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Estimation of managed loblolly pine stand age and density with Landsat ETM+ data

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Abstract

We analyzed the relationship between Landsat ETM+ reflectance values and commercially managed loblolly pine (*Pinus taeda* L.) stand characteristics in east Texas. Multivariate regression techniques were used to predict age and tree density for all stands. A linear combination of NDVI, ETM4/ETM3 and the tasseled cap wetness index was a better predictor of stand age ($R^2 = 78\%$) than other combinations of original bands and derived indices. However, models involving transformed bands did not improve the overall predictability of stand density ($R^2 = 60\%$). Results from the principal component analyses (PCA) conducted on mature stands (age > 18 years) yielded valuable information about the relationship between stand structure and reflectance values recorded by the ETM+ sensor. The first principal component was interpreted as a measure of stand complexity. A linear regression model with infrared bands 4 and 5 as independent variables was able to account for 76% of the variability in stand structure. A second model with transformed bands did not increase the amount of variability in stand structure. Results obtained from this study demonstrate the relationship between loblolly pine stand characteristics and ETM+ reflectance values and the utility of certain transformed bands. Forest managers could use ETM+ data for gaining insights about stand characteristics and this information would be also useful for generating maps required for developing forest management plans.

Keywords: *Pinus taeda* L.; Loblolly pine forests; Stand characteristics; ETM+; Regression analysis; Texas

1. Introduction

Forests are a vital environmental and economic resource and an important component of the global carbon cycle (Running and Nemani, 1988; Running et al., 1989). Ecologically, forests represent critical habitat for many plant and animal species and they play a key role in nutrient cycling, hydrology and other critical ecosystem functions. Forests are economically important to humans and are used for building materials, paper, fuel and many other applications. In terms of carbon, standing forests represents a large carbon pool with disturbed forests acting as carbon sources and regenerating forests as carbon sinks (Foody et al., 1996; Wulder et al., 2004). In this context, commercially managed forests play an important economic and environmental role. Sustainable management of these forests requires forest inventories that include information about forest characteristics and their spatial distribution. Furthermore, because forests undergo change, it becomes imperative that inventory data be updated periodically (Dodge and Bryant, 1976; Avery and Burkhart, 1994).

Traditionally, inventory information has been collected using field surveys or aerial photo interpretation or a combination of these techniques (Lund and Thomas, 1989; Avery and Burkhart, 1994; Kilpelainen and Tokola, 1999). Field survey methods are expensive, labor intensive and time consuming (Trotter et al., 1997). Acquiring and interpreting aerial photos can also be expensive and labor intensive, in addition to requiring trained personnel with knowledge of local forest management practices. Lack of consistency among human analysts in delineating features is another disadvantage of the manual photo-interpretation process (Avery and Berlin, 1992; Lillesand et al., 2000).

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Remotely sensed satellite data could provide some of the required information for updating stand inventories (Danson and Curran, 1993; Wulder et al., 2004) in commercially managed forests. However, the relationship between spectral reflectance and important stand characteristics in different geographic settings is not well documented (Lu et al., 2004). Consequently, the utility of satellite data must be tested for different species at different geographic locations and under different management strategies. This paper describes a study of the relationship between Landsat ETM+ data and stand characteristics in a commercially managed loblolly pine (*Pinus taeda* L.) stand in east Texas.

Studies conducted elsewhere have demonstrated relationships between stand characteristics such as age, stand density, canopy closure, leaf area index (LAI) and satellite reflectance values (Fiorella and Ripple, 1993; Ahern et al., 1991; Gemmell, 1995; Steininger, 2000; Wulder et al., 2004) and some of the studies have demonstrated the importance of the infrared region of the electromagnetic spectrum (Tucker et al., 1985; Justice et al., 1985). Butera (1986) tested the relationship between the canopy closure and the simulated Thematic Mapper (TM) spectral bands in Colorado, USA. In this study, TM data bands predicted forest canopy closure with 57–74% accuracy. Peterson et al. (1986) analyzed forest structure in Sequoia National Park (California, USA) using simulated TM data. Statistically significant relationships were found between the TM bands and stand characteristics such as canopy closure and basal area. Franklin (1986) used regression techniques and conducted similar analyses in Mendocino National Forest (California, USA) and found that leaf biomass and stand basal area of Shasta red fir (*Abies magnifica* var. *shastensis* Lemmon) influenced TM data. In one study, Landsat TM infrared bands were sensitive to forest stand density (Horler and Ahern, 1986).

Danson and Curran (1993) analyzed the factors affecting the response of the near-infrared and red bands of Landsat TM and SPOT HRV data in Corsican pine (*P. nigra* var. *maritima*) stands in England. The near-infrared band of the TM data was highly correlated with structural variables in the stands such as density, height, and mean tree diameter at breast height (dbh). A Landsat band ratio (band 4/band 5) was highly correlated with Douglas-fir (*Pseudotsunga menziesii* (Mirb) Franco) stand age in the western Cascade Mountains of Oregon, USA (Fiorella and Ripple, 1993). The wetness component of the tasseled cap transformation of Landsat data was useful for distinguishing young, mature and old-growth forest stands in the US Pacific Northwest (Cohen et al., 1995). Jakubauskas and Price (1997) examined the relationship between the structural characters of Yellowstone lodgepole pine (*P. contorta* var. *latifolia* Engelm.) and spectral reflectance values of TM data and concluded that several forest stand variables can be predicted from the satellite data. They also concluded that the infrared band region of TM data is important for analyzing forest stand characteristics. Nilson et al. (2001) analyzed changes caused by thinning in boreal forests and concluded that there was an increase in a red reflectance value and a decrease in the near-infrared reflectance value in thinned stands. Wulder et al. (2004) used Landsat ETM+ imagery to analyze lodgepole pine (*P. contorta*) in the Morice Forest District of British Columbia, Canada. Landsat data were able to predict stand age with a standard error of 2.39 years. All of these studies, and others, suggest that satellite data are potentially valuable for characterizing key stand characteristics in different settings.

In spite of these studies, satellite data are not routinely used for stand inventories in commercial forestry (Smith et al., 2003). One reason is that few studies have tested the utility of satellite data specifically in commercially managed forest stands. Another impediment is the perceived mismatch between the information generated from satellite data and the data needs of the forest managers. For example, leaf area index (LAI) and leaf biomass are forest parameters commonly estimated from satellite data because they are useful for studies of biogeochemical cycles. However, LAI and leaf biomass have no direct practical use from the perspective of commercial stand management (Holmgren and Thuresson, 1998). Information derived from satellite imagery must accurately capture relevant stand characteristics including age, density, height and basal area, as well as variations within similar age stands caused by biophysical characteristics. If this could be accomplished, then satellite imagery could be used to augment traditional survey techniques and provide critical updates (Wulder et al., 2004) as well as valuable information for stratifying and identifying variability within stands (Trotter et al., 1997; Gemmell et al., 2001; Wilson and Sader, 2002).

In this study we analyzed the relationship between reflectance values recorded by Landsat ETM+ sensor and loblolly pine stand characteristics using multivariate regression analyses (Franklin, 1986; Jakubauskas and Price, 1997; Wulder et al., 2004). If satellite reflectance values can be related to stand characteristics then valuable insights could be gained by resource managers. This information would enable them to monitor changes taking place within the stands due to management practices and natural factors such as pest infestation and stress. Also, they could use this information to select and prioritize stands for detailed field survey. Regression models generated from these analyses could be used in forest growth models and carbon cycle studies.

2. Study area

A privately owned and managed forest in east Texas (31°21′N latitude; 93°58′W longitude), USA, was selected for this study. There were 380 stands (management units) in this forest with a total area of 5076 ha. The western portion of the tract was in San Augustine County; however, most of the study area was in Sabine County (Fig. 1). These counties receive an annual average rainfall of 123 cm, with monthly averages ranging from 7.4 cm in July to 12.2 cm in May. Mean temperature ranges between 2.2° C in January and 33.9° C in July. Elevation ranges between 46 and 107 m above mean sea level and this part of the county has mostly sandy acidic loamy soils with very deep reddish clayey subsoils.

Loblolly pine and slash pine (*P. elliottii* Engelm.) are the two conifer species growing in this forest. Loblolly stands were grouped and managed as follows: pre-merchantable,

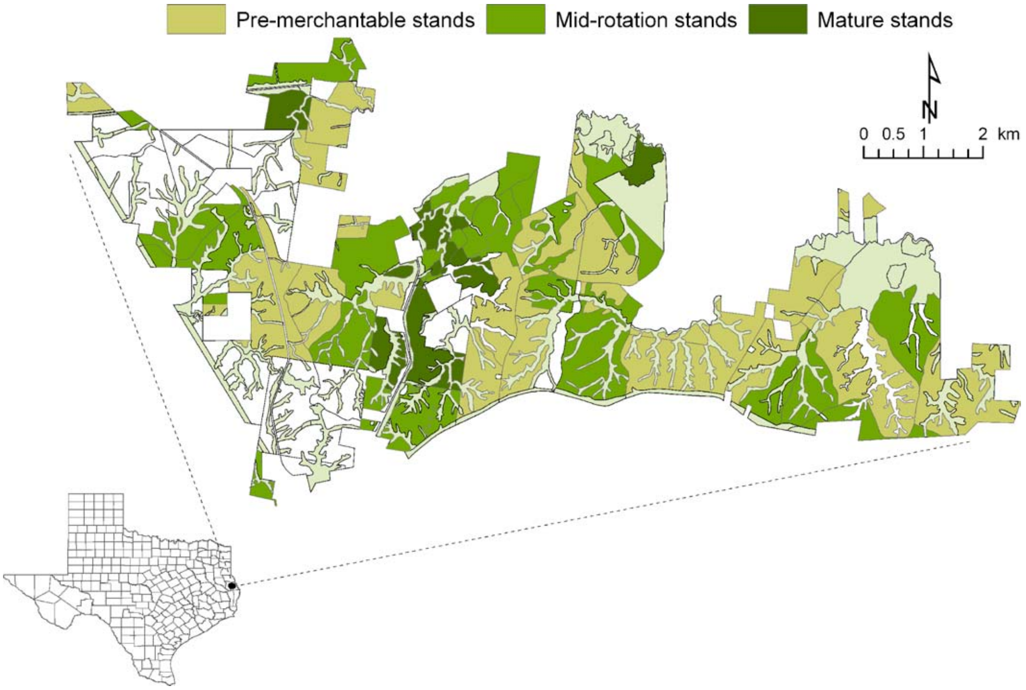

Fig. 1. Geographic location of the study area in Sabine County, Texas, USA.

mid-rotation, and mature. Sivanpillai (2002) provides a detailed description of stand management practices adapted in this study area. The length of time stands remain in the first group was usually 8 years, but can vary based on site quality, site preparation, competition from other vegetation and stand density. Older stands within this group (>5 years) are very dense, with complete canopy closure. Variability within the second group (>8 and <18 years) may be due to type of thinning and residual stand density. Following thinning operations there are gaps within the canopy and the soils between rows of trees are often exposed. This is an important factor that could influence the reflectance values and for these stands it would be a combination of the values from trees and background (soil) materials. Variability in the mature forest (>18 years) may be due to management method, mortality and tree removal, variations in tree height, and the presence of hardwood trees in the overstory. Reflectance values for these stands are influenced by a host of the above-mentioned factors but canopy closure is also an important factor. In general, most planted stands were harvested at approximately 30 years of age.

3. Materials and methods

3.1. Stand inventory data

Forest stand inventory data collected in 1998 were obtained as Geographic Information System (GIS)-based polygons in ESRI shapefile (ESRI, 2000) format. The data included information about tree species, establishment year, plantation method, and average number of trees per acre for all stands. However, for older stands, in addition to the above variables, site condition, mean diameter at breast height (dbh), total height, basal area and management methods were also recorded. Of the 380 stands in the study area, 220 stands consisted of loblolly pine plantation between 2 and 26 years of age. The remaining stands had slash pine, pine-hardwood mix or hardwood species and were excluded from further analyses. Narrow and linear stands that were not wide enough to accommodate three or more ETM+ pixels were eliminated since reflectance values from other features (such as roads) would influence the pixel values recorded for these stands. Smaller stands (less than 3 × 3 ETM+ pixels) were also eliminated from subsequent analyses since their boundary could not be precisely located on the satellite image due to positional errors in the image and GIS data. After screening, 78 loblolly pine stands were selected representing the three management groups and the summary statistics for each group are presented in Table 1. Field visits were conducted to verify that no major changes such as clear-cutting or thinning had occurred in these stands.

Table 1
Summary statistics for the three types of commercially managed loblolly pine stands in east Texas

Variable	Mean	Standard deviation	Minimum	Maximum
Pre-merchantable ($n = 27$)				
Age (years)	6.52	0.643	5.00	7.00
Density (trees/ha)	1670.6	300.9	963.7	2295.7
Mid-rotation ($n = 33$)				
Age (years)	9.82	1.402	8.00	13.00
Density (trees/ha)	1317.8	271.9	966.2	2043.6
Mature ($n = 18$)				
Age (years)	21.2	4.5	15.0	26.0
Density (trees/ha)	657.0	427.0	222.0	1442.0
dbh (cm)	21.4	5.1	12.9	27.9
Height (m)	17.5	3.9	13.4	22.9

3.2. Satellite data processing

Based on earlier studies conducted at the Texas A&M University, Spatial Sciences Laboratory (SSL), Landsat imagery acquired in autumn were able to separate deciduous vegetation from conifers in east Texas. Consequently, a cloud-free Landsat ETM+ scene (Path 25, Row 38) acquired on 6 October 1999 was obtained from the TexasView (http://www.texasview.org) which maintains an archive of Texas satellite data. The image was georectified by the US Geological Survey, Earth Resource Observation Satellite Data Center in Sioux Falls, SD to correct for geometric and terrain distortions. Raw digital numbers associated with the ETM+ pixels were converted to at-satellite radiance using gain and offset values provided by the USGS (Markham and Barker, 1986; Huang et al., 2002).

Stand boundaries for the 78 loblolly stands were overlaid on all six non-thermal bands of ETM+ using ERDAS Imagine software, PC version 8.4 (ERDAS, 1996). Spectral values for each stand were extracted by digitizing non-overlapping windows on screen (Fiorella and Ripple, 1993; Jakubauskas and Price, 1997). Pixels along the stand boundaries were excluded to minimize edge-effects (Makela and Pekkarinen, 2001), which could introduce errors in subsequent analyses.

3.3. Transformed bands and vegetation indices

Transformed bands and vegetation indices are often used to reduce the information content from multiple bands to a single band or index that could be related to certain vegetation phenomenon (Campbell, 2002; Jensen, 2004). For example, several vegetation indices have been developed to highlight differences in vegetation reflectance across the red and infrared regions of the electromagnetic spectrum (Lu et al., 2004). The following transformed bands and vegetation indices were derived from the six bands of the ETM+ data:

1. Greenness condition index (GI) = ETM4/ETM3.
2. Normalized difference vegetation index (NDVI) = ETM4 − ETM3/ETM4 + ETM3.
3. Vegetation condition index (VCI) = ETM7/ETM4.
4. Mid-IR/red reflectance index (MIRI) = ETM7 − ETM3/ETM7 + ETM3.

The tasseled cap transformation (Huang et al., 2002) was used to generate the brightness (TC_B), greenness (TC_G) and wetness (TC_W) index values for each pixel. Tasseled cap components were generated from a linear combination of the six non-thermal ETM+ bands and are widely used in vegetation mapping and monitoring applications (Lillesand et al., 2000; Jensen, 2004).

3.4. Statistical analyses

Stepwise multivariate regression analyses were used to analyze the relationship between stand characteristics (age and density as dependent variables) and the six original and seven transformed ETM+ bands as independent variables. Stepwise regression analysis selects a subset of independent variables that explain most of the variability in the dependent variable. Independent variables of the final model were selected based on a combination of both their individual contribution to the model and the overall R^2-value.

For the mature stands, principal component analyses (PCA) were conducted on the stand attributes (age, density, dbh and height). Eigenvalues obtained from the correlation matrix of the stand attributes and the percent of variance explained were used to determine the number of principal components to be used for subsequent analyses (Manly, 1995). A correlation matrix was used in the analyses since it standardizes the data to zero mean and unit standard deviation thus minimizing the problems associated with differences in the measurement scale for each variable (Danson and Curran, 1993; Manly, 1995). Stepwise regression analyses were used to analyze the relationship between the principal components of the stand characteristics (principal components as dependent variable) and the six original and seven transformed ETM+ bands as independent variables. As before, independent variables of the final model were selected based on a combination of both their individual contribution to the model and the overall R^2-value.

4. Results

4.1. Estimating stand age using satellite data

A linear combination of ETM+ bands 4 and 7 (near and mid-infrared) were better predictors of stand age (adjusted $R^2 = 68\%$) than other ETM+ bands. An inverse relationship was observed between band 4 reflectance values and age, whereas a direct relationship was observed between band 7 reflectance values and age (Table 2). Among the transformed bands, a linear combination of NDVI, ETM4/ETM3 and the brightness component of the tasseled cap transformation were better predictors of stand age (adjusted $R^2 = 78\%$) than any other combination of transformed ETM+ bands (Table 2). NDVI and brightness values were higher for pre-merchantable stands and their values decreased with increasing stand age. The ETM4/ETM3 ratio band, however, increased as stands matured. Since the greenness component of the tasseled cap

Table 2
Results from the stepwise regression procedure (with highest adjusted R^2 values) when stand age was regressed with LANDSAT (original and transformed) bands

Dependent variable	Independent variables	Coefficient	Constant	R^2 (adj)	RMSE
Age	Band 4	−0.347			
	Band 7	0.201	68.6	68.2	3.44
Age	NDVI	−840.8			
	TM4/TM3	128.9			
	TC_B	−0.261	122	77.5	2.89

Both regression models significant at 95% level ($p = 0.05$); RMSE: root mean square error; NDVI: normalized difference vegetation index; ETM4/ETM3: band 4/band 3 ratio; TC_B: brightness component of the tasseled cap transformation.

Table 3
Results from the stepwise regression procedure (with highest adjusted R^2 values) when stand density was regressed with LANDSAT (original and transformed) bands

Dependent variable	Independent variables	Coefficient	Constant	R^2 (adj)	RMSE
Density	Band 4	25.5			
	Band 7	−37.9			
	Band 1	123.6	−21314	60.4	312.5
Density	NDVI	32255			
	ETM4/ETM3	−5422			
	TC_B	32.8			
	TC_W	26.4	−8703	60.1	313.4

Both regression models significant at 95% level ($p = 0.05$); RMSE: root mean square error; NDVI: normalized difference vegetation index; ETM4/ETM3: band 4/band 3 ratio; TC_B: brightness component of the tasseled cap transformation; TC_W: wetness component of the tasseled cap transformation.

transformation and the NDVI are highly correlated, the stepwise regression analyses chose only one of them.

Regression models with the transformed bands were able to account for more variability in age (adjusted $R^2 = 78\%$) than those with original ETM+ bands (adjusted $R^2 = 68\%$). The root mean square error obtained for the model with transformed bands was also lower (2.89 years) than the model with original bands (3.44 years).

4.2. Estimating stand density using satellite data

The regression model with ETM+ bands 1, 4 and 7 (Table 3) as independent variables was a better predictor of stand density (adjusted $R^2 = 60\%$) than other combinations of ETM+ bands. Reflectance in bands 4 and 1 increased with stand density while reflectance in band 7 decreased.

The regression model with transformed bands did not explain any more variability in stand density ($R^2 = 60\%$) than that captured by the original ETM+ bands. For the latter, NDVI, ETM4/ETM3 and the brightness (TC_B) and wetness (TC_W) components of the tasseled cap transformation, were the best predictors of stand density. NDVI, brightness and wetness values were higher for dense stands while ETM4/ETM3 values decreased. The root mean square values associated with both regression models were similar (Table 3).

4.3. Relationship between reflectance values and structural characteristics of mature stands

Results from the PCA indicate that the first principal component (PC1) of the stand structural variables (age, density, dbh and height) accounted for 92% of their variance (Table 4). Age, dbh and total height were inversely (negatively) loaded on PC1 whereas stand density was positively loaded based on inspection of the PCA eigenvectors (Table 5). Since the remaining principal components had eigenvalues less than 1, we omitted them from further analyses. Younger but dense stands had higher PC1 scores, whereas older stands containing taller trees with lower density had lower scores. PC1 was interpreted as a measure of stand structure or complexity, where low values corresponded to complex (older and taller with fewer stems) stands and higher values corresponded to less complex (young and shorter with dense stems) stands. In older stands there are more gaps in the canopy due to mortality and thinning, resulting in multiple scattering and absorption (Danson and Curran, 1993). Also, the variability in height is higher as stands mature and this could result in shadows and internal scattering of light. Results obtained from the PCA generated a single variable associated with forest structural conditions within mature stands. This index variable was used as the dependent variable in the subsequent regression analyses.

Table 4
Eigenvalues computed from correlation matrix of age, density, dbh, total height

Principal component	Eigenvalue	Variance (%)	Cumulative variance (%)
1	3.669	91.7	91.7
2	0.227	5.7	97.4
3	0.063	1.6	99.0
4	0.041	1.0	100.0

Table 5
Eigenvectors computed from correlation matrix of age, density, dbh and height

Stand variables	Eigenvectors		
	PC1	PC2	PC3
Age	−0.504	0.429	0.330
Density	0.501	−0.509	−0.002
dbh	−0.507	−0.254	−0.804
Height	−0.487	−0.702	0.494

A linear combination of ETM+ bands 4, 5 and 7 were better predictors (adjusted $R^2 = 76\%$) of mature stand structure (PC1) than any other combination of ETM+ bands (Table 6). Reflectance in ETM+ bands 4, 5 and 7 decreased as stands became older and more complex. The model with transformed ETM+ bands did not show any improvement over the model with original ETM+ bands. Vegetation condition index (VCI), brightness and wetness components of the tasseled cap transformation were better predictors (adjusted $R^2 = 76\%$) than any other combination of transformed bands (Table 6). These results confirm that for mature and complex stands,

Table 6
Results from the stepwise regression procedures when the first principal component, interpreted as stand structure, was regressed with LANDSAT (original and transformed) bands

Dependent variable	Independent variables	Coefficient	Constant	R^2 (adj)
PC1	Mean 4	0.183		
	Mean 5	0.834		
	Mean 7	1.200	−19.61	76.0
PC1	TC_B	0.207		
	TC_W	0.420		
	VCI	58.2	−75.1	76.1

Both regression models significant at 95% level ($p = 0.05$); RMSE: root mean square error; TC_B: brightness component of the tasseled cap transformation; TC_W: wetness component of the tasseled cap transformation; VCI: vegetation condition index (band 7/band 4 ratio).

overall bio-physical structure influences reflectance characteristics. Principal component analyses were able to provide insights about the relationship between stand structure and Landsat reflectance values.

5. Discussion

A combination of transformed bands (NDVI, ETM4/ETM3 ratio, brightness component) explained more variance in stand age than other combinations of transformed ETM+ bands. Among original ETM+ bands, a combination of bands 4 and 7 accounted for more variance in stand age than other combinations. Infrared reflectance bands have been found to be significant predictors of stand age in other studies based on correlation, regression or other statistical analyses (Danson and Curran, 1993; Foody et al., 1996; Lu et al., 2004). NDVI values were strongly correlated with vegetation condition index band and are associated with vegetation growth and vigor. Some studies have found that NDVI values were related to forest structural parameters (Sader et al., 1989). R^2 values obtained in this study were higher than those obtained when ETM+ bands 1, 4, 5 and 7 ($R^2 = 62\%$) and transformed bands ($R^2 = 58\%$) were used to predict stand age in lodgepole pine forest (Jakubauskas and Price, 1997). Similarly a combination of ETM+ bands 3, 5 and 7 and the wetness index of the tasseled cap transformation explained most ($R^2 = 68\%$) of the variance in lodgepole pine stands in Canada (Wulder et al., 2004). Results from these analyses demonstrate that reflectance values recorded by the satellite are related to the stand age. ETM+ data could be useful for detecting differences within stands based on the reflectance values recorded by the pixels. This information could be used to compare multiple stands of a similar age. Differences in reflectance values could alert the forest managers to potential problems that are occurring within the stand.

For young and dense stands, there were fewer gaps in the canopy therefore infrared reflectance was very high. However, in mature stands with lower density, there are more gaps in the canopy resulting in canopy shadows. In this situation, infrared radiation would penetrate deeper into the forest and internal scattering and absorption might take place, reducing total outgoing radiance (Danson and Curran, 1993). In certain instances, stand density was estimated rather than measured due to access constraints. For example, 8-year-old stands were dense and it was not possible to lay plots and obtain values. The estimated value for density is used based on past year records and management practices. This could have resulted in the lower R^2 values obtained for density in comparison to age. Infrared bands were found to be significant predictors of stand density for loblolly pine, a result that has been observed for other conifer species. These results are similar to those obtained in other studies (e.g., Jakubauskas and Price, 1997), but the R^2 values obtained for managed stands were higher than those obtained for natural forests. This information could be used to identify differences in tree density within large stands. Statistical estimates obtained through traditional methods produce a single value for the entire stand along with a standard deviation. However, spatial distribution captured by ETM+ data could be used to identify or subdivide large stands and devise suitable and effective management strategies.

Results from this study are in agreement with those that analyzed the relationship between conifer stand characteristics and satellite reflectance in the US and elsewhere. These results demonstrate that the reflectance values recorded by ETM+ sensors are related to loblolly stand characteristics, and could be used by resource managers to gain insights about variations within managed stands. This information could also be used to update existing stand maps, identify locations within stands that might require treatments, and plan other management activities. However, the models generated in this study are limited to this geographic area and commercially managed loblolly pine stands. Nevertheless this methodology could be adapted to other species and geographic regions.

Forest managers could also obtain information about past changes in their stand using the 30 m resolution Landsat data that have been collected since mid 1980s. For monitoring future changes data collected by Landsat and other moderate resolution sensors such as ResourceSat (Indian Remote Sensing program) and SPOT 5 satellites could be used. These multitemporal datasets would be useful for obtaining information about stand characteristics after events like pest infestation or natural disasters. Addition of other indices such as moisture stress index (Rock et al., 1986), soil adjusted vegetation index (Huete, 1988), mid-infrared index (Musick and Pelletier, 1988), and stand structural index (Fiorella and Ripple, 1993) could improve the results by incorporating differences in leaf moisture and background soil.

Recent studies have demonstrated that certain forest stand characteristics could be derived from light detection and ranging (LIDAR) data. For example, Roberts et al. (2005) estimated height and crown dimensions of 4- and 16-year-old loblolly pine plantations in Mississippi (USA) and Texas (USA). They concluded that tree height estimates had higher precision than crown dimension estimates, and that LIDAR data could be useful for deriving vertical structure of forest stands. Hall et al. (2005) and Lefsky et al. (2005) demonstrated that LIDAR data could be used estimate stand characteristics in Colorado (USA) and the US Pacific Northwest, respectively. Information derived from LIDAR data could be used in conjunction with the information derived from Landsat data to gain insights about stand characteristics. Periodically updated information through satellite remote sensing technology could provide valuable information about changes to stand structure and help forest resource managers to devise suitable management plans.

6. Conclusions

In this study, relationship between reflectance data recorded by the Landsat ETM+ data and commercially managed loblolly pine stand characteristics were analyzed through multivariate regression analyses techniques. Statistically significant relationships were found between loblolly pine stand characteristics and corresponding reflectance values recorded by the ETM+ sensor.

A combination of transformed ETM+ bands, NDVI, ETM4/ETM3 and the brightness component of the tasseled cap transformation were better predictors of stand age than the raw ETM+ bands. Combination of these three transformed bands yielded an adjusted R^2-value of 77.5%, with a standard error of 2.89 years.

A linear combination of ETM+ bands 4, 7 and 1 yielded an adjusted R^2-value of 60.4%. However, the transformed bands did not improve the predictive power of the models generated for estimating stand density.

Principal component analyses and subsequent regression model building provided insights about the relationship between stand structure and ETM+ reflectance values. The first principal component was interpreted as a measure of stand complexity and was regressed against original and transformed ETM+ bands. A linear combination of the three infrared bands of ETM+ data yielded an adjusted R^2-value of 76%.

Based on the results from this study we conclude that ETM+ data are useful to estimate age and density and gain insights about structural characteristics about commercially managed loblolly pine stands.

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