Advances in Mapping Woody Plant Canopies using the NASA MISR Instrument on Terra

Mark Chopping, Lihong Su, Naushad Kollikathara, and Libertad Urena
Department of Earth and Environmental Studies, Montclair State University
Montclair, NJ 07043, USA
chopping@pegasus.montclair.edu

Abstract—Red (672 nm) band reflectance estimates from the NASA Multi-angle Imaging Spectro-Radiometer (MISR) on the Earth Observing System Terra satellite were used to obtain maps of woody plant fractional crown cover, mean canopy height, and biomass for large parts of south-eastern Arizona and southern New Mexico (>200,000 km²). MISR red band bidirectional reflectance estimates in nine views mapped to a 250 m grid were used to adjust the Simple Geometric-optical Model (SGM) that is based on the principles of Boolean geometry first exploited in Li-Strahler geometric-optical (GO) models. The soil-understory background signal was decoupled a priori by exploiting relationships with the nadir camera reflectance data and the kernel weights of the LiSparse-RossThin kernel-driven bidirectional reflectance distribution function (BRDF) model. Maps of fractional crown cover, mean canopy height, and biomass were produced via retrievals of the mean crown radius and shape parameters from inversion of the SGM using the Praxis algorithm. The mean absolute error in randomly sampled and filtered estimates of fractional crow cover, mean canopy height, and woody biomass was 0.10, 2.2 meters, and 4.5 tons acre⁻¹ (10.1 Mg ha⁻¹), with RMS errors of 0.12, 3.3 and 6.2 (14.0), and coefficients of determination (R²) of 0.78, 0.69, and 0.81, respectively, significant at the 0.01 level (N=576).

Keywords- MISR; forest; biomass; canopy structure

I. INTRODUCTION

Spatially explicit information on forest carbon storage (woody biomass), emissions to the atmosphere from wildfires, fire fuel loads and fire potential, stand age, forest regrowth and secondary succession and associated rates, is required for effective forest management as well as to address science questions that concern the C cycle; e.g., the potential for sequestration through forest regrowth. Obtaining timely maps of biomass is more important than ever because the effects of recent climate change on western forests are now being witnessed [1-2] and the western US may be emerging from a period of relative humidity [3]. Answering these questions requires wall-to-wall estimates of wood plant canopy cover, height and, biomass that can be obtained using moderate resolution remote sensing methods. Although sophisticated approaches to integrating ground survey and moderate resolution remote sensing data mitigate the weaknesses of the latter in terms of information content [4], important limitations remain. In this study we pursue a multi-angle approach to mapping that seeks to exploit the structural effects of canopies on observed radiation fields in the red wavelengths by fitting a geometric-optical (GO) canopy reflectance model to MISR red band data mapped to a 250 m grid, with the aim of providing maps of estimated fractional crown cover, mean canopy height, and woody biomass. Canopy structural effects are manifested as shadow-hiding and volume scattering phenomena that may be translated to ecologically useful parameters with direct physical meaning through the adjustment of a GO model. The advantages of multi-angle approaches have been documented rather comprehensively in [5]. The use of discrete object models such as GO and hybrid geometric-optical/radiative transfer (GORT) models represents one approach to exploiting these data [5, 6]. GO models treat the surface as an assemblage of discrete, identical, and relatively large geometric objects placed in a Poisson distribution above an underlying surface [7], which is often considered Lambertian. Object shape and height parameters are therefore mean values.

The remotely sensed observation is modeled as a linear combination of contributions from viewed sunlit and shaded crown and background components, with each contribution a product of component reflectance and the fraction of the sensor’s instantaneous field-of-view occupied by the component, calculated according to the principles of Boolean geometry. GO models vary in complexity, with more recent versions including terms that allow for volumetric scattering within crowns rather than simple signatures; and in the way the background is handled [8]. They hold the potential for obtaining canopy information that is useful in multiple disciplines [9]. For successful canopy reflectance modeling of heterogeneous, clumped, or nonclosed canopies it is important to account adequately for the contribution of the background of soil and understory [10-14]. This is especially true where soils are bright, as in arid and semi-arid regions. Modelers have moved from the use of simple Lambertian backgrounds, through imposing a single, static background bidirectional reflectance distribution function (BRDF) [8], to the injection of a spatially dynamic background BRDF [14].

II. METHODS

The study area encompasses parts of south-eastern Arizona and southern New Mexico (>200,000 km²) that include desert grassland, often with significant woody shrub encroachment; riparian and river valley woodland along the Rio Grande, San
Pedro, Salt, and Gila rivers; and upland forest (including the Coronado, Lincoln, Cibola, Apache, Sitgreaves, and Tonto National Forests, and the Gila National Forest and Wilderness (Figure 1). This area includes parts of the Basin and Range, White Mountain-San Francisco Peaks-Mogollon Rim, and Sacramento-Manzano Mountain ecological subregions.

The Simple Geometric Model (SGM) predicts spectral bidirectional reflectance at specified viewing and illumination angles. It was derived as an adaptation of a Li-Ross kernel-driven BRDF model in which certain assumptions are relaxed, notably that the contributions of sunlit crown and background are not similar [15]. A further modification imposed the requirement for the background contribution to be specified with respect to angle [16], here encapsulated in the empirical four-parameter Walthall BRDF model [17]. The SGM is formulated using a Ross volume scattering function to account for within-crown scattering (1):

\[ R = G_B \cdot k_G + C_R \cdot k_C \]  

where \( R \) is modeled bidirectional reflectance, \( G_B \) is the Walthall model representing the background response, \( C_R \) is the Ross function, and \( k_G \) and \( k_C \) are the proportions of background and crown, respectively, in the MISR instantaneous field-of-view. All terms are functions of the illumination and viewing geometry (zenith and azimuth angles). Internal parameters are mean crown radius (\( r \)), crown shape (\( b/r \), where \( b \) is crown vertical radius), plant number density (\( \lambda \)), and crown height ratio (\( h/b \), where \( h \) is crown center height). Leaf reflectance is fixed at 0.09. The coefficients of the Walthall model that define the background brightness magnitude and anisotropy are estimated a priori via regression equations that were developed using 19 grass- and shrub-dominated sites of widely differing configurations (very sparse though very dense understory and few/many small/large shrubs) in the US Department of Agriculture (USDA), Agricultural Research Service Jornada Experimental Range 37 km north of Las Cruces, New Mexico.

NASA's MISR instrument is flown on the Earth Observing System (EOS) Terra satellite. It was designed to obtain spectral radiance images at nine angles in the along-track direction at up to 70 degrees in zenith, enabling quasi-simultaneous views of the surface, atmosphere and clouds. One camera views at nadir (close to 0° view zenith angle), while the others view at zenith angles of ±26.1°, ±46.5°, ±60.0°, and 70.5°. Spatial samples are acquired every 275 meters. Over a period of 7 minutes, a 360 km wide swath of Earth comes into view at all 9 angles. Global coverage is achieved every 9 days, with repeat coverage between 2 and 9 days depending on latitude. MISR has excellent radiometric resolution and a wide dynamic range, preventing saturation over snow-covered surfaces. Great attention has been paid to providing accurate absolute calibration using on-board hardware consisting of deployable solar diffuser plates and several types of photodiodes [18].

MISR data used include terrain-projected nadir and off-nadir red band spectral radiances, terrain-projected nadir spectral radiances in all bands (446, 558, 672, and 866 nm), mean spectral optical depth at 558 nm and 17.6 km resolution, and geometric parameters (illumination and viewing angles). Note that only the red band (672 nm) data were used to adjust the SGM. The MISR spectral radiance data were corrected for atmospheric absorption and scattering using the Simplified Method for Atmospheric Correction (SMAC) algorithm [19], version 4 and MISR estimates of aerosol optical depth. A kriging method was used to smooth the MISR 17.6 km resolution aerosol optical depth data prior to estimation of surface bidirectional reflection factors.

MISR red band data in all cameras from May-June 2002 were used to invert the LiSparse-RossThin kernel-driven BRDF model [20] to obtain estimates of the isotropic (diffuse brightness), geometric, and volume scattering components. These values were used along with the nadir camera blue, green, and near-infrared surface reflectance estimates to predict the background response for every location via regression equations in which each of the four Walthall model parameters is estimated independently. The SGM was then adjusted against the MISR red band data in all views by allowing mean crown radius (\( r \)) and crown shape (\( b/r \)) to be free parameters, using numerical methods and the predicted background value for each observation at its specific angular configuration. Plant number density (\( \lambda \)) and crown height ratio (\( h/b \)) were fixed at 0.012 and 2.0, respectively. The minimization algorithm used was Praxis, an adaptation of the Powell algorithm [21], with the objective being the minimization of the absolute root mean square error (RMSE) between model and observations. This provided retrievals of \( r \) and \( b/r \), allowing calculation of fractional crown cover (FCC) (2), and mean canopy height (\( h \)), with FCC\( h \) taken as a coarse proxy for biomass.

\[ FCC = 1 - \exp \left( \lambda \pi r^2 \right) \]  

It is possible to estimate fractional crown cover and mean canopy height by adjusting \( r \) and \( b/r \) parameters because the respective effects on observed data patterns differ: increasing \( r \) is equivalent to increasing fractional cover (which mainly leads to a darkening for all viewing angles with a relatively small change in shape), while increasing \( b/r \) results in a stronger change in the degree of observed anisotropy. If plant number density (\( \lambda \)) is fixed and \( r \) is adjusted, this is equivalent to retrieving fractional plant (crown) cover. Since the \( r \) values retrieved are those that provide the best match with fractional crown cover with a fixed value for \( \lambda \), some error in the calculated \( h \) values is expected. Additional error is expected owing to extrapolation of the empirically-derived background over large areas and other model assumptions.

III. Results

The first attempt to map parameters using a single MISR overpass for each satellite path resulted in distributions for forested areas showing good qualitative matches with maps from the United States Forest Service (USFS). Here, a comparison with data from USFS maps of crown cover, canopy height, and biomass for the Interior West was effected by extracting values for 1063 randomly selected forest locations. The resulting data were filtered for high root mean square error (RMSE) on model fitting, outliers > ±2 standard deviations from the mean, and cloud and cloud-shadow contamination, leaving just less than 50% of data points. FCC and mean canopy height were retrieved directly with no adjustment, while biomass was estimated by regression of FCC\( h \) against the USFS map data. Coefficients of determination for biomass,
forest cover, and mean canopy height were 0.76, 0.58 and 0.53 after filtering. In spite of very good fits to data (mean RMSE = 0.033), the maps were clearly contaminated by cloud cover and cloud shadow and probably by other atmospheric anomalies (contrails, thin high cirrus). The second attempt employed MISR data from three non-consecutive Terra overpasses within 1 month and implemented a compositing algorithm using the best fit to data (lowest |RMSE|) as the selection criterion. This resulted in better final inversion statistics (mean RMSE = 0.006) but also in the appearance of two distinct sets of FCC data points (Figure 2 (a)). On inspection of the FCC map with respect to a hillshade map derived from elevation data from the Shuttle Radar Topography Mission (not shown), it was clear that topographic shading was responsible. The compositing criteria were therefore expanded to include filtering of shaded locations, resulting in importantly improved results (Figure 2 (d)-(f)). The mean absolute error in estimates of fractional crown cover, mean canopy height, and woody biomass were 0.10, 2.2 meters, and 4.5 tons acre⁻¹ (10.1 Mg ha⁻¹), with RMSE errors of 0.12, 3.3 and 6.2 (14.0), respectively (Table 1). The relationships between retrieved and reference crown cover, canopy height and woody biomass were significant (N=576, p<0.01) and could not have occurred by chance. A stronger relationship was found for biomass (R² = 0.81) than for FCC or mean canopy height (R² = 0.78 and 0.69, respectively). These results are fully discussed in [22].

The discussion of results has been confined here to forested areas but the approach is based on quantifying the effects of canopy physical structure, so results also include areas dominated by woody shrubs. In general, model fitting RMSE was higher for shrub-dominated areas than for forest as the effects of canopy structure are stronger for taller vegetation structures. Further validation of the retrievals for forest are under way using USFS Forest Inventory Analysis data. Retrievals over desert grassland with shrub encroachment will be made with reference to estimates from woody plant maps for large parts of the Jornada Experimental Range (New Mexico), and Walnut Gulch Experimental Watershed (Arizona), constructed using a segmentation algorithm to extract woody plant cover (shrubs and trees) from high resolution (1 m) panchromatic Ikonos imagery.

Figure 1. Crown radius map of the study area showing the two sets of validation points. Set one is blue (shaded locations, corresponding to the upper cluster in Figure 2 (a)); set two is red (illuminated locations, corresponding to the lower cluster in Figure 2 (a)).

![Figure 1](image1.png)

Figure 2. Retrievals plotted against reference data extracted from the USFS IW-FIA maps, with no restriction on RMSE: (a) woody biomass (b) crown cover (c) mean canopy height; and with filtering: (d) woody biomass (e) crown cover (f) mean canopy height.

![Figure 2](image2.png)

Figure 3. Maps of (a) fractional crown cover (b) mean canopy height (c) biomass (Mg C ha⁻¹) for all woody plants.

![Figure 3](image3.png)
TABLE I. SUMMARY OF MISR/SGM RETRIEVAL RESULTS

<table>
<thead>
<tr>
<th></th>
<th>FCC Canopy</th>
<th>Woody Biomass</th>
</tr>
</thead>
<tbody>
<tr>
<td>height (m)</td>
<td>(tons acre-1)</td>
<td>(Mg ha-1)</td>
</tr>
<tr>
<td>Mean Relative Error (%)</td>
<td>30</td>
<td>28</td>
</tr>
<tr>
<td>Mean Absolute Error</td>
<td>0.10</td>
<td>2.2</td>
</tr>
<tr>
<td>Mean (MISR)</td>
<td>0.48</td>
<td>10.3</td>
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<tr>
<td>Mean (USFS)</td>
<td>0.38</td>
<td>8.7</td>
</tr>
<tr>
<td>Root Mean Square Error</td>
<td>0.12</td>
<td>3.3</td>
</tr>
<tr>
<td>R²</td>
<td>0.78</td>
<td>0.69</td>
</tr>
</tbody>
</table>

IV. CONCLUSIONS

This study has shown that moderate resolution multi-angle remote sensing data from MISR can be used to produce maps of forest crown cover, canopy height, and biomass over large areas that include structural parameters with a straightforward interpretation (crown shape, FCC, canopy height, biomass). It is to our knowledge unique in that it successfully exploits the structural effects of canopies reflected in observed anisotropy patterns in one wavelength, rather than using spectral measures. The advantages of the multiangle approach demonstrated here over active remote sensing methods (radar, lidar) is that it enables timely and extensive wall-to-wall estimates of key forest parameters over large areas at low cost and highlights the value of NASA EOS multi-angle imaging in ecological applications.

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REFERENCES