

Estimation of some forest stand parameters using different satellite images: Case Studies from Kelkit and İğdir Planning Units

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Abstract: Accurate and up-to-date information on forest composition and structure is essential for effective management, yet conventional inventory methods require considerable time, labor, and cost. Remote sensing provides an efficient alternative by enabling the estimation of stand parameters through reliable and rapid techniques. This study investigates the relationships between remotely sensed data and key stand parameters—including number of trees, basal area, and volume—measured from field sample plots in even-aged pure Scots pine (*Pinus sylvestris*) stands and uneven-aged pure fir (*Abies nordmanniana* subsp. *bornmuelleriana*) stands. Research was conducted in Kelkit/Gümüşhane, dominated by *Pinus sylvestris*, and İğdir/Kastamonu, characterized by *Abies nordmanniana* subsp. *bornmuelleriana*. Five different remote sensing datasets were employed, including Göktürk-2, Rasat, and aerial photographs captured with digital cameras, which had not previously been applied for similar purposes. Using multiple regression analysis in SPSS 20.0, relationships between stand parameters and satellite reflectance/pixel values, along with vegetation indices derived from ERDAS Imagine, were evaluated. Results indicated that Landsat 8 imagery produced the most accurate estimations for all parameters in both regions. The adjusted R^2 values for volume, basal area, and tree number were 0.44, 0.77, and 0.77, respectively, in Kelkit, and 0.60, 0.75, and 0.80 in İğdir. Models with the highest coefficients of determination and lowest standard errors were selected and applied to both study areas. Final outputs were compared with the existing stand type maps, demonstrating the effectiveness of remote sensing in improving forest inventory and management.

Keywords: Digital aerial photograph, Forest management, Göktürk-2, Stand parameters, Rasat, Remote sensing

Bazı meşcere bileşenlerinin farklı uydu görüntüleri yardımıyla tahmin edilmesi: Kelkit ve İğdir Planlama Birimi örneği

Öz: Ormanların yapı ve kuruluşu hakkında daha az para ve emek harcayarak bilgi sahibi olma ve bunu güncelleme isteği önemini korumaktadır. Bu noktada, özellikle meşcere bileşenlerinin güncel, güvenilir ve hızlı yöntemlerle belirlenmesi büyük avantajlar sağlamaktadır. Gerçekleştirilen çalışmada, aynı yaşlı saf Sarıçam ve değişik yaşlı olarak işletilen saf Gökknar meşcerelerinden alınan örnek alanlarda yapılan ölçümler sonucunda elde edilen bazı meşcere bileşenleri ile uzaktan algılama verileri arasındaki ilişkiler araştırılmıştır. Çalışma alanları olarak, aynı yaşlı saf Sarıçam meşcerelerinin ağırlıklı olarak yer aldığı Kelkit (Gümüşhane) ile değişik yaşlı saf Gökknar meşceresinin içerisinde yer aldığı İğdir (Kastamonu) Orman İşletme Şeflikleri seçilmiştir. Çalışmada daha önce birlikte benzer amaçla kullanılmamış olan Göktürk-2, Rasat ve dijital kamera ile çekilmiş hava fotoğraflarının da olduğu 5 farklı uzaktan algılama verisi kullanılmıştır. Uydu görüntülerine ilişkin yansıma/piksel değerleri ve bu değerler kullanılarak hesaplanan farklı indeksler Erdas Imagine yazılımı yardımıyla elde edilmiş ve seçilen meşcere bileşenleri olan ağaç sayısı, hacim ve göğüs yüzeyi arasındaki ilişkiler SPSS 20.0 programı kullanılarak çoklu doğrusal regresyon modelleri ile ortaya konmuştur. Ağaç sayısı, hacim ve göğüs yüzeyi için geliştirilen modellerde en yüksek tahminleri Landsat uydusu sağlamıştır. Kelkit araştırma alanı için ağaç sayısı, hacim ve göğüs yüzeyi düzeltilmiş belirtme katsayıları sırasıyla 0.44, 0.77 ve 0.77; İğdir araştırma alanı için ise bu değer sırasıyla 0.60, 0.75 ve 0.80 olarak bulunmuştur. Her iki bölgede de, en yüksek doğruluk ve en düşük standart hataya sahip modeller seçilmiş, bu modellerin çıktıları, mevcut meşcere haritalarıyla karşılaştırılarak doğrulukları değerlendirilmiştir.

Anahtar kelimeler: Dijital hava fotoğrafı, Orman amenajmanı, Göktürk-2, Meşcere bileşenleri, Rasat, Uzaktan algılama

1. Introduction

Nearly all of Türkiye's forests are state-owned and managed by the General Directorate of Forestry, in line with forest management plans. These plans are prepared by the Forest Management and Planning Department of the General Directorate of Forestry, at the forest planning unit level, for 10- or 20-year periods. All production activities and

utilization of other values provided by the forest ecosystems are conducted out in accordance with management plans, which form the fundamental basis for regulating the utilization of forest ecosystems. Therefore, forest management plans are fundamental tools for regulating the utilization of forest ecosystems, including wood raw material production, non-wood forest product supply, and other non-provisional services, within the framework of sustainability

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principles. However, successful forest resource planning requires up-to-date and reliable information (Schreuder et al., 1993; Kangas et al., 2006). This information on forest ecosystems is provided by forest inventories.

Forest inventory is a crucial phase of planning. A forest inventory with sufficient detail and accuracy is a prerequisite for accurate planning and is therefore crucial for forest management. The purpose of a forest inventory is to obtain both qualitative and quantitative information about forest resources and their physical environment within the specified timeframe and within the constraints of predicted accuracy and cost. The primary objective is to reveal the current status of forests (area, volume, etc.) and changes over time (such as growth and increment). In recent years, the scope of forest inventory has expanded due to the increasing and widespread use of forests for multiple purposes (Laar and Akça, 1997). Determining volume and volume increment per unit area in a forest inventory is the most significant factor influencing costs in terms of money, time, and labor. Due to time and economic constraints, stand volume is calculated using data obtained from sample plots rather than across the entire area.

During the inventory, the cheapest source of information and the measurement method that provide the required accuracy and reduces inventory costs are selected based on the location and nature of the parameter to be measured. An example of this is the use of aerial photographs and satellite imagery instead of ground measurements for estimating growing stock. While inventory methods previously relied solely on ground measurements, aerial photographs have since been utilized for this purpose.

Although the tree inventory in Türkiye was based on methods used in France, Germany, and Austria until 1955 (Günel, 1973), the management regulation enacted in 1955 introduced a combined inventory system that integrated ground measurements and aerial photographs (Eraslan, 1963). However, due to the inability to obtain aerial photographs for all forests in a short time, this method was not actively used between 1955 and 1963 (Eraslan, 1985; Eraslan, 1992). The year 1963 was significant year for Türkiye's national economy as well as for its forestry sector. To achieve the forestry sector targets set in the development plans between 1963 and 1972, management plans for all forests in Türkiye were completed over a 10-year period. During this period, aerial photographs, taken in black and white at various scales until 1991, were subsequently converted to color infrared. Since 2008, aerial photographs have been taken by the "General Command of Mapping" using a 4-band digital camera with a spatial resolution of 30 cm or 45 cm.

Following the launch of Landsat-1, the first natural resource-monitoring satellite, in 1972 (USGS, 2025), and the rapid recognition of its benefits, various countries developed and launched their own natural resource-monitoring satellites into space. Türkiye commissioned Bilsat in 2003, its first natural resource-monitoring satellite capable of providing 12 m pan and 26 m multispectral imagery (TÜBİTAK, 2025). Bilsat was inactive in 2006 due to battery depletion, and Türkiye's second natural resource satellite, Rasat, was launched in 2011. This satellite, with a spatial resolution of 7.5 m in pan and 15 m in multispectral bands, acquired approximately 1,200 images covering the country in three years, and these images were made available to public institutions and organizations. The satellite, which had a mission life of three years, became inactive after the

commissioning of Göktürk-2. The Göktürk-2 satellite, which has a pan image resolution of 2.5 m and a multispectral resolution of 5 m and is classified as a high-resolution satellite, was launched in December 2012 and the images obtained have since been shared with public institutions and organizations.

Satellite imagery is now used as the primary source of information in hard-to-reach areas where ground-based measurements are expensive and time-consuming. In Türkiye, starting in 1963, aerial photographs were used for similar purposes in the planning process as part of the combined inventory method. In recent years, with the development of satellite technologies, satellite imagery and high-resolution aerial photographs taken with digital cameras have begun to be used both for stand classification and for the estimation of various stand components in scientific studies. Satellite imagery, used in practice to distinguish stand types on the screen in Türkiye, is also used in some academic studies, both globally and in our country, to estimate various stand parameters such as volume, tree count, and basal area. A regression model was developed to determine stand volume, density, and canopy closure using Landsat TM/ETM+ satellite images by Naseri (2003), Khorrami (2004), and Mohammadi (2007). A decision support system was developed by Astola et al. (2004) to estimate volume, median diameter, number of trees, and mixture ratio using Ikonos satellite images. Landsat TM satellite images were used to estimate different stand parameters by Franco-Lopez et al. (2001), Makela and Pekkarinen (2004), Gjertsen (2007), Mc Robert, et al. (2002). Similar studies were carried out by Kajisa et al. (2008) using Landsat-ETM+ images, while Reese et al. (2002) and Holmström et al. (2002) used Spot satellite images.

In Türkiye, Özkan (2003) researched the relationships among number of trees, tree density, basal area, dbh and medium height using regression analysis with Spot-5 satellite data. İnan (2004) analyzed 25 vegetation indices and 4 different texture measurements with 5 different window sizes using Landsat TM and ETM+ data. Özdemir and Mert (2007) investigated the relationships between Quickbird (pan-sharpened) satellite data and standing volume per hectare using simple regression analysis. Ateşoğlu (2009) estimated diameter, basal area and crown closure using Landsat 7 ETM+, Spot HR-VIR, Aster (VNIR) image data and vegetation indices based on measurements taken in 41 sampling areas. Günlü et al. (2011) calculated the accuracy of stand map by performing supervised classification with Landsat 7 ETM+. Günlü et al. (2013) used Quickbird and Landsat 7 ETM+ satellite images to reveal the relationship between stand volume through regression analysis. Şenyurt et al. (2013) estimated stand diameter, volume, basal area, and number of trees using Landsat 8 satellite imagery. Mısırlı (2013) estimated stand volume using 25 different vegetation indices using Landsat 7 ETM+ satellite imagery. Özgün (2014) researched stand volume, basal area, and number of trees using Landsat 7 TM satellite imagery. Günlü et al. (2015) estimated the relationships between stand volume, basal area, number of trees, diameter, height, stand age, site index, leaf area index, and WorldView-2 and Aster satellite images using multiple regression analysis, based on data from 108 sample areas taken within the boundaries of Yenice Forest planning unit. Bulut et al. (2016) investigated the relationships between stand volume, stand density, basal area parameters obtained from ground measurements in 120

sample areas of Black pine and Scots pine stands in Çankırı Research Forest using the band values of Göktürk-2 satellite images and the coefficient of determination. Yılmaz (2017) tried to estimate stand volume, basal area, tree diameter and number of trees using multiple regression analysis in areas dominated by Turkish red pine, Scots pine, cedar, beech, oak and hornbeam stands in Reşadiye using Landsat TM satellite images and vegetation indices. Göğerçin and Günlü (2017) tried to reveal various stand parameters such as stand volume, basal area, number of trees, diameter and stand height of Anatolian black pine plantations with the help of Göktürk-2 satellite images. Özkan and Demirel (2018) investigated the relationships among aerial photograph spectral values (blue, green, red, infrared) and species characteristics within the boundaries of Adıyaman Forest Enterprise with diameter, average height, volume, number of trees, and basal area. Günlü and Kadioğulları (2018) tried to estimate the relationships among stand parameters such as volume, basal area, density, and median diameter using regression models based on Landsat ETM+ and QuickBird satellite images. Sakıcı and Günlü (2018) tried to estimate the parameters of volume, basal area, stand median diameter, and tree number in Anatolian black pine stands in the Kastamonu region using Landsat 8 satellite imagery. Günlü et al. (2021) aimed to reveal stand volume, basal area, number of trees, and aboveground biomass using WorldView-2 satellite imagery. Bahadır et al. (2025) using Aerial LiDAR (UAV-LiDAR) and photogrammetric point clouds data, estimated four different tree metrics (tree height, crown width, diameter at breast height, crown base height) as a result of the segmentation for individual trees for stone pine (*Pinus pinea*) and spruce (*Picea orientalis*) forests. In conclusion based on object-based accuracy analysis, the average segmentation accuracy was 79% and the spatial error at the tree center was ± 0.785 m. Bulut et al. (2023) using Landsat 8 and Sentinel-2 data, estimated stand volume, basal area, number of trees, mean diameter, and top height. Demirel and Sakıcı (2025), developed regression models for stand diameter, number of trees, basal area, volume, density parameters using Sentinel-1 and Sentinel-2, 146 Anatolian black pine and 96 scots pine sample plots.

Numerous studies have been conducted globally and in Türkiye on the estimation of stand parameters. Studies

conducted in Türkiye generally consider only bands or indices derived from images, which generally limits success rates to below 60%. This study aimed to achieve higher estimation accuracy by using reflectance values instead of pixel values. Reflectance values were calculated for all satellites in this study, while only pixel values from aerial photography data were used.

2. Materials and Methods

2.1. Study area

To estimate stand parameters in even-aged and uneven-aged forests, two different study areas were selected. To achieve the specified objectives, the selected study areas are located within the boundaries of the Kelkit and İğdir Forest Planning Units in Türkiye (Figure 1). The Kelkit Forest Planning Unit (Gümüşhane) covers an area of 5,039 ha, and manages even-aged Scots pine forests. Its altitude ranges from 500 to 1700 m, with an average slope of 30%. The İğdir Forest Planning Unit (Kastamonu) covers an area of 675 ha, and manages mixed-aged fir forests. The altitude ranges from 1400 to 2500 m with an average slope is around 35%.

2.2. Data sources used in the study

Forest management plans, stand type maps, and sample plot data produced for the Kelkit PU in 2012 and the İğdir PU in 2013 were used as the basis. Remote sensing data sources included Göktürk-2 (2013), Landsat 8 (2013), Rasat (2013), WorldView-2 (2011), and high-resolution digital aerial photographs taken in 2013.

2.3. Measurements in the sampling area

In the research area, including stand types of the Kelkit PU, sampling plots were chosen with sizes of 400 m² and 600 m², depending on the degree of closure. A total of 130 sampling plots were considered in the Scots pine forests. The number of stand type distribution of the sample areas was as follows: Çsa-5, Çsab-2, Çsbc-55, Çsc-15, Çscd-22, BÇs-15, and open areas-16.

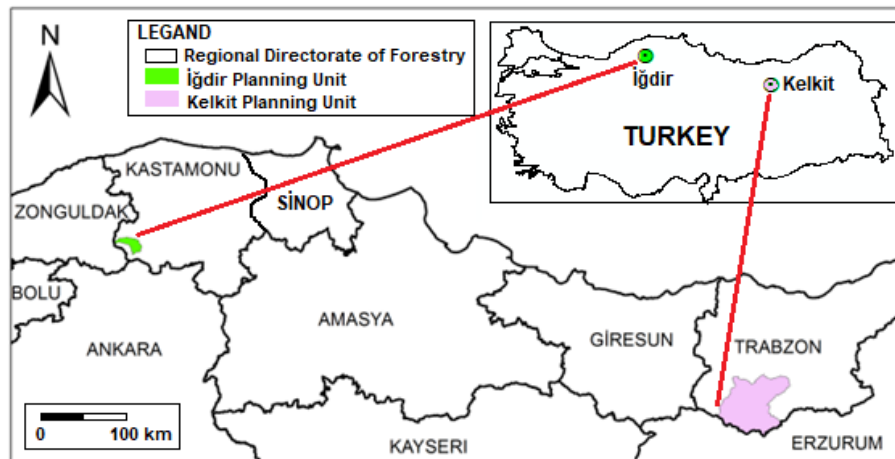


Figure 1. Locations of Kelkit and İğdir Planning unit

Measurements were carried out at a total of 107 plots in the İğdir PU within the Caucasian fir forests, with a sample plot size of 600 m². In each sampling area, the diameter of all trees larger than 7.9 cm was measured, and the tree species were determined and recorded on the inventory sheet. The number of stand type distribution of the sample areas was as follows: GA (selection forest with a higher number of trees in the thicker diameter ranges compared to optimal, but fewer in the medium and finer diameter ranges)-41, and GD (actual selection forest, not resembling any of the A, B, or C deviation types, or consisting of a mixture of those) - 64. GB or GC stand types were not observed in the study area.

2.4. Method

Remote sensing data cannot be used directly to measure parameters such as stand volume and biomass. Satellite sensors can measure various parameters, such as reflectance values from the crowns of trees in the forest or tree height obtained from laser measurements. Optical sensor systems record spectral reflectance from the upper layers of the forest canopy. Therefore, statistical relationships between measurable values and forest characteristics are utilized. There is a strong relationship between biomass and visible bands. There is a strong negative correlation between the middle infrared bands and stand volume (İnan, 2004). The mid-infrared bands are most sensitive to changes in stand volume, and their reflectance values, are directly affected by increases in stand canopy. These changes occur because, under optimal forest conditions, increases in biomass and volume simultaneously lead to increased stand canopy cover, which in turn increases the canopy area within the stand, reducing reflectance from the live canopy and soil. Shading created by the stand canopy plays an important role in the relationship between changes in stand volume and all bands.

In this study, the relationships between reflectance values obtained from satellite imagery and digital aerial photographic bands and three different selected stand parameters were investigated by developing a regression model. Linear regression is widely used in remote sensing studies for estimating stand components due to its ease of use and interpretation (Zheng et al., 2004). The MATLAB program was used to convert pixel values to reflectance values in satellite images.

Since the study relied on stand parameters calculated from ground measurements, a total of 237 sampling plots were taken across both study areas to estimate standing volume, number of trees, and basal area.

2.5. Analysis of stand parameters using satellite images

In developing models that estimate stand composition, various indices were used, in addition to reflectance values obtained for each band and each pixel of satellite imagery and aerial photography. As is well known, the number assigned to each pixel in satellite imagery is determined by the rate at which the electromagnetic energy to which the receiver is sensitive is reflected by objects on the surface corresponding to that pixel. For situations where the correlation between pixel numbers and plant structural characteristics alone is insufficient, researchers have developed auxiliary indices. These indices are listed in Table 1.

Since the dataset exceeded the number of 30, the normal distribution of each factor and the homogeneity of the data were examined, and extreme sampling areas that disrupted the normal distribution were removed.

Correlation and multiple regression analyses were conducted to obtain models for the reflectance values for different bands of each satellite image, the ratios of these reflectance values to each other, and the vegetation indices and stand parameters. The percentage of stand parameters predicted by these models was calculated. For this purpose, multiple regression models were created to establish the relationship between stand parameters and remotely sensed data, using stand parameters (volume, basal area, and number of trees) as dependent variables, and the reflectance values for the bands and the resulting vegetation indices as independent variables. Regression models were developed separately for each study area and three different stand parameters. The standard error and R² values of the developed models were calculated.

2.6. Testing the developed models for research areas

A total of 18 models with the lowest standard error percentage and the highest adjusted R² were selected from among the models developed for the three different stand parameters considered within the scope of the study and were tested for both research areas.

Table 1. Vegetation indices and band combinations

Vegetation indices	Formula
ARVI	(NIR-2Red+Blue) / (NIR+2Red-Blue) - Kaufman and Tanre (1992)
SAVI	(NIR-RED) / (NIR+RED+L)(1+L) , L=0.5 - Huete (1988)
NDVI	NIR-RED / NIR+RED – Rouse vd. (1973)
ND53	BAND5 – BAND3 / BAND5 + BAND3
ND54	BAND5 – BAND4 / BAND5 + BAND4
ND43	BAND4 – BAND3 / BAND4 + BAND3
ND64	BAND6 – BAND4 / BAND6 + BAND4
ND65	BAND6 – BAND5 / BAND6 + BAND5
Albedo	BAND1+BAND2+BAND3+BAND4+BAND5+BAND7
B6/B1	BAND6/BAND1
B6/B4	BAND6/BAND4
B6/B5	BAND6/BAND5
B6/B7	BAND6/BAND7
B7/B3	BAND7/BAND3

3. Results

3.1. Correlation Analysis

Considering the Kelkit research area, it was determined that there was a significant relationship between the three stand parameters, with the strongest relationship being between volume and basal area, with a value of 0.997 (Table 2).

Considering the İğdir study area, a significant relationship was found between basal area and the other two components, while no strong relationship was found between the number of trees and the volume. The strongest relationship was found between volume and basal area, with a value of 0.966 (Table 3).

3.2. Regression models for the Kelkit research area

In the Kelkit research area, where four different satellite images were tested: Landsat 8, Rasat, Göktürk-2, and WorldView-2, numerous regression models were created using data from a total of 130 sampling plots, including 5 Çsa, 2 Çşab, 55 Çsbc, 15 Çsc, 22 Çscd, 15 BÇs, and 16 open areas. From the obtained models, those with the highest adjusted R² and the lowest standard errors were selected and presented below (Table 4).

When the results were examined, it was determined that, models developed using Landsat-8 satellite data provided the highest estimates of the number of trees, volume, and basal area, with adjusted R² of 0.44, 0.77 and 0.77, respectively. When volume was considered, Landsat-8 was followed by WorldView-2, Rasat and Göktürk-2 respectively. Basal area showed similar results to volume. When the number of trees was considered, Landsat-8 achieved the highest R² with an R² of 0.44, followed by Rasat, Worldview-2 and Göktürk-2 respectively.

The models developed for the number of trees, volume and basal area are given in equations 1, 2 and 3.

$$N = 55568,7 - 384989,4 * B1 + 227166,7 * B3 - 61141 * B5 - 23047,3 * B7 + 37311,6 * SAVI - 602,7 * B6 / B4 + 4181,8 * B7 / B3 - 3806,1 * 1 / B1 + 589,8 * 1 / B3 \quad (1)$$

The above model, developed with the help of Landsat 8 satellite, has adjusted R² of 0.44 and a standard error of 270 trees/ha, and explains the number of trees per hectare in the research area by 44% and with a standard deviation of 270 trees/ha.

$$V = 10304,8 - 41992,5 * B1 - 1129,5 * B5 + 3283,8 * B7 - 229,5 * B6 / B7 - 552,3 * B7 / B3 - 564,8 * 1 / B1 + 106,2 * 1 / B3 - 22,1 * 1 / B4 - 93,2 * 1 / B5 \quad (2)$$

The above model, developed with the help of Landsat 8 satellite, has adjusted R² of 0.77 and a standard error of 39.6 m³/ha, and explains 77% of the volume per hectare of stand types in the research area with a standard deviation of 39.6 m³.

$$GY = 1505,3 - 6191,6 * B1 - 157,4 * B5 + 486,4 * B7 - 33,1 * B6 / B7 - 81,8 * B7 / B3 - 81,8 * 1 / B1 + 15,2 * 1 / B3 - 3,3 * 1 / B4 - 13 * 1 / B5 \quad (3)$$

The above model, developed with the help of Landsat 8 satellite, has adjusted R² of 0.77 and a standard error of 5.7 m²/ha, and explains 77% of the basal area per hectare of the stand types in the research area with a standard deviation of 5.7 m².

When the results were evaluated collectively, it was determined that the regression models for tree count were less accurate than those for volume and basal area. The Landsat 8 satellite model, which has the highest adjusted R² result, showed that bands 5 and 7 are more effective. The reason for the low results of our national satellite Göktürk-2 regression model is likely due to inadequate infrared bands (B1: Coastal Aerosol, B3: Green, B4: Red, B5: Near-Infrared, B6: SWIR 1, B7: SWIR 2 bands of Landsat 8).

3.3. Regression models for the İğdir research area

In the İğdir research area, where four different images were tested: Landsat 8, Rasat, Göktürk-2, and aerial photographs taken with a digital camera. A number of regression models were created using data from a total of 107 sampling plots, including 41 GA, 64 GD, and 2 open-field stand types. From the obtained models, those with the highest adjusted R² and the lowest standard errors were selected and presented below (Table 5).

Table 2. Results of correlation analysis of stand parameters in Kelkit research area

	N	V	BA
N	1		
V	0.420**	1	
BA	0.453**	0.997**	1

(N: Number of trees, V: Volume, BA: Basal area, **: Significant at the 0.01 level)

Table 3. Results of correlation analysis of stand parameters in İğdir research area

	N	V	BA
N	1		
V	0.152**	1	
BA	0.378**	0.966**	1

Table 4. Regression model outputs for the Kelkit research area

Platform	Statistics	Number of sample plot	N	V	BA
Landsat 8	Adjusted R ²	125	0.44	0.77	0.77
	Standard error (count)		270	39.6	5.7
Rasat	Adjusted R ²	125	0.38	0.73	0.74
	Standard error		284	42.5	6.1
Göktürk-2	Adjusted R ²	125	0.33	0.42	0.43
	Standard error		296	62.5	8.9
WorldView-2	Adjusted R ²	125	0.36	0.75	0.76
	Standard error		288	40.8	5.9

(Standard error, N: trees/ha, V: m³/ha, BA: m²/ha)

Table 5. Regression model outputs for the İğdir research area

Platform	Statistics	Number of sample plots	N	V	BA
Landsat 8	Adjusted R ²	103	0.60	0.75	0.80
	Standard error		178	90.9	7.1
Rasat	Adjusted R ²	103	0.51	0.62	0.66
	Standard error		197	112.1	9.2
Göktürk-2	Adjusted R ²	103	0.53	0.58	0.64
	Standard error		193	117.5	9.5
Digital Aerial Photography	Adjusted R ²	103	0.57	0.65	0.69
	Standard error		186	107.4	8.8

(Standard error, N: trees/ha, V: m³/ha, BA: m²/ha)

Model results showed that Landsat 8 provided the highest estimates of the number of trees, volume, and basal area, with adjusted R² of 0.60, 0.75 and 0.80, respectively. When considering volume, Landsat 8 was followed by Rasat, while Göktürk-2 performed poorly. When considering the number of trees, Landsat 8 was followed by aerial imagery. The success rate for basal area was the same as for volume.

The models developed for tree number, volume and basal area were given in equations 4, 5 and 6.

$$N = 1422,2 - 26219,1 * B3 - 1192,1 * ARVI - 102,6 * 1/B4 - 68,3 * 1/B7 + 1238,4 * 1/\sqrt{B7} \quad (4)$$

The model (4), developed with the help of Landsat 8 satellite, has adjusted R² of 0.60 and a standard error of 178 trees/ha, and explains the number of trees per hectare of GA and GD stand types in the research area with a deviation of 178 trees, by 60%.

$$V = -1181 - 4942,6 * ARVI - 5223,8 * SAVI + 11426,3 * ndvi - 970,7 * B6/B5 - 91,4 * 1/B3 + 385,3 * 1/B5 + 12,3 * 1/B7 \quad (5)$$

The (5) model, developed with the help of Landsat 8 satellite, has an adjusted R² of 0.75 and a standard error of 90.9 m³/ha, and explains the hectare volume of GA and GD stand types in the research area with a deviation of 90.9 m³/ha, at a rate of 75%.

$$GY = -91,1 - 280,5 * ARVI - 276 * SAVI + 765,4 * NDVI - 44 * B6/B1 - 5,4 * 1/B4 + 22,3 * 1/B5 + 1,4 * 1/B7(15) \quad (6)$$

The model (6), developed with the help of Landsat 8 satellite, has adjusted R² of 0.80 and a standard error of 7.1 m²/ha, and explains the basal area of the GA and GD stand types in the research area with a deviation of 7.1 m²/ha, at a rate of 80%.

When the results were evaluated collectively, it was seen that Landsat 8 satellite performed best in the prediction values of all stand parameters in the regression models obtained for the number of trees, volume and basal area.

In the study, the obtained models were also applied to both research areas and the obtained results were interpreted by overlapping with the current stand type map.

3.4. Comparison of developed models with stand map

Among the developed models, the models with the highest R² and lowest standard error were selected and applied to both study areas. For illustrative purposes, this study considered only the volume parameter, and equations (2) and (5) were used for the Kelkit and the İğdir study areas. The layers created for each band were calculated for each pixel using the "raster calculator" command in ArcMap 10.1.

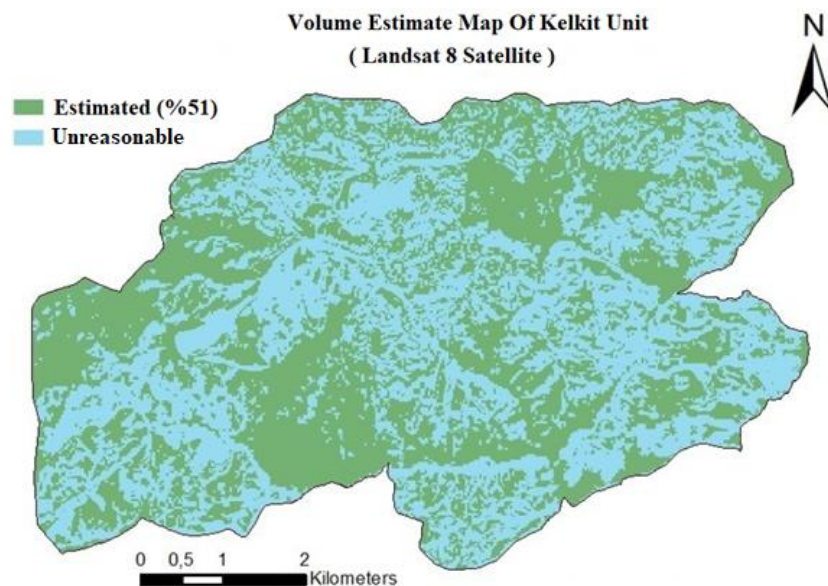


Figure 2. Comparison of stand type map and model outputs in Kelkit research area in terms of stand volume

When the volume map created using stand type map values is compared with the model volume map, the areas located in the same volume class overlap at the level of 51% (Figure 2).

A similar study was carried out for the İğdir research area, and since the stand volume reached high values in this area and the number of classes to be created was very high, classes were created at 100 m³ per hectare intervals and a model volume map was created with the help of formula number 5 (Figure 3).

When the volume map created using stand volume values is compared with the model volume map, the areas located in the same volume class overlap at the level of 62 % (Figure 2).

The reason why success levels fell below expectations for both research areas is that, when delineating stand types during the preparation of forest management plans, the smallest mapping unit is considered to be 5,000 m², and smaller areas are incorporated into surrounding stand types. Given the 30 m spatial resolution of Landsat 8, it produces pixels with an area of 900 m². According to the regulations, representing areas of this size on a 1/25,000 scale stand map is not possible. Furthermore, when preparing the stand type map, local gaps, such as those under roads, power lines, and so on, cannot be represented as separate polygons for the reasons explained above. Consequently, although comparing the obtained model results with the exact stand volume data may not seem reliable, it was deemed important to provide a general idea.

4. Discussion and conclusion

In this study, stand parameters such as volume, basal area, and number of trees were estimated using Rasat, Göktürk-2, and digital aerial photographs, as well as Landsat-8 and Worldview-2 satellite data. A total of 237 sampling plot data were used from the Kelkit and İğdir planning units, which contain stands of two different forest forms managed as even-aged and uneven-aged. The stand parameters calculated from the sample plot data were correlated with the reflectance values obtained for each band of the satellite images using regression analysis, and numerous models were developed.

As a result of the study, it was also possible to compare the results obtained from Turkish medium and high resolution national satellite images with the results obtained from other Landsat 8 and WorldView-2 images obtained from abroad, thus demonstrating the comparative effectiveness of our national satellites in Türkiye.

Among the developed models, considering the number of trees, volume and basal area, Landsat 8 satellite provided the highest success rates of 44%, 77% and 77% for the Kelkit research area and 60%, 75% and 80% for the İğdir research area, respectively.

When the results were evaluated, it was observed that the regression models for the number of trees yielded lower prediction results than those for basal area and volume, and that Landsat 8 satellites were prominent in predicting all stand parameters. Digital aerial photographs, however, yielded significantly lower predictions for all stand parameters. When examining the models generated using Landsat 8 satellite data, it was observed that the SAVI index (NIR, RED) bands and the SWIR bands were more influential in the Kelkit study area.

When the results are compared with the literature, it is observed that some stand parameters have higher coefficient of determination and others have lower. Mohammadi (2007) found R² of 43% and an error of 97.49 m³/ha for the model developed for volume, and an R² of 73.4% and an error of 170 trees/ha. Comparing the results of the study with those obtained by Mohammadi (2007), the number of trees is found to be quite low, while the volume estimate is found to be higher when considering models developed using Landsat 8.

Ateşoğlu (2009), found the adjusted R² for the number of trees to be 0.33 and the standard error to be 313 trees/ha in a study area dominated by beech using Landsat 7, Spot, and Aster satellite images. He estimated 12% of the number of trees with an error of 356 trees/ha using Spot. For the basal area, the adjusted R² yielded as 0.75 at maximum and the standard error as 4.8 m²/ha using Landsat 7. For the volume, it is estimated as 53 m³/ha with a 51% error, again using Landsat 7. In the İğdir and Kelkit research areas, the number of trees was estimated as 44% for Scots pine and 60% for Caucasian fir.

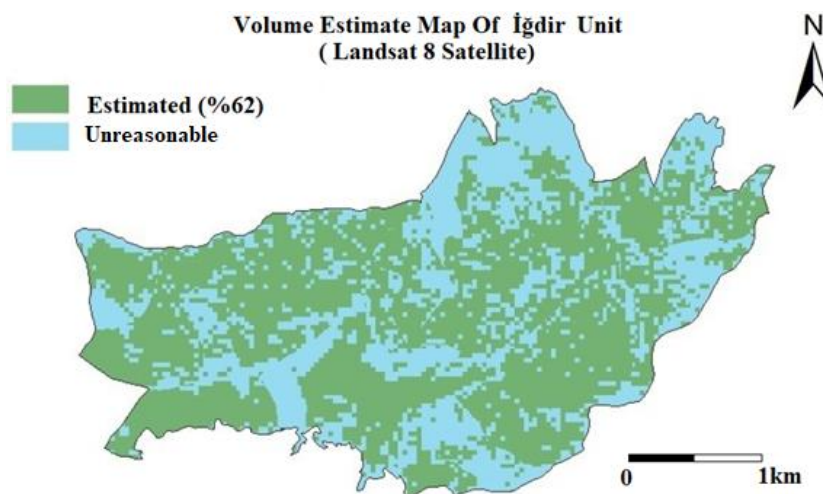


Figure 3. Comparison of stand type map and model outputs in İğdir research area in terms of stand volume

Compared with the results obtained by Mısır (2013), estimated stand volume by 60% using Landsat 7 ETM+ imagery and with 25 different vegetation indices, higher results were obtained for Scots pine and fir. When compared with the results of Şenyurt et al. (2013), who explained 65% and 58% of basal area and the number of trees using Landsat satellite imagery using regression models, it is observed that the models obtained in estimating high basal area and tree count are quite low.

Among stand parameters, the lowest values obtained using remote sensing are the number of trees. This is primarily due to the fact that satellite imagery only considers the color tone of the tree crowns, and trunks below the canopy of the stand, which are therefore ignored or undetected, do not yield meaningful results. Estimated values for basal area and volume are close to each other due to the correlation between the two parameters. While the obtained results for volume and basal area are promising for use in forest management plans, similar studies are needed in mixed stands, steep slopes and broad-leaved forests. However, the study demonstrates that success levels can be increased by making some improvements.

One important improvement is ensuring that the platforms used have high spectral resolution. With the exception of Landsat 8, the other platforms used in this study either lack infrared coverage like Rasat or have extensive coverage of short-wave infrared bands, which are more sensitive to chlorophyll in tree leaves. Using satellites with a wide range of infrared bands or shorter-wavelength infrared bands will increase success. Landsat-8, the satellite with the most successful models, has two different infrared bands. Rasat lacks infrared, while Göktürk-2 and Worldview-2 have bands less sensitive to chlorophyll than Landsat-8. The design of these satellites should definitely consider dividing the infrared wavelength into 3-4 segments. Furthermore, similar models should be developed to account for different geographical regions and species. As in the current study, different models should be developed for different tree species, development stages, canopy cover, and even habitat to increase success. Geological maps can also be used in areas where habitat maps are not available. During the model development phase, sampling plot data can be used. Using reflectance values, radiometric image enhancement, and incorporating LiDAR data and tree heights into the model can significantly increase success. If the shortcomings detailed above are addressed, ground-based measurements can be significantly reduced, especially in practice.

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