

Forest Stand Canopy Structure Attribute Estimation from High Resolution Digital Airborne Imagery

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Abstract—A study of forest stand canopy variable assessment using digital, airborne, multispectral imagery is presented. Variable estimation involves stem density, canopy closure, and mean crown diameter, and it is based on quantification of spatial autocorrelation among pixel digital numbers (DN) using variogram analysis and an alternative, non-parametric approach known as slope-break analysis. Variable estimation proceeds from identification of tree tops. Variable accuracy assessment is obtained via value comparison with a spatially precise set of 34 Forest Inventory and Analysis (FIA) design plots installed in five cover types common in the Midwest region. Results show that slope-break-based variable estimates are superior to those obtained using variograms. Estimated root mean square errors for the former average at the plot level were 6.5 percent for stem density, 3.5 percent for canopy closure, and 2.5 percent for mean crown diameter. These error rates are equivalent, if not superior to (lower than), those obtained via traditional forest stand cruising by experienced personnel. The approach benefits from parsimonious parameterization and is amenable to automation.

Introduction

High spatial resolution digital imagery holds promise for extracting forest canopy structure information, including delineation of individual tree crowns (Brandtberg, 1997), canopy closure, stem density, species composition and crown classification (Gerylo and others 1998; Sheng and others 2001). However, to date, forest inventory and canopy structure information is still almost exclusively derived from aerial photographs (Wulder and others 2002) via manual interpretation, a process known to be time consuming, labor intensive, and error-prone (Biging and others 1991). This is likely due to the absence of examples of methodologies that operate on high resolution imagery and are capable of reliably assessing forest canopy structure variables in a variety of forest conditions. The handful of studies that have successfully used such imagery in forest inventory parameter estimation operated on a single stand, or a very limited number of, typically coniferous, stands. Spatially extended investigations have been hindered by logistic concerns related to the acquisition of field information (Gong and others 1999), imagery idiosyncrasies (variable brightness regimes, registration issues) (Mikkola and Pellikka 2002), and absence of process automation paradigms (McGraw and others 1998). Hence, little is known about whether high spatial resolution imagery can be used to reliably predict forest

structure attributes for stands different from those used for methodology.

The USDA Forest Service Forest Inventory and Analysis (FIA) program is perhaps the only effort with the knowledge, experience, infrastructure, and demonstrated capability to realistically support investigations that require spatially explicit forest inventory information over a variety of cover types, ecological conditions, and ownership regimes at the national level. However, in its current configuration, the FIA program assesses only some of the key aspect of canopy structure: height, stem location relative crown position with dominance class for each tree. Two other variables, canopy closure at the plot level and individual tree crown size, usually expressed as horizontal crown width (or diameter), known to be important inputs to forest models (Sprinz and Burkhart, 1987; Deutschman and others 1997; Trichon, 2001) and critical in modeling forest fires (Keane and others 1999) remain unknown. Reliable estimation of these two variables, along with identification of individual trees, (both considered prerequisites for a complete description of forest stand canopy structure) from high resolution digital imagery analysis would complement the FIA-collected data, and could be widely applied to a variety of forest conditions.

Unlike coarse resolution imagery where each pixel comprises the composite reflectance of many trees, in high spatial resolution digital imagery of forested landscapes each tree crown is represented by multiple pixels.

Some of them correspond to the sunlit portion of tree crowns; others represent crown portions in shadow. View and illumination angle, tree geometry, foliage orientation and bidirectional reflectance operate synergistically to result in a variation of radiance, represented by pixel digital numbers (DN), at different locations within an individual crown (Leckie and others 1992). Spectral DN values also vary as a function of the tree crown depth and reach a maximum (highest reflectance) near the crown center, diminishing as distance from crown center increases) (Li and Strahler, 1992). Hence, individual trees may be discerned in high resolution imagery as localized regions of DN characterized by higher values in the center, or close to the center, of the region and progressively lower DN values towards the region's periphery. The identification and descriptive characterization of such regions in the imagery, and, therefore, the identification of individual tree crowns and their attributes (e.g., distance between crowns), can potentially be accomplished by quantifying the spatial autocorrelation present in the imagery, or, equivalently, the maximum distance at which pixels exhibit DN value correlation.

The objective of this study was to investigate whether forest stand canopy structure variable estimates (stem density, average crown diameter, canopy closure) could be obtained reliably via pixel DN spatial autocorrelation structure analysis. The investigation was performed on five cover types common to the Great Lakes region using a detailed set of field observations that conform to the current FIA field data collection protocol from multiple, non-adjacent stands.

Methods

The two study sites in Michigan's Grand Traverse and Wexford Counties, were about 10 km apart: Site I's 8,805 hectares centered at 48°38'N, 85°35'W and Site II's 12,626 hectares centered at 44°29'N, 85°32'W. Both sites are flat and contain a wide variety of forest cover types, including most of those found in Michigan's northern lower peninsula: 1. aspen [big tooth (*Populus grandidentata*) and quaking (*Populus tremuloides*) aspen], 2. northern hardwoods [mainly sugar maple (*Acer saccharum*), red maple (*Acer rubrum*), American beech (*Fagus americana*), black cherry (*Prunus serotina*), basswood (*Tilia americana*) and white ash (*Fraxinus americana*)], 3. oak [white (*Quercus alba*) and red (*Quercus rubra*) oak], 4. natural pine [mainly white pine (*Pinus strobus*)], and 5. pine plantations [mainly red pine (*Pinus resinosa*)].

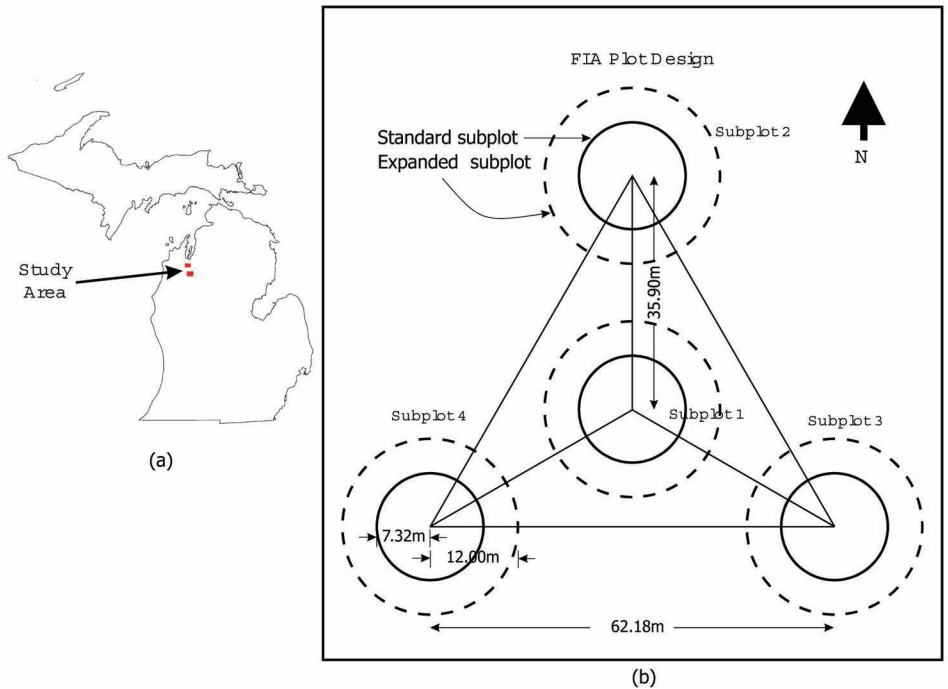
Imagery was acquired on August 11, 1999, using the Digital Airborne Imaging System (DAIS [Space Imaging,

1999]). The 16-bit, four-band images over the visible and near infrared (NIR) part of the electromagnetic spectrum was acquired by frame (digital array) cameras equipped with appropriate band-specific filters on a 2x2 arrangement. Nominal resolution ranged from 0.890 to 0.926m and flight height averaged 2000m above ground level.

A total of 34 plots, (16 at site I and 18 at site II), were established in five forest cover types that had a minimum of 60 percent canopy closure. Plots were situated on flat ground, and within the interior of homogeneous stands. Stand homogeneity was evaluated with field inspections. Field data was collected in the summer of 2000, using a protocol patterned on the National FIA plot design (fig. 1). To ensure an adequate sample of trees in each subplot, subplot radius was increased from the standard 7.32m to between 10 and 15m, depending on the mean tree stem diameter for the plot. Canopy structure variables, including the horizontal extent of individual tree crowns as observed from the ground, and stem locations were assessed. All spatial and tabular data on tree crowns and stem locations were organized as Geographic Information System layers transformed into the coordinate system of the plot's corresponding DAIS image.

The derivation of canopy structure variables followed a four step procedure (fig. 2). Initially, for each image frame containing a plot, spatially distributed estimates of spectral autocorrelations were computed for each pixel via variogram analysis (Curran and Atkinson, 1998) and a non-parametric approach known as slope-break analysis (Wulder and others 2000). The latter is described below. In the second step, often referred to as local maximum filtering (LMF), the distributed autocorrelation estimates obtained by using the variogram and slope break analyses, here after referred to as variogram range and slope break length respectively, were used to determine the size of a kernel (moving window) passed over the pixels representing a plot. At each instance of the moving window, the pixel with the highest DN was identified as a tree top. Subsequently, the number of identified tree tops was used as an estimate of stem density for the plot. In the third step, the variogram range and slope break length identified in step one for each pixel identified as a tree top in step two were used to delineate the tree crown around each of the tree top pixels. Because variogram analysis produces omnidirectional imagery autocorrelation estimates, the tree crowns delineated using variograms were circular. The directional autocorrelation estimates produced using the slope break approach, delineated crowns that, in general, approximated ellipsoids. In the final step, the overlay of all crowns produced estimates of plot canopy closure and mean crown size. The estimates of stem density, canopy closure and crown size were then compared to those obtained with field measurements.

Figure 1. a. Location of the study area, and b. pictorial depiction of the Forest Inventory and Analysis plot design used for the collection of field observations of canopy structure.



Although all imagery bands were initially considered for the estimation of canopy structure parameters, preliminary investigations showed that the use of the blue band produced results consistently inferior to those obtained by using the remaining bands. This finding was attributed to the substantial scattering of sunlight at the blue wavelength, and, hence, diffuse canopy illumination, which results in reduction of imagery contrast and an overestimation of imagery spatial autocorrelation over forested landscapes (Gatzolis, 2003). Given the similarity of canopy structure parameter estimates obtained by using the green, red, and NIR bands on a selected subset of plots and in the interest of reducing the computational and processing load, only the NIR band was used further.

Slope break-based estimates of local image autocorrelation were obtained by relaxing the parametric structure of the variogram. For each pixel in the imagery, an omnidirectional set of transects was analyzed to assess the distance (in whole pixel increments) at which a minimum DN was encountered. Slope breaks could also be described as the first inflection point in the gradient of reflectance or brightness along a transect. Although a large number of transects can be considered, in practice, slope breaks are computed along the eight cardinal directions. The extent of spatial autocorrelation or, equivalently, the slope break length, was computed as the average distance from the center of the processed pixel to the inflection points along all transects. The standard slope breaks algorithm introduced by Wulder et al. (2000) was modified in this study and furnished with a set of heuristics, which were adaptive to the local brightness conditions

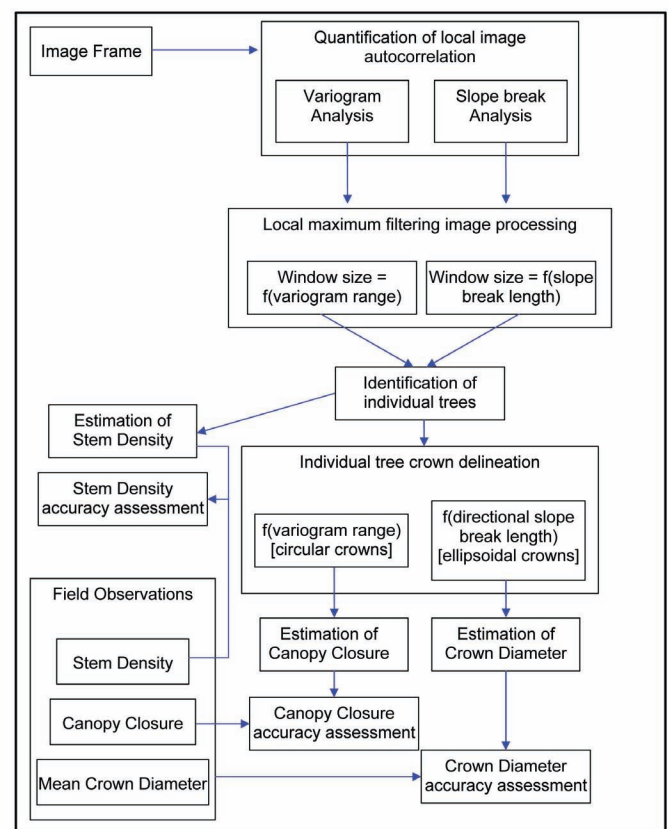


Figure 2. Flow chart of the procedures employed in the estimation of canopy structure parameters from high resolution digital imagery and assessment of their accuracy against field observations.

(DN along the processed transect) and were designed to prevent the extension of the transect inflection point beyond the edge of a crown towards shaded canopy openings. Local imagery autocorrelation estimates via slope breaks offered substantial improvement in computation efficiency when compared to those obtained via variogram analysis. Because, however, fewer pixels were engaged in the computation of slope breaks, the resulting autocorrelation estimates were likely more susceptible to bias introduced by random noise embedded in pixel DNs (Pouliot and others 2002).

Results and Discussion

Variogram ranges and slope break lengths computed for a large number of pixels representing tree crowns showed the former to vary substantially less than the latter. For all 136 subplots, the mean variogram range exceeded the mean slope break length. Often though, the variogram range computed for a particular pixel would be shorter than its slope break equivalent measure, particularly for pixels positioned at or near the center of the sunlit portion of a large crown. Slope break lengths computed for transects parallel to the solar plane and extending through canopy openings were sometimes shorter for pixels situated on sunward crown portions than those for crown portions facing away from the sun. Such instances occurred sporadically in northern hardwoods and oak subplots and rarely in the other cover types.

Strong linear relationships were found between predicted and observed plot stem densities for both variogram and slope break methods (table 1). Linear regression models developed by fitting image-processing-derived canopy structure variables onto variable estimates obtained from field observations exhibited regression slope coefficients always less than 1, with the exception of canopy closure estimated using variograms

for which the regression slope coefficient was 1.078. This observation suggests LMF image processing, in general, would tend to overestimate stem density and mean crown size for low density stands and/or those composed of small diameter crowns, and underestimate them in high stem density or large crown forest stands. Unlike stem density and crown diameter, the estimation bias appeared to be analysis-method specific, with variograms underestimating the canopy closure of stands containing openings and slope breaks overestimating it. The estimation bias patterns are evident when prediction errors are plotted against the corresponding observed values (figs. 3 to 5). Irrespective of analysis method, densities at approximately the 350 stem/ha level, and mean crown diameter of 5m, yielded minimal or no estimation bias. Variogram-derived stem density exhibited, in regard to observed density, root mean square errors (RMSE) approximately two times larger than the slope break-derived stem densities (table 2). Variograms and slope breaks appeared to perform equally well in the assessment of crown closure with RMSE of only about 3.5 percent. Finally, slope breaks emerged as crown diameter predictors superior to variograms with an RMSE for the former only about 1/3 of that for the later (2.5 and 6.9 percent respectively, table 2).

Several oak and northern hardwood subplots in this study contained large, mature trees with crowns of complex morphology and often two or more reflectance maxima, and several canopy openings. These subplots sometimes had crowns of similar size and uniform distribution and sometimes had crowns of variable size and distribution. Further stand structure complexities were introduced by tree tops of shorter codominant trees positioned at the edge of larger adjacent crowns with which they formed composite crowns. Individual tree crowns in such instances were sometimes difficult to discern even with field inspection. In the presence of large-crown trees, and uniform crown and canopy opening size distribution,

Table 1. Parameter values of linear regression models constructed by fitting canopy structure estimates generated via local-maximum-filtering-based image processing to corresponding estimates derived from field observations in 34 FIA-design plots.

LMF Prediction Method		R ²	Slope	Intercept	Observed Values		
					Range	Mean	St.Dev.
Stem Density (trees / ha)	Variograms	0.986	0.741*	91.81*	180 – 707	449.2	164.2
	Slope Breaks	0.996	0.864*	44.70*			
Canopy Closure (percent)	Variograms	0.941	1.098*	-7.70*	66.0 – 98.8	83.9	10.3
	Slope Breaks	0.930	0.817*	15.30*			
Mean Crown Diameter (m)	Variograms	0.942	0.700*	1.58*	4.00 – 7.54	5.1	1.0
	Slope Breaks	0.990	0.921*	0.42*			

* Significant at $\alpha = 0.01$

Stem Density Prediction Errors

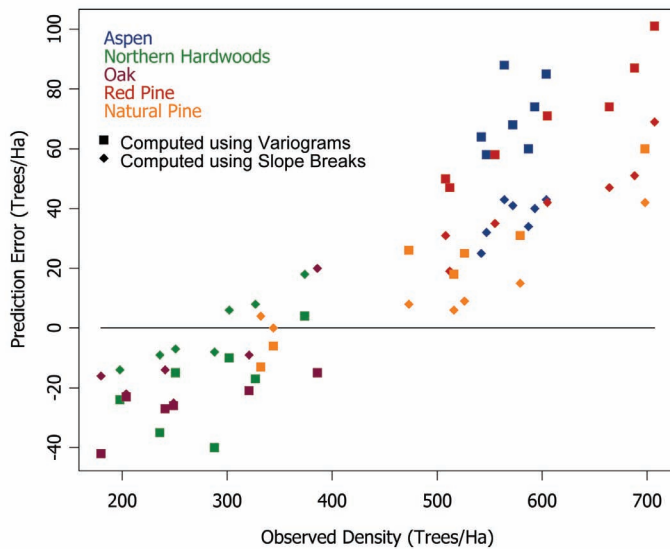
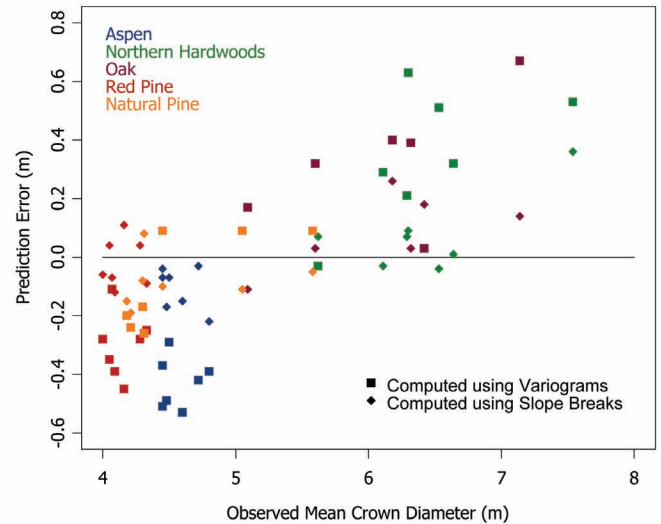


Figure 3. Plot stem density discrepancies between values obtained by using local-maximum-filtering-based image processing and corresponding field measurements.

Mean Crown Diameter Prediction Errors



Canopy Closure Prediction Errors

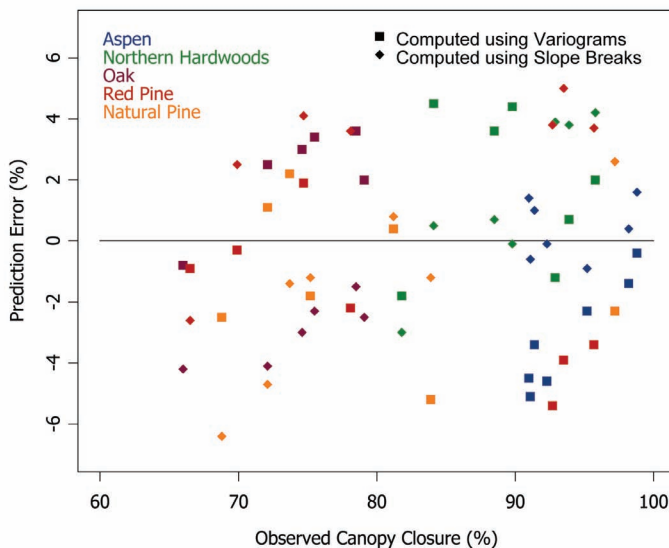


Figure 4. Plot canopy closure discrepancies between values obtained by using local-maximum-filtering-based image processing and corresponding field measurements.

the slope break-based and variogram-based methods performed equivalently in stem density prediction. By contrast, the presence of crown size variability or variable-sized canopy openings resulted in better accuracy for slope break-derived predictions of stem density, thereby corroborating that slope breaks are capable of adjusting well to local stand structure conditions. Low levels of variability in canopy openings and crown sizes precluded a reliable assessment of those canopy structure

conditions on stem density predictions for the other three cover types.

Errors of commission in identifying trees due to multiple tree crown maxima and corresponding tree tops identified using variograms in the presence of large northern hardwoods and oak trees produced mean crown diameter underestimation proportional to crown size but appeared to only minimally affect the accuracy of canopy closure predictions. Because it requires only 1 out of 10 trees with average crown diameter of 10m to be mistakenly identified as two separate stems in a subplot for an 8 percent reduction in subplot mean crown diameter value to occur, crown diameter predictions in large tree crown stands were more susceptible to errors of tree commission than of omission.

Stem density was underestimated for most of the natural pine and all of the red pine plantation and aspen subplots largely because the presence of small crowns increased omission error rates. Errors of omission would often occur where most of the sun-facing crown of a codominant tree was shadowed by adjacent dominant trees, resulting in a lower brightness value for the top of that tree.

A special case of variogram range-based stem density overestimation could arise in stands in which tree arrangement follows systematic and anisotropic patterns such as in red pine plantations with past thinning operations restricted along plantation rows. In thinned red pine plantation stands, the reduced variability in canopy reflectance along planting rows often resulted in variogram ranges that exceed the planting space between rows by 50 percent or more, particularly for planting row

Table 2. Root Mean Square Error (RMSE) between canopy structure variable estimates predicted via local-maximum-filtering-based image processing and corresponding field measurements. Values in parentheses represent percent absolute error from observed values.

	LMF Prediction Method	RMSE
Stem Density (trees / ha)	Variograms	50.67 (11.3)
	Slope Breaks	29.06 (6.5)
Canopy Closure (percent)	Variograms	3.00 (3.6)
	Slope Breaks	2.93 (3.5)
Mean Crown Diameter (m)	Variograms	0.36 (6.9)
	Slope Breaks	0.13 (2.5)

orientation in the east-west direction. Variogram range overestimation was then translated into artificially large moving windows, and ultimately tree omission errors. Such canopy structure conditions would also promote overestimation of canopy closure and crown diameter, because the stand canopy portion actually occupied by omitted trees would be typically assigned during the crown delineation process to adjacent trees along the rows, thus inflating crown diameter, while rarely predicting canopy openings.

The imposition of heuristic rules on slope break computations was intended to avoid substantial overestimation of LMF window sizes, and canopy closure and mean crown diameter predictions. Without the heuristics, canopy openings between trees would occur only as sliver polygons between adjoined crowns because of crown representation fidelity issues due to the limited number of directions analyzed around each identified tree top. The implication of these limitations on canopy structure variable values would likely be negligible in high canopy closure stands but could be substantial in the presence of canopy openings.

The application of these methods for canopy structure prediction via high resolution imagery might not be advisable for stands with medium or low canopy closure or where stand conditions permit direct illumination of the forest floor or background vegetation. In such conditions, grass, exposed soil, or bushes could easily be misidentified as tree tops during LMF processing, and variogram ranges could represent the mean diameter of canopy openings rather than the size of crowns. The 60 percent minimum canopy closure threshold imposed as a prerequisite for plot installation in this study precluded any occurrences of sunlit background in the plots. Although openings did exist and were sometimes equivalent in size to the crowns of dominant trees, the height of adjacent trees placed them in shadow. Band-ratio-based imagery pre-processing could potentially reduce the effect of non-vegetated, sunlit stand background on predicted canopy variable values.

Conclusion

The two forms of DN autocorrelation quantification used in this study, one parametric based on variogram analysis and one non-parametric based on a set of simple heuristic rules, have revealed promising potential of high spatial resolution digital imagery as a source for extraction of reliable forest canopy structure information. The few known other investigations that have attempted stem density predictions, primarily in coniferous forests, found prediction error rates that have rendered them and the methodologies employed of little utility for inventory or management purposes. In this study, the field acquisition of a detailed and positionally precise set of observations on stand structure was distributed among five deciduous and coniferous cover types in northern Michigan. This has provided a better understanding of the relationships between canopy characteristics and reflectance regimes embedded in digital imagery. The study has also developed methods that are capable of producing reliable predictions not only for forest stand density but also for canopy closure and mean crown diameter.

Unlike traditional investigations that rely strictly on the spectral properties of pixels representing tree crown portions to describe the horizontal structure of forest canopies, all analysis methodologies employed in this study are local in scope. As such, they are independent of brightness variability between image frames and bidirectional reflectance effects, issues that are known to burden the application of traditional spectrally-based investigations (Gatzliolis, 2003). Therefore, the methods presented here are perhaps well-suited to determining the canopy structure of plots that are sparsely distributed across the landscape, such as those in the FIA plot allocation scheme. With high resolution imagery lately available even from satellite platforms, and in light of the projected reduction in acquisition cost, it is likely that certain types of forest inventory information at the individual tree level extracted from such imagery would become an integral part of forest management and planning.

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