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Estimating average tree crown size using spatial information from Ikonos and QuickBird images: Across-sensor and across-site comparisons

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ABSTRACT

The forest canopy is the medium for energy, mass, and momentum exchanges between the forest ecosystem and the atmosphere. Tree crown size is a critical aspect of canopy structure that significantly influences these biophysical processes in the canopy. Tree crown size is also strongly related to other canopy structural parameters, such as tree height, diameter at breast height and biomass. But information about tree crown sizes is difficult to obtain and rarely available from traditional forest inventory. The study objective was to test the hypothesis that a model previously developed for estimation of tree crown size can be generalized across sensors and sites. Our study sites include the Racoon Ecological Management Area in southeast Ohio, USA and the Duke Forest in North Carolina Piedmont, USA. We sampled a series of circular plots in the summers of 2005 and 2007. We derived average tree crown diameter (CD) for trees with diameter at breast height (DBH) greater than 6.4 cm (2.5 in) for each sampling plot. We developed statistical models using image spatial information from Ikonos and QuickBird images as the independent variable and CD for stands in Ohio as the dependent variable. The models provide an explanation of tree crown size for the hardwood stands comparable to other approaches ($R^2=\sim 0.5$ and RMSE = 0.83 m). Moreover, the models that estimate tree crown size using the ratio of image variances at two spatial resolutions can be applied across sensors and sites, i.e. the statistical models developed with Ikonos images can be applied directly to estimate tree crown size with QuickBird image, and the statistical models developed in Ohio can be applied directly to estimate tree crown size with images in North Carolina. These results indicate that the model developed based on image variance ratio at two spatial resolutions can be used to take advantage of existing sampling plot data and images to estimate CD with more recent images, enhancing the efficiency of forest resources inventory and monitoring.

1. Introduction

Forest canopy is the medium for energy, mass, and momentum exchanges between the forest ecosystem and the atmosphere. These exchanges determine the nature of goods and services that terrestrial ecosystems can offer and depend on canopy structure (Chen & Coughenour, 1994; Ni et al., 1997; Song et al., 2009). Tree crown size is one of the key canopy structural parameters because crowns are the space within which leaves are attached to the trees. Thus, for a stand with given leaf area index (LAI), crown size indicates how the leaves are organized in space. Associating leaves with crowns allows the representation of gaps between crowns, making simulation of sub-canopy solar radiation regimes more realistic (Song & Band, 2004). Gaps in the canopy are critical for modeling plant regeneration on the forest floor (Botkin et al., 1972; Shugart & West, 1977; Urban, 1990). Consideration of between-crown gaps is a major step toward more realistic characterizations of forest canopies from the traditional turbid medium representation where leaves are assumed to be randomly distributed in the entire canopy space without crown boundaries. Song et al. (2009) found that a uniform canopy representation can lead to overestimation of radiation interception, transpiration, and carbon assimilation in the canopy. Therefore, tree crown size is essential for more accurate understanding of ecosystem function. Unlike diameter at breast height (DBH), tree crown size is difficult to measure in the field. The ability to estimate tree crown size from remote sensing would provide a major benefit for research and management efforts.

Earlier remotely sensed data from space are not suitable for tree crown size retrieval because the pixel size is usually much bigger than a typical tree crown size. Strahler et al. (1986) referred to the spatial resolution of these images with respect to object size as L-resolution. Previous efforts to estimate tree crown size from Landsat TM imagery achieved some success (Cohen & Spies, 1992; Franklin & Strahler, 1988; Woodcock et al., 1994, 1997; Wu & Strahler, 1993). Due to the limitation in spatial resolution of remote sensing data from space earlier, a significant amount of work extracting tree crown size was based on high spatial resolution air photos (Brandtberg & Walter,

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1998; Culvenor, 2002; Leckie et al., 2003; Pollock, 1996; Wulder et al., 2000). Automatic detection of tree crowns from aerial photos is generally accomplished in two steps: (1) tree crown detection and (2) tree crown delineation (Pouliot et al., 2002). Automatic detection requires that the pixel size be much smaller than the tree crown size to define tree crown boundaries; however, high spatial resolution increases variation in within-crown brightness, making tree crown identification difficult. Automatic detection often assumes that each tree has a distinct boundary with no overlap between adjacent crowns, but such overlap is common in a real forest. Therefore, validation shows that direct delineation of tree crowns on high spatial resolution aerial photos can lead to significant errors in both the number of crowns and the crown size on a tree-by-tree basis (Brandtberg & Walter, 1998; Leckie et al., 2003; Wulder et al., 2000). The detection–delineation approach can achieve much better accuracy in tree crown diameter when aggregated among multiple plots (Pouliot et al., 2002). Brown et al. (2005) evaluated the potential of very high spatial resolution aerial photos in estimating biomass with manual delineation of individual crowns and found that working with the aerial photos took only a third of the time needed for conventional fieldwork.

Small footprint Lidar data offer an alternative promising approach to estimate tree crown size remotely (Falkowski et al., 2006, 2008; Lee & Lucas, 2007; Persson et al., 2002; Popescu & Wynne, 2004; Popescu et al., 2003). Similar to optical imagery, extraction of tree crown size with Lidar data also requires two steps: (1) tree detection, and (2) tree crown delineation. The techniques used for tree detection in optical imagery are also been widely used with Lidar data, particularly the local maximum approach. Lidar imagery directly provides height information for the top of the canopy. Extracting tree crown size using Lidar data relies on the canopy height model (CHM), which is derived from subtracting the digital elevation model for the ground from Lidar height data (Popescu et al., 2003).

Although small footprint Lidar data have advantage over high spatial resolution optical imagery with canopy height information, the data are extremely expensive to acquire at present. High spatial resolution optical images, such as Ikonos and QuickBird, are much cost effective, and they are now available for almost anywhere in the world. Asner et al. (2002) studied the potential of using Ikonos imagery to map tree crown size by comparing measurements on the image with crown size measured on the ground, and they found that measurements on the image were biased toward large trees. Clark et al. (2004) demonstrated the value of Ikonos image in forest demographic research. Palace et al. (2008) developed an automatic tree crown detection and delineation algorithm, and found that it provided better estimates of mean crown width than manual delineation from Asner et al. (2002). However, Palace et al. (2008) found that the automatic algorithm was not able to detect understory trees and overestimated the size and frequency of large trees. Wulder et al. (2004) compared an Ikonos image with an airborne image collected at the same spatial resolution and found that the 1 m panchromatic Ikonos image can be used to identify 85% of tree crowns, but with a 51% commission error. Song and Woodcock (2003) developed a new approach to extract tree crown size based on the behavior of image semivariograms at different spatial resolutions to estimate average tree crown size on a stand basis. The approach performed well for stands dominated by conifer trees, but not as well for hardwood dominated stands (Song, 2007). Wolter et al. (2009) further advanced the approach of using image variance ratios by incorporating numerous other image spatial and spectral statistics to extract multiple canopy structure parameters, including tree crown size, based on SPOT images at 5 and 10 m spatial resolutions.

The objective of this paper is to further investigate the applicability of the Song-Woodcock (2003) model to hardwood dominated stands. We also intend to test the hypothesis that the approach has the potential to work across sensors and sites because the spatial information used in the algorithm depends only on the scene structure, not on the absolute brightness values. If validated, the model would provide a sound theoretical basis for mapping recent forest canopy structure using historical high resolution images and existing forest inventory plot data collected at the same time.

2. Theory

Each pixel in a remotely sensed image is tied to a location in space, thus, the brightness value of a pixel can be treated as a realization of a regionalized variable at the pixel location. Thus, the semivariogram tool in geostatistics can be used to understand the relationship between scene structure and the characteristics of the semivariogram. A semivariogram is a plot of semivariance against the lag that separates the points used to estimate the semivariance. Semivariance is defined as

$$\gamma_f(h) = \frac{1}{2}E\{(f(x)-f(x+h))^2\}, \tag{1}$$

where $\gamma_f(h)$ is the semivariance for points with a lag h in space; $f(x)$ is the realization of a spatial random function $f(.)$ at location x, and $f(x+h)$ is the realization of the same function at another point with a lag h from x. $E\{.\}$ denotes expectation.

Jupp et al. (1988) and Woodcock et al. (1988a) provided the theoretical basis for the linkage between the scene structure and the semivariogram derived from a remotely sensed image. Using high spatial resolution aerial photos, Woodcock et al. (1988b) showed that the range of the image semivariogram contains information on object size and the sill of the image semivariogram is related to the cover of objects. Remotely sensed images are always obtained with a finite size of instantaneous field of view (IFOV). The brightness value of a pixel in an optical imagery is determined by the spatial average of the reflected energy at a particular spectral range within the IFOV. Therefore, the spatial information of a remotely sensed imagery depends on both the scene structure and the size of the IFOV. For remotely sensed imagery over a relatively uniform and large forest, the range of the semivariogram for the image is the combined length of the object size and pixel size. Therefore, the range reflects the object size when the pixel size is significantly smaller than the object size. As the pixel size increases, the range is increasingly dominated by the pixel size, making extracting crown size difficult. In the meantime, the sill of the semivariogram also decreases as the pixel size increases. Jupp (1999) demonstrated the behavior of the semivariogram as a function of object size and the size of IFOV with a disc scene model. The model assumes an unbounded scene with discs in contrasting brightness or color randomly distributed in the scene. The discs can overlap, but the color of the disc remains the same in the overlapped area. The disc scene model is analogous to a forest scene when viewed from a space-borne satellite because the tree crowns in a two-dimensional image resemble discs. Based on the disc scene model, Song and Woodcock (2003) developed a model that relates the ratio of the sill at two spatial resolutions to the diameter of the object as

$$\frac{C_{Z1}}{C_{Z2}} = \frac{\int_0^1 tT(t)(e^{\lambda A_c T(tD_{p1}/D_o}-1)dt}{\int_0^1 tT(t)(e^{\lambda A_c T(tD_{p2}/D_o}-1)dt}, \tag{2}$$

where D_{p1} and D_{p2} are the diameters of IFOV at two spatial resolutions, and D_o is the diameter of the object (the discs); C_{Z1} and C_{Z2} are the sills of the regularized semivariograms at the spatial resolutions of D_{p1} and D_{p2}, respectively. We use r_{Z1Z2} to denote the ratio in the rest of the paper (e.g., r12 denotes the ratio of image variances at 1×1 m to that at 2×2 m). The disc area is A. $T(t)$ is the overlap function for the discs in the scene:

$$T(s) = \begin{cases} 1 & s=0 \\ \frac{1}{\pi}(t-\sin(t)) & s<1 \\ 0 & s\geq1 \end{cases}, \tag{3}$$