Geometric-Optical Modeling of Desert Grassland Canopy Structure with MISR

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Abstract: A new method is described for the retrieval of fractional cover of large woody plants (shrubs) at the landscape scale using moderate resolution multiangle remote sensing data from the Multiangle Imaging SpectroRadiometer (MISR) and an hybrid geometric-optical (GO) canopy reflectance model. The major difficulty in applying such models in desert grasslands is the spatially dynamic nature of the combined soil and understory background reflectance. The best method found was multiple regression on the weights of a kernel-driven model and MISR nadir camera blue, green, and near infra-red bidirectional reflectance factors. The results of forward modeling for a 5.25 km^2 area in the USDA, ARS Jornada Experimental Range (n=441) showed excellent agreement with the MISR data in both shape and magnitude. Inversion of the model allowed estimation of fractional shrub cover with an RMSE of 0.03.

1. Introduction

This study focuses on retrieval of large, woody plant (shrub) fractional cover from moderate resolution remote sensing data, a first but important step in estimating the structural attributes of desert grassland canopies: over the last 150 years encroachment of shrubs into grasslands has occurred in many arid and semiarid regions of the world, including the western United States, northern Mexico, southern Africa, South America, New Zealand, and Australia [1]. Vegetation in deserts plays an important role in determining regional to global characteristics of the Earth's climate and biogeochemistry [2]: loss of vegetation and the resulting increase in the fraction of exposed soil raises regional albedo and air temperatures and also lowers the infiltration of soil moisture, leading to higher runoff losses of rainwater, greater losses of soil nutrients, and the persistence of regional desertification. In addition, exposed desert soils are a source of wind-borne dust, which can affect the radiative balance of the planet depending on the mineralogy of dust and its persistence in the atmosphere [3]. Other tangible effects include a decrease in the usefulness of the land for herbivory (but not necessarily vegetation productivity); changes in C, N, and water cycling; a redistribution of C towards below-ground pools; and changes in the spatial arrangement of vegetation, nutrients and soil resources to a more clumped and patchy distribution [3], allowing for enhanced entrainment of dust into the air [4].

Geometric-optical (GO) models are increasingly used in remote sensing of vegetation – primarily forests – as they provide a means of decomposing the mixed remote sensing observation into its main components, allowing estimation of canopy parameters such as crown cover, stand density and foliage volume, using either numerical or lookup table methods [5]. GO models treat the surface as an assemblage of geometric objects of equal size, shape and height, evenly distributed within a spatial unit. A tree or shrub crown is usually represented by a spheroid whose center is located at a specified mean height above a diffuse scattering surface (Figure 1). These models were originally developed for use in forested environments [6] where the soil-understory background is usually darker and thus makes a relatively small contribution to the remotely sensed signal (Figure 1 (a)); it can thus often be assumed Lambertian, obviating the need to estimate a background BRDF as was shown to be necessary for arid land surfaces in [7]. This is because the cover of understory plant varies spatially and has an important impact on both brightness and reflectance anisotropy (Figure 1 (c)). As the background in arid environments accounts for a large proportion of the sensor's instantaneous field-of-view and since shrubs occur in both grass dominated and shrub dominated zones, accurate estimates of shrub cover and other canopy parameters cannot be made without adequate specification of the background contribution.

2. Method

Multiangle spectral radiance data from the MISR flown on the NASA Earth Observing System Terra satellite were used [8]. The multiangle images were acquired from an overpass at the end of the dry season (mid-June, 2002) for a 5.25 km^2 area in the USDA, ARS Jornada Experimental Range, near Las Cruces, New Mexico, USA. Red band (672 nm) data were used directly in canopy reflectance modeling as these are acquired by MISR at 275 m in nine cameras: at nadir viewing and at eight other viewing angles (26.1°, 45.6°, 60.0°, and 70.5° in the forward and backward directions). Nadir view blue, green, red, and near infra-red spectral radiance data at 275 m were also used. Surface reflectance estimates were obtained via corrections for atmospheric scattering and absorption, including estimates of aerosol optical depth and ozone (but not water vapor) using SMAC version 4 [9].

A modified version of the simple geometric model (SGM) – a canopy reflectance model that incorporates geometric optics with a leaf area index-dependent volume scattering term – was used here. The SGM was developed by relaxing some important assumptions made by kernel-driven BRDF models [10] and is formulated as: $BRF = G \; . \; k_G \; + C \; . \; k_C$, where BRF is bidirectional reflectance factor, k_G and k_C are the calculated proportions of sunlit and viewed background and crown, respectively; *G* is the calibrated Walthall model [11]; and *C* is the simplified Ross turbid medium approximation for optically-thin or thick plane parallel canopies [12]. The model's parameters are plant number density, mean crown radius, crown shape (b/r), crown center height (h/b), and leaf area index (LAI). Good matches were obtained against a radiosity-based model calibrated with detailed ground measurements and against multiangle observations from the air [13].

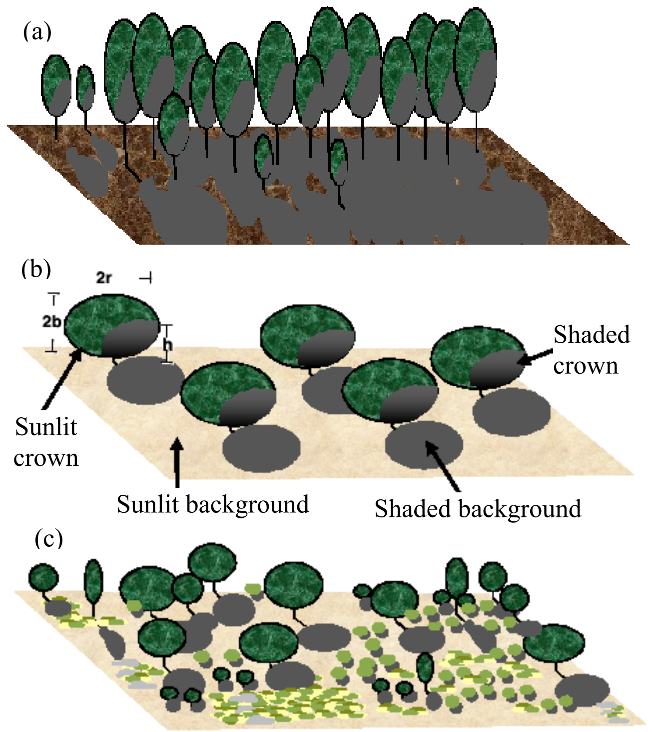

Fig. 1. Geometric-optical model representations: (a) forest environment of trees over a dark, dense, and uniform background (b) idealized arid zone shrub-dominated community on a bright, sparse, prominent background (c) arid zone shrub-dominated community on a discontinuous background with a spatially-varying BRDF.

Within the SGM the empirical, four-parameter Walthall model represents the background contribution. As the first step, soil-understory BRDFs were estimated for a sample of 19 locations representing a very wide range of understory densities and canopy configurations. This was achieved in each case by adjusting the four Walthall parameters against the model with upper canopy plant (shrub) number density and mean radius set to measured values, to match the corresponding MISR data set. The minimization criterion was the absolute Root Mean Square Error (RMSE) and background BRDFs obtained in this way are referred to as "optimal". The measured values of shrub number density and mean radius were obtained by applying thresholds on windows from a 1 m IKONOS panchromatic image from May 2001, one year prior to the MISR acquisition. These data also provide the fractional shrub cover estimates, which are the reference data for this study. The second step in estimating the background contribution was to find a good predictor of the four Walthall model parameters. Selected candidate metrics included nadir view red reflectance, the volume scattering kernel weight from inversion of a linear LiSparse-RossThin model, and the modified Rahman-Pinty-Verstraete □*0* (diffuse scattering) parameter (red band). Low reliability led to large inaccuracies in estimating shrub cover: there is not enough information in a single metric to accurately predict the soil-understory response. A suitable relation was found using multiple regression on the isotropic, geometric and volume scattering kernel weights of the LiSparse-RossThin model (red band) and this was further enhanced by including nadir camera blue, green, and near infra-red BRFs. Inversion of the SGM was effected for mean shrub width, with shrub number density, b/r and h/b fixed at 0.012 (750 plants/250 m^2), 0.2 and 2.0, respectively, using numerical methods.

2. Results

Forward modeling using the IKONOS-derived shrub statistics, empirical background response; with b/r=0.2 (oblate crowns) and h/b=2.0 (typical), provided excellent matches to MISR (data not shown). The background anisotropy in the MISR plane is accurately estimated, resulting in modeled BRFs very close to the observed MISR data sets (Figure 2).

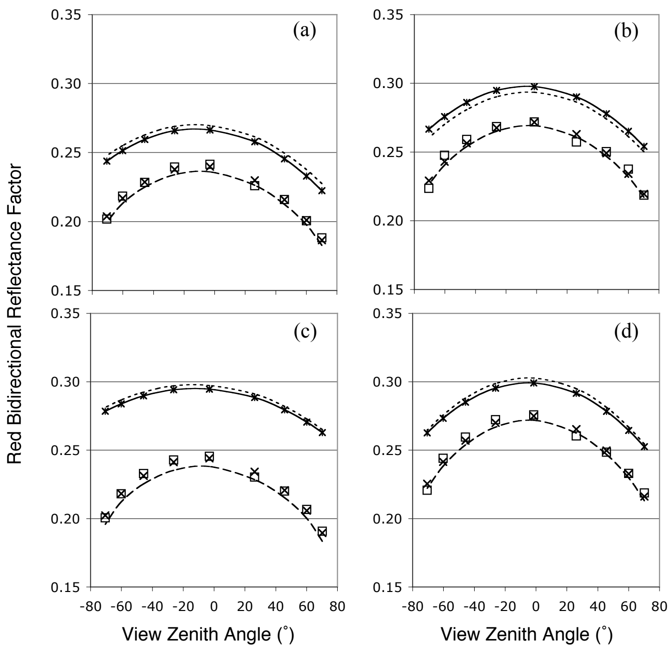

Fig. 2. Model performance (a) dense understory, fractional shrub cover = 0.12 (b) (c) (d) sparse understory, fractional shrub cover = 0.07, 0.19 and 0.10, respectively. MISR (□) SGM (×) optimal background (……) estimated background (---*---) $G.k_G$ (- - -).

The coefficient of determination (R^2) between observed and modeled data for the 19 data sets used in calibration of the regression model is ~1.00 if the optimal background BRDF is used, declining to 0.74 if the background is estimated (Figure 3). Retrieved fractional shrub cover values for all 441 locations resulted in a RMSE of 0.03 and an R^2 of 0.19 with respect to measured values (Figure 4). Estimation error is normally distributed and is partly owing to inaccuracies in the IKONOS-derived cover values and to the lag between acquisitions, even though conditions will not have changed dramatically during this drought period. The presence of highly-vegetated swales is another factor as these are not handled explicitly in the GO modeling.

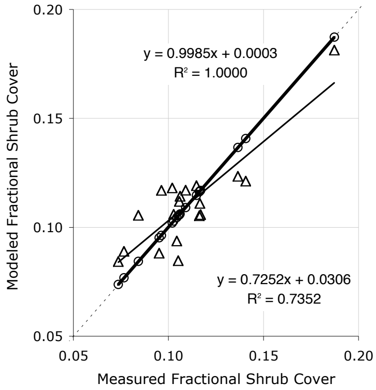

Fig. 3. Impact of using estimated (Δ) over optimal (o) background BRDFs for 19 cases covering a wide range of configurations.

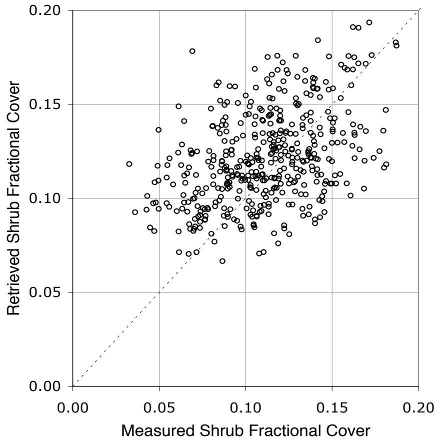

Fig. 4. Retrieved *vs* measured fractional shrub cover for covering a 21 x 21 x 250 m area in desert grassland (441 inversions).

3. Summary

A new method for the retrieval of shrub cover in desert grasslands using moderate resolution MISR data and a GO model was presented. Central to this method is the use of Li-Ross model kernel weights and nadir multispectral data to estimate the magnitude and anisotropy of the soil-understory complex. Future work will further refine these techniques.

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