variables	t statistics	*P*-value
Model group	Dependent variables	Independent variables				
Quadratic mean diameter	dg	Constant	31.1458	1.469	21.195	0.000
		ETM 1	-0.1587	0.029	-5.444	0.000
		ETM 5	0.0771	0.012	6.178	0.000
R_a^2 = 0.25			Bias= -3.17	Bias%= -1.27	RMSE= 1.702	RMSE%= 6.82
Tree density	N	Constant	427.1724	50.366	8.481	0.000
		ETM 5	20.2064	2.752	7.343	0.000
		ETM 7	-27.8432	3.320	-8.386	0.000
R_a^2 = 0.44			Bias= 1.41	Bias%= 2.77	RMSE= 139.931	RMSE%= 27.45
Basal area	BA	Constant	39.7179	2.571	15.445	0.000
		ETM 1	-0.6364	0.088	-7.244	0.000
		ETM 2	0.4446	0.068	6.514	0.000
R_a^2 = 0.32			Bias= 1.73	Bias%= 9.07	RMSE= 2.22	RMSE%= 11.62
Stand volume	V	Constant	117.8140	11.587	10.168	0.000
		ETM 5	4.1649	0.629	6.623	0.000
		ETM 7	-5.6362	0.767	-7.352	0.000
R_a^2 = 0.37			Bias= -6.02	Bias%= -4.25	RMSE= 29.13	RMSE%= 20.56

R_a^2 : adjusted coefficient of determination, S.E.: standard error, t statistics: probability values, RMSE: the root mean square error.

be significant predictors of stand volume, basal area, tree density and quadratic mean diameter based on correlation, regression and other statistical analyses (Zheng *et al*. 2004, Hall *et al*. 2006, Mohammadi *et al*. 2010. Hall *et al.* (2006) investigated the possibility of estimation of stand volume using Landsat ETM+ data. The model for stand volume was developed with an adjusted R^2 = 0.71. Mohammadi *et al.* (2010) modelled stand volume and tree density using Landsat ETM+ data. The models for tree density and stand volume were obtained with an adjusted R^2 = 0.73 and R^2 = 0.43, respectively. When our results were compared with the previous studies, it was seen that the results obtained in some of the studies examined and given below are better than those of our study. When the reasons for the low results from our study are examined, the reasons for the low output can be listed as follows: the study area mainly consists of young and dense forest stands. There are fewer openings in canopy of the forest stands. Thus, the infrared digital number value is very high. However, in old aged stands with lower density, there are openings in the crown closure causing crown closure shadows. In this case, infrared radiation would enter deeper into the forest areas, thus, inner and sucking may occur, decreasing rising radiance (Danson and Curran 1993).

The performance of prediction ability of the models with the QuickBird band digital number values differed among the forest structural parameters. The research results showed that the estimation of the forest structural parameters (especially stand volume and basal area) is possible with sufficient accuracy when compared with Landsat ETM+ image. Whereas the models had moderate explanation power with stand volume and basal area (R^2 = 0.57 and R^2 = 0.45). The models had weak explanation power with tree density and quadratic mean diameter (table 7 and 8). After two thousand years, novel satellite images such as those from QuickBird and WorldView have been used to predict forest strcutural parameters. Özdemir and Karnieli (2011) researched the possibility of predicting forest stand

Table 6. Parameters of the 'best fit' regression models of forest structural parameters based on vegetation indices (Landsat ETM+ satellite image).

Parámetros de los modelos de regresión de "mejor ajuste" de los parámetros estructurales de los bosques basados en los índices de vegetación (imagen satelital Landsat ETM+).

Model description			Coefficients of independent variables	S.E. of variables	t statistics	*P*-value
Model group	Dependent variables	Independent variables				
Quadratic mean diameter	dg	Constant	25.21	0.167	150.928	0.000
		NDVI	-183.565	45.627	-4.023	0.000
		DVI	0.097	0.026	3.722	0.000
		SAVI	110.435	30.495	3.621	0.000
$R_a^2 = 0.17$			Bias= -8.06	Bias%= -3.19	RMSE= 1.61	RMSE%= 6.40
Tree density	N	Constant	-5,946.63	1921.28	-3.095	0.000
		DVI	8.92	2.20	4.054	0.000
		NLI	6,760.23	1,990.53	3.396	0.000
		SAVI	-790.38	302.75	-2.611	0.000
$R_a^2 = 0.28$			Bias= -7.94	Bias%= -1.48	RMSE= 126.86	RMSE%= 23.74
Basal area	BA	Constant	214.12	32.03	6.685	0.000
		NLI	-201.026	33.13	-6.067	0.000
		DVI	-0.253	0.038	-6.598	0.000
		SAVI	171.351	35.56	4.818	0.000
		NDVI	-195.162	53.46	-3.651	0.000
$R_a^2 = 0.34$			Bias= 2.13	Bias%= 1.09	RMSE= 2.22	RMSE%= 11.42
Stand volume	V	Constant	2,762.78	408.45	6.764	0.000
		DVI	1.527	0.154	9.938	0.000
		NLI	-2,687.45	422.044	-6.368	0.000
$R_a^2 = 0.36$			Bias= 1.30	Bias%= 8.69	RMSE= 36.43	RMSE%= 24.33

R_a^2: adjusted coefficient of determination, S.E.: standard error, t statistics: probability values, RMSE: the root mean square error.

parameters using the image texture obtained from Worldview-2 satellite data in a dryland forest. They found that the R^2 and RMSE values were 0.38 and 109.56 n ha^{-1} for tree density, 0.54 and 1.79 m^2 ha^{-1} for basal area, and 0.42 and 27.18 m^3 ha^{-1} for stand volume. When examining some studies for predicting stand parameters using the QuickBird satellite image, it is seen that better results are obtained compared with our study. Hirata *et al.* (2008) used the QuickBird satellite image to predict stand density and stand volume in coniferous plantations. They found significant relations between stand density and stand volume with QuickBird data (R^2 = 0.82 and R^2 = 0.78, respectively). Özdemir (2008) used the pansharpaned QuickBird data to predict stem volume in a sparse Crimean juniper using shadow area and crown area. It was found that the R^2 and RMSE values were 0.67 and 12.5 %; 0.51 and 15.2 %, respectively. In a case study conducted by Mora *et al.* (2010) a medium relationship (R^2 = 0.53) was found between the mean stand height and the reflectance values obtained from the QuickBird satellite images. Günlü *et al.* (2013) investigated the QuickBird satellite image for predicting stand volume in pure beech stands. They found the R^2 and RMSE values were 0.70 and 28.56 m^3 ha^{-1} for the stand volume.

When the results were examined, it was seen that the QuickBird satellite image used in the study was inadequate for mapping and monitoring the forest stand attributes. Owing to the fact that 488 sample plots taken in the study are primarily of different stand development stages, crown closures and site classes, the stand structures in the sample plots are also different. The stand crown closure is significant atribute in this issue. Particularly in a low cover stand

Table 7. Parameters of the 'best fit' regression models of forest structural parameters based on the digital number values, Band 1-3 and Band 4 (QuickBird satellite image).

Parámetros de los modelos de regresión de "mejor ajuste" de los parámetros estructurales de los bosques basados en los valores numéricos digitales, banda 1-3 y banda 4 (imagen satelital QuickBird).

Model description			Coefficients of independent variables	S.E. of variables	t statistics	*P*-value
Model group	Dependent variables	Independent variables				
Quadratic mean diameter	dg	Constant	32.49	1.10	29.50	0.000
		Band4	-0.015	0.002	-6.78	0.000
R_a^2 = 0.30			Bias= -1.32	Bias%= -5.28	RMSE= 1.64	RMSE%= 6.54
Tree density	N	Constant	98.27	71.94	1.36	0.000
		Band4	0.98	0.14	6.85	0.000
R_a^2 = 0.29			Bias= -8.62	Bias%= -1.47	RMSE= 116.63	RMSE%= 19.92
Basal area	BA	Constant	47.98	3.51	13.65	0.000
		Band1	-0.25	0.04	-6.58	0.000
		Band2	0.12	0.01	-4.04	0.000
		Band4	-0.02	0.02	5.74	0.000
R_a^2 = 0.45			Bias= -2.08	Bias%= -1.05	RMSE= 1.79	RMSE%= 9.14
Stand volume	V	Constant	212.66	32.25	6.59	0.000
		Band1	1.80	0.50	3.59	0.000
		Band2	-1.80	0.38	-4.65	0.000
		Band3	0.61	0.20	3.07	0.000
R_a^2 = 0.57			Bias= -5.98	Bias%= -3.87	RMSE= 25.37	RMSE%= 16.42

R_a^2 : adjusted coefficient of determination, S.E.: standard error, t statistics: probability values, RMSE: the root mean square error.

in the study area, stratums such as weeds, shrubs, soil etc. have affected the digital number values of the satellite data. Thus, in estimating forest stand parameters using satellite data, the different stratums in the lower layers of the stand may cause confusion.

CONCLUSIONS

Results from statistical analyses indicated that digital number values (except for tree density) and VIs recorded by the QuickBird satellite sensor are better predictors than Landsat ETM+ satellite sensor. Based on these results, we conclude that QuickBird satellite data are beneficial for the estimation of forest structural parameters, whereas the Landsat ETM+ satellite data are not useful for the prediction of those parameters in the western part of Turkey. The study results indicate significant potential for the use of QuickBird satellite image of, at least, estimating some forest structural parameter (stand volume and basal area) of conifer forests in the study area. However, further studies are required to apply this research design in different forest ecosystems (pure and mixed forest areas) situations including various topographical factors, different acquired time or location of other satellite images and different stand structures (mixed or deciduous forest areas) to look for wider use of both satellite images in forest management. In addition, different modeling techniques may be used to predict forest structural attributes using remote sensing data. For example, the use of different other models, such as artificial neural networks and mixed-effect modeling techniques, may enhance model success criteria.

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Table 8. Parameters of the 'best fit' regression models of forest structural parameters based on vegetation indices (QuickBird satellite image).

Parámetros de los modelos de regresión de "mejor ajuste" de los parámetros estructurales de los bosques basados en los índices de vegetación (imagen satelital QuickBird).

Model description			Coefficients of Independent variables	S.E. of variables	t statistics	*P*-value
Model Group	Dependent variables	Independent variables				
Quadratic mean diameter	dg	Constant	1971.90	1,027.96	1.91	0.000
		NLI	-1,954.04	1,031.89	-1.89	0.000
		SR	4.65	0.61	7.63	0.000
		DVI	-0.026	0.01	-3.04	0.000
R_a^2 = 0.44			Bias= -3.18	Bias%= -1.26	RMSE= 1.34	RMSE%= 5.35
Tree density	N	Constant	224,945.7	27,174.49	-8.27	0.000
		SR	274.49	123.33	2.22	0.000
		TVI	-21,282.51	3,967.29	-5.36	0.000
		NLI	226,241.88	27,253.11	8.30	0.000
		SAVI	12,583.64	2,691.41	4.67	0.000
R_a^2 = 0.41			Bias= -1.54	Bias%= -2.76	RMSE= 114.15	RMSE%= 20.39
Basal area	BA	Constant	1,140.53	642.74	1.77	0.000
		DVI	-0.026	0.01	-3.01	0.000
		TVI	176.49	60.34	2.92	0.000
		NLI	-1,126.25	645.53	-1.74	0.000
		SAVI	-98.79	40.63	-2.43	0.000
R_a^2 = 0.41			Bias= -1.29	Bias%= -6.56	RMSE= 1.74	RMSE%= 8.86
Stand volume	V	Constant	-18,703.87	8,357.72	-2.23	0.000
		SR	104.17	9.19	11.33	0.000
		DVI	-0.687	0.08	-8.05	0.000
		NLI	18,851.66	8,389.42	2.24	0.000
R_a^2 = 0.54			Bias= 2.10	Bias%= 1.38	RMSE= 22.85	RMSE%= 15.03

R_a^2: adjusted coefficient of determination, S.E.: standard error, t statistics: probability values, RMSE: root mean square error.

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