Reflections in Bumpy Terrain: Implications of Canopy Surface Variations for the Radiation Balance of Vegetation

Segun Ogunjemiyo, Geoffrey Parker, and Dar Roberts

***Abstract*—Data from an optical imaging sensor and a small-footprint lidar were used to examine the relation between canopy reflectance and outer surface complexity in forest stands in the southern Cascades of Washington state. Albedo was estimated from the Airborne Visible Infrared/Imaging Spectrometer; canopy surface variation (termed "rugosity") was estimated from small-footprint lidar; and stand ages were obtained through U.S. Forest Service records and global information system coverages. Results showed that albedo from Douglas-fir/western hemlock stands decreased, and variation in the outer surface of the canopy increased with age. Estimates of rugosity increased most rapidly in young stands and then more slowly after about 150 years. Albedo declined by 10% across the age sequence, suggesting that older stands of this forest type enjoy a substantial advantage in energy input. The results highlight the impacts of land-cover change on local energy balance and climate.**

***Index Terms*—Airborne Visible Infrared/Imaging Spectrometer (AVIRIS), albedo, reflectance, rugosity, small-footprint lidar.**

I. Introduction

VEGETATION is a main component of an ecosystem, which is regarded as an active surface interacting with solar radiation. The results of this interaction are absorption, reflection, and emission of radiation. Understanding the processes governing the partitioning of radiant energy between these components is a crucial factor in parameterizing the response of vegetation in global, regional, and local area models used to study climate change.

The total reflectivity over the wavelengths of 300–3000 nm is called albedo. The proportion of the incident solar radiation reflected by the surface depends on a host of factors, among which are the structure and composition of the surface. A snow-covered surface could reflect as much as 80% of the incident radiation, and as the snow melts, the amount decreases rapidly and may drop to 10% within a few weeks, completely changing the surface energy balance [1]. In a forested landscape, vegetation changes are the primary cause of the seasonal variation in albedo. For closed-canopy forests, the mean annual albedo ranges from 5% to 20% [2], [3]. Land surface albedo directly controls the net solar radiation absorbed at the surface and, thus, the surface energy balance, thereby driving local climate processes. Large-scale climatic consequences of surface albedo changes are predicted by various circulation models [4]–[6].

An increasing need to improve estimates of canopy reflection for parameterization of sensible heat flux and estimation of energy balance in forest stands is the primary reasons for the development of a variety of models that describe energy partition processes, which occur as incident solar radiation penetrates through forest canopies [7]. For the same reasons, different methods have been developed in the past decades to quantify forest albedo at different spatial scales. Both the Advanced Very High Resolution Radiometer (AVHRR) and Moderate Resolution Imaging Spectroradiometer (MODIS) sensors have been used to estimate forest albedo on a regional scale [8]–[10]. Studies have also been conducted to relate albedo to surface biophysical and phenological attributes, such as vegetation height and plant age [11], [12]. Results from some of these studies showed a decline, which varies among forest types, in the reflection coefficient with increasing height of vegetation. Other plant attributes, such as crown sizes, shadowing, gap sizes, and shade fractions, have also been shown to increase as stands age [13], [14]. Direct measurements in one forest type have shown that outer canopy complexity increases with stand age; and there is a conceptual basis for a decrease in reflectivity with canopy complexity. However, we are not aware of any direct measurements of the relation between albedo and canopy inhomogeneities, within a single vegetation type.

The aim of this study is to quantify the relation between canopy reflectance and outer surface complexity ("rugosity") in Douglas-fir/western hemlock stands in the southern Cascades of Washington State. The term "rugosity" was first used in the study of canopy structure in eastern deciduous forest to distinguish the variation in the outer canopy surface from "roughness," which is usually a parameter derived from aerodynamic studies [15], [16]. We used information on rugosity and surface albedo obtained for the same collection of stands with different sensors, with estimated properties aggregated to the same, georectified spatial scale.

II. Methods

We studied forests of the Douglas-fir/western hemlock type found at low elevations (250–620 m ASL) in the Central

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Cascades of southern Washington State. We focused on a contiguous patch (about 30 km^2) of stands of various ages and disturbance histories, centered at the Wind River Canopy Crane Research Facility (WRCCRF), which is located in the T. T. Munger Research Natural Area of the Gifford Pinchot National Forest. Many of the stands are younger than 150 years due to recent harvesting, blowdowns, and fires, but there are others in the old-growth state [17].

The Aeroscan multiple-return lidar instrument, operated by EarthData Technologies, was flown for the National Aeronautics and Space Administration's Goddard Space Flight Center on August 3–4, 1999 at 4 km AGL. A 1997-m-wide swath about 15 km long was obtained, with centerline coordinates of 45° 49′39.79 N, 122° 1′24.60 W to 45° 49′39.79 N, 121° 54′55.48 W. In this run, data were acquired at 15 kHz. Lidar footprints were about 0.93 m in diameter with average cross-track spacing of 2.93 m.

The Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) was flown on a Jet Propulsion Laboratory (JPL) ER2 over the same area on July 17, 1998. This instrument provides spectral information from 224 contiguous wavebands (370–2500 nm) with a nominal spatial resolution of 20 m [18]. Albedo was calculated for each pixel as the sum of the product of modeled surface irridiance and AVIRIS apparent surface reflectance between 370–2500 nm at a specific view angle [19]. This "directional" albedo differs from spherical albedo, in which reflected flux is averaged across all view angles and wavelengths for a specific incidence angle using the bidirectional reflectance distribution function of a surface. For a Lambertian surface, directional albedo and spherical albedo will be the same. Spectral mixture analysis (SMA) was used to estimate fractions of green vegetation and shade [20]. SMA is a technique that decomposes a mixed spectral signature into a number of "pure" spectra, called endmembers, each weighted by an estimate of fractional coverage. Using reference endmembers, a forested area was modeled as green vegetation, shadows (shade), branches, stems, and litter (nonphotosynthetic vegetation), and soil.

GIS coverages of the site, including the stand age coverage, were obtained through the National Forest Service Database and were rasterized to the same pixel resolution as the AVIRIS products. Spatial subsets of the maps, with boundaries defined by the lidar flight path, were made. The coordinates of the lidar footprints were transformed to UTM and georeferenced to AVIRIS and stand age maps. The footprints corresponding to each image pixel were determined and were used to calculate rugosity as the standard deviation of the first return range. The resulting images have patches with the number of pixels varying from 20 in the smallest polygon to 8600 in the largest polygon (the L-shaped old-growth stand in Fig. 1). The lidar scene encompassed 122 stands that spread over 45 distinct age classes. The estimates obtained by averaging over the stands and age classes were used to obtain correlation between the different variables.

III. Results

Spatial variation in surface rugosity, estimated albedo, and stand age show similar patterns in this landscape (Fig. 1). The mosaic of stands from the Forest Service coverage is clearly mirrored in details in the maps of albedo and rugosity. The relationship between albedo and rugosity is shown in Fig. 2. This relation suggests that shortwave reflectivity declines about 3% for every 4-m increase in canopy rugosity. Maximum albedo, of 16%, is found in stands with a smooth top and the minimum of 5% occurs where the outer canopy is most complex.

As suggested by the correspondence among the maps in Fig. 1, various reflectance variables are highly interrelated with stand age and surface rugosity (Fig. 3). Green vegetation fraction declines, and shade fraction increases, both linearly, with increased surface rugosity; the shade fraction has a somewhat higher sensitivity to canopy complexity. Rugosity increases and albedo decreases with stand age, but both appear to saturate at about 150 years.

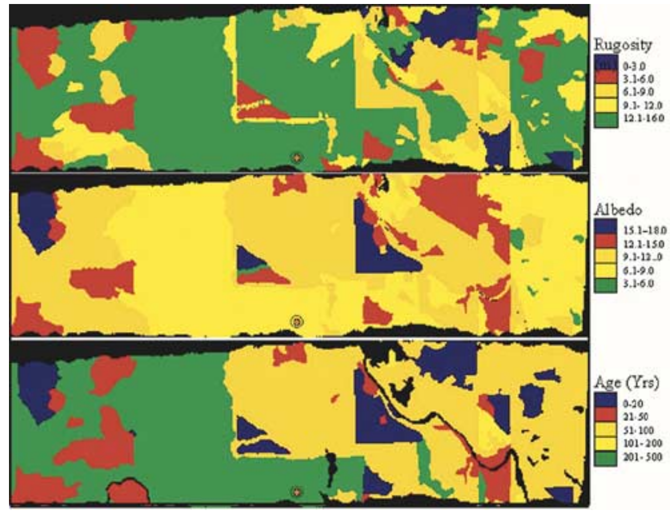

Fig. 1. Rugosity, albedo, and forest age maps from an east–west transect over the Gifford Pinchot Forest in southern Washington. The symbol at the bottom center in each panel is the location of the canopy crane of the Wind River Canopy Crane Research Facility.

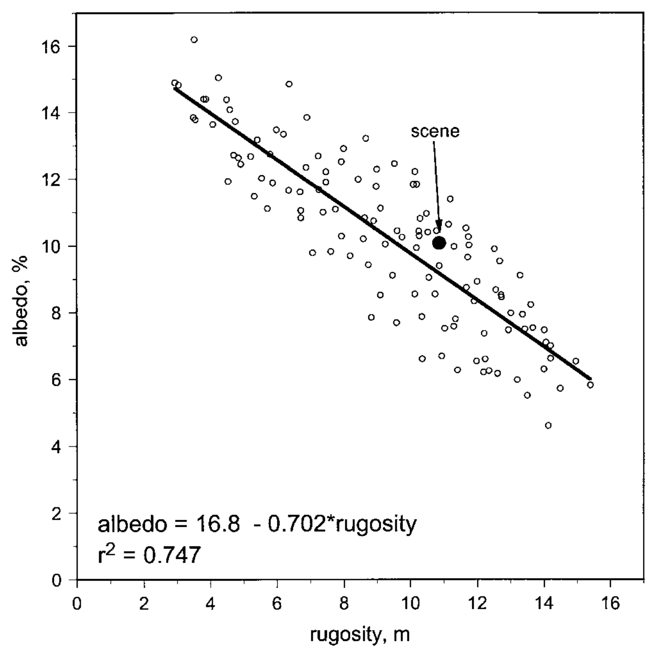

Fig. 2. Stand albedo as a function of canopy rugosity. Arrowed points are for the entire scene and for the vicinity of the WRCCRF in Fig. 1.

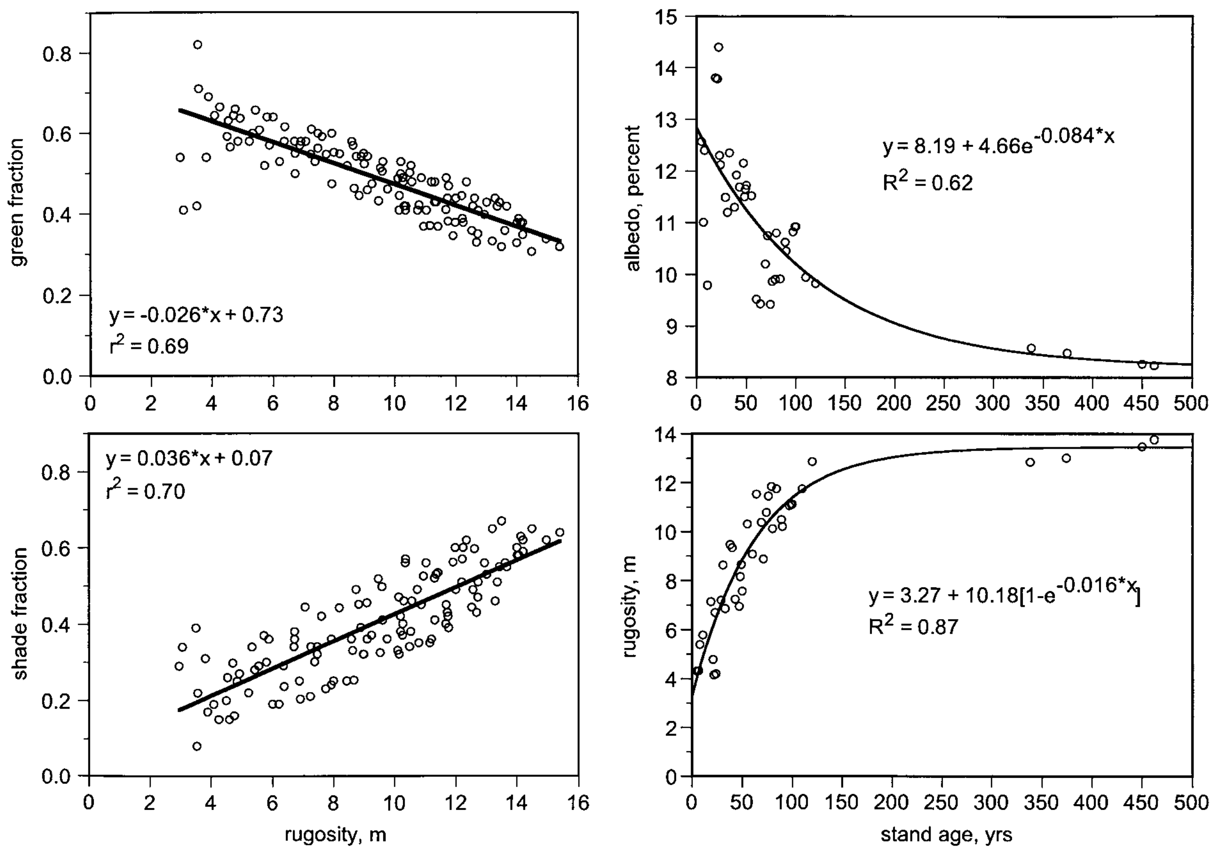

Fig. 3. Interrelations between (upper left) green fraction and (lower left) shade fraction with rugosity and (upper right) of rugosity and (lower right) albedo with stand age.

IV. Discussion

Spatial scale is potentially important when comparing lidar rugosity and AVIRIS measures. Given a 20-m instantaneous field of view on AVIRIS and the size and spatial pattern of trees in this area, fully illuminated closely spaced crowns or a gap may have similar rugosity, yet completely different albedo. Some of this is evident in Fig. 1, in which the lowest rugosity in old growth forest is located in gaps, which also correspond to areas with the lowest albedo. However, because we are dealing with stand averages, the finer scale impacts of stand structure tend to be averaged out.

We found that during stand aging in this forest type, shading and canopy complexity increased, while the green fraction and reflectance decreased. These patterns appear to confirm the hypothesis that as the outer surfaces of canopies become more complex during development, the complexity promotes absorption of scattered light, leading to decreased reflectance and a higher shade fraction. A significant proportion of the variation in rugosity ($r^2 = 0.87$) is accounted for by stand age, indicating the potential of rugosity as a means for improving estimates of stand age.

Forest of different regions differs in characteristic crown shapes—the pattern of change of rugosity with stand age likely reflects these differences. For example, the western forests in this study are composed of disjunct trees with narrow columnar crowns, whereas broad-leaved forests may have umbrella-shaped crowns that nearly connect. A canopy of umbrella-like crowns should be less rugose overall, as there is less chance for scattered radiation to be reabsorbed, compared with the situation in the deep gaps of western conifers.

There are few direct surface measurements to relate to the estimated albedo and rugosity in the studied area. The rugosity and mean annual albedo measured within the crane circle were 16.2 m and 7%, respectively [15], [21]. This observation pair is close to the rugosity (15.3 m) and albedo (8.0%) estimated remotely (Fig. 2). However, ground-based albedo measurements are not available for younger stands in this region, so this specific relation remains to be confirmed.

The interaction of photons with the rough surface of tree crowns and with the soil in between crown openings is the most important factor causing the observed variation in the directional reflectance distribution of plant canopies. There is apparent variation in albedo across the image scene in Fig. 1. About 62% of this variation is accounted for by stand age (Fig. 3). Because of the high vegetation cover of the stands in the image scene, soil contribution to the variation would only be significant in area with sparse vegetation cover (i.e., bare ground and shrubs stands). In practice, many factors complicate accurate computation of albedo. Reflectance from land surface elements and from the atmosphere is anisotropic, i.e., the measured albedo depends on the relative positions of airborne sensor and sun with respect to the surface point monitored. The bidirectional reflectance may distort albedo estimates over densely vegetated areas [22] and over an aerosol-loaded atmosphere [23].

The observed albedo declines from 16% to 6% with the change in canopy complexity (i.e., rugosity increasing from 3–16 m) typical of development toward old-growth. The difference of 10% of nonreflected radiation energy over this chronosequence is a significant amount of energy for the production base of the stand. Since the overall penetration of light to the forest floor differs little across this chronosequence (the mean is about 5% according to [18]), this implies a large change in absorbed energy during development. A young stand would absorb about 79% of energy ($=100 - 16 - 5$), but an older stand would absorb 89%, an increase of about 12.7% in available energy. If old growth forests are in steady state with respect to carbon balance, the increase in energy input suggests a substantial decline in radiation-use efficiency.

The large differences in albedo between canopies of different structure may be important for the energy balance of landscapes. Owing to human modification and natural disturbance events, large tracts of uniform canopies are rarely found. Most large vegetated regions of the earth are patchy and internally inhomogeneous at a variety of spatial scales. The aggregate reflectivity at large scales (10.1% for the scene in Fig. 1) will depend on the disposition of components within. Because rugosity and albedo vary nonlinearly with age, errors in estimating large-scale energy balances or in identifying forests of particular ages are possible. Also, because the albedo estimates reported here are measures of directional rather than total reflectance from the canopy surface, their usage in energy calculations could generate errors, the magnitude of which would depend on the degree of the reflecting surface departure from a Lambertian surface.

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