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Interpretation and topographic compensation of conifer canopy self-shadowing

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ABSTRACT

The self-shadowing of conifer canopies results from the size and arrangement of trees within a stand and is a first-order term controlling radiance from forested terrain at common pixel scales of tens of meters. Although self-shadowing is a useful attribute for forest remote-sensing classification, compensation for the topographic effects of self-shadowing has proven problematic. This study used airborne canopy LiDAR measurements of 80 Pacific Northwest, USA conifer stands ranging in development stage from pre-canopy closure to old-growth in order to model canopy self-shadowing for four solar zenith angles (SZA). The shadow data were compared to physical measurements used to characterize forest stands, and were also used to test and improve terrain compensation models for remotely sensed images of forested terrain. Canopy self-shadowing on flat terrain strongly correlates with the canopy's geometric complexity as measured by the rumple index (canopy surface area/ground surface area) (R^2=0.94–0.87 depending on SZA), but is less correlated with other stand measurements: 95th percentile canopy height (R^2=0.68), mean diameter at breast height (dbh) (R^2=0.65), basal area ha^{-1} (R^2=0.18), and canopy stem count ha^{-1} (R^2=0.18). The results in this paper support interpretation of self-shadowing as a function of canopy complexity, which is an important ecological characteristic in its own right. Modeling of canopy self-shadowing was used to assess the accuracy of the Sun-Canopy-Sensor (SCS) topographic correction, and to develop a new empirical Adaptive Shade Compensation (ASC) topographic compensation model. ASC used measured shadow (as an estimate of canopy complexity) and the SCS term (to describe the illumination geometry) as independent variables in multiple regressions to determine the topographic correction. The ASC model provided more accurate radiance corrections with limited variation in results across the full range of canopy complexities and incidence angles.

1. Introduction

The ability to use canopy self-shadowing to classify and derive stand parameters in forest remote sensing has long been recognized (*e.g.*, Li and Strahler, 1985). Because stands with trees of different sizes, shapes, and arrangements cast different amounts of shadow, self-shadowing as a fraction of the image correlates with the complexity of the canopy structure. This allows classification based on forest structure using differences in the canopy self-shadowing (Fig. 1a–b). Table 1 summarizes terminology related to shadowing as used in this paper.

Canopy self-shadow is frequently used in spectral mixture analysis (SMA) of moderate-resolution images (*e.g.*, Landsat Thematic Mapper, TM), to analyze canopy structure at sub-pixel scales. SMA estimates sub-pixel fractions of spectrally distinct and physically meaningful endmembers as estimates of the proportion of materials in an image (Adams and Gillespie, 2006; Adams et al., 1993, 1995; Foody, 2004; Settle and Drake, 1993). In images of forest landscapes, spectral endmembers for green vegetation (GV), non-photosynthetic vegetation (NPV) such as wood, soil, and topographic shading and shadow (spectrally grouped as "Shade": Adams and Gillespie, 2006) are commonly used. At pixel scales of tens of meters, canopy self-shadowing is the dominant contribution to Shade for conifer forests (*e.g.*, Gillespie et al., 2006).

Adams et al. (1995) used Shade to distinguish between Amazonian forest types based on the self-shadowing differences of dominant tree species. Peddle et al. (1999) found that use of the Shade endmember improved estimation of boreal forest biophysical properties. Lu et al. (2003) used SMA with the Shade endmember for Amazonian forest classification and biomass estimation. Sabol et al. (2002) used the Shade fraction in the Pacific Northwest, USA, to rank stands by structural stage from early canopy closure (20–30 years old) through old-growth (>200 years old). Tottrup et al. (2007) found that increases in the Shade fraction corresponded with greater forest maturity in Southeast Asia.

Although the use of canopy self-shadowing is perhaps best developed with SMA, it is also used with other remote-sensing

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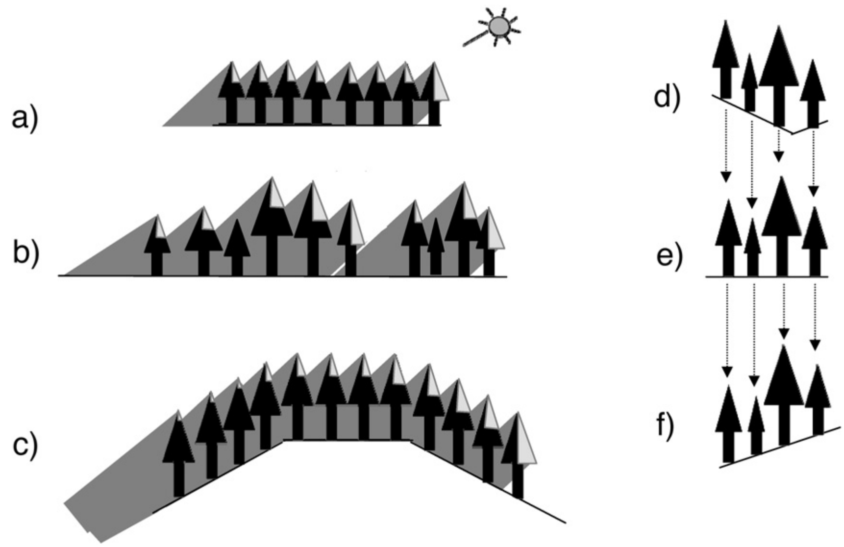

Fig. 1. Effect of canopy complexity and topography on tree shade. Simple forest canopies (a) create less tree shade than complex canopies (b). For any stand within a forest, topography decreases tree shade on sun-facing slopes and increases tree shade on slopes facing away from the sun, changing the area of sunlit canopy (bright canopy areas). Variations in topography can mimic variations in canopy complexity, increasing the difficulty of classifying stand complexity (c). Bright areas on tree figures in 1-c show sunlit canopy area; rest of canopy area would be in shadow. This study uses LiDAR-derived canopy models (d) and adjusts the underlying topography to represent the canopy as it would exist on flat terrain (e). Tree shade is then modeled using the hillshade function of ArcGrid with 183 slope-aspect combinations (f) and 80 canopy surface models.

methodologies. Shadow is an important component of the Tasseled Cap Wetness transformation that has been used to classify forests based on structural stage (Cohen and Spies, 1992). The proportion of area in tree shadow also has been used in high-resolution (<1 m) satellite remote sensing to estimate forest biomass (Leboeuf et al., 2007) and to estimate diameter at breast height (dbh) and crown area (Greenberg et al., 2005).

Correlation of Shade with ground-measured stand characteristics has proven difficult. Many remote-sensing studies use data such as tree species, dbh, and tree stem density from ground-level plot studies to interpret and validate their satellite images (*e.g.*, Song and Woodcock, 2002). Ground-level measurements, however, commonly correlate poorly with the canopy surface as seen in satellite images, making the interpretation of Shade ambiguous. Allometrically derived canopy surfaces may understate the complexity of canopies, underlining the need for more quantitative measures of fine-scale structure. Topographically induced changes in shading and shadowing create additional ambiguity and are major sources of variation in Landsat images (Gu and Gillespie, 1988).

This study directly examines the relationship of canopy structure and self-shadowing. Airborne LiDAR (LIght Detection And Ranging) data were used to model the exposed canopy surface of 80 conifer stands in the Pacific Northwest ranging from pre-canopy closure to old-growth. We use the LiDAR data to address two questions essential to forest studies that use tree shade:

- How well do common measures of stand characteristics correlate with innate canopy self-shadowing?
- Can the topographic influence on self-shadowing be removed while preserving the innate, topographically independent Shade differences between closed-canopy conifer stands (i.e., tree shade of horizontal surfaces plus leaf shade)?

In this paper, we first investigate the correlation of canopy shadowing to common measures of stand characteristics. The use of canopy shadowing to analyze forest conditions requires that purely topographic effects on canopy shadowing be accurately corrected. Therefore, we next investigate canopy shadowing and models that relate shadowing to geometric factors of slope and illumination. We then test the leading topographic correction model (SCS) with canopy shadowing as measured from LiDAR digital elevation models (DEMs). Finally, we substitute an empirical function relating canopy shadowing to geometric factors into radiance correction models for the suppression of topographic effects. We call this the Adaptive Shade Compensation (ASC) model. Because canopy shadowing is a dominant factor controlling canopy radiance (Gu and Gillespie, 1988), shadow-correction models are also radiance correction models that can be used for reducing the effects of topography in images.

1.1. Forests and tree shade

Canopy complexity of conifer forests in the Pacific Northwest generally increases as stands mature (Franklin and Dyrness, 1988; Franklin et al., 2002). At canopy closure, stands are characterized by short trees (relative to their mature heights), high tree densities, and homogeneous canopies (Acker et al., 1998; Franklin et al., 2002; Oliver and Larson, 1996). As stands develop, they have fewer but taller canopy

Table 1
Terminology related to the spectral endmember shade

Term	Definition
Shading	Darkening due to illumination variation controlled by viewing and illumination geometry
Shadow	Dark image object resulting when topographic objects block sunlight
Self-shadowing	Unresolved shadowing due to objects (*e.g.*, trees) within a pixel as opposed to shadowing from resolved shadowing from up-sun objects in other pixels
Shade (capitalized)	Low-amplitude spectrum used as a spectral endmember in spectral mixture analysis and resulting from a combination of shading and unresolved shadows, or from resolved shadows (Adams and Gillespie, 2006)
shade (uncapitalized)	Generic term for shading and shadowing in the landscape and not restricted to the spectral sense of Shade as used in Spectral Mixture Analysis
Hill shade, topographic shade	Darkening due to shading as defined above, by topography and solar illumination angle
Tree shade	Darkening due to canopy self-shadowing generally calculated assuming trees are solid, opaque objects
Leaf shade	Unresolved shadowing within a tree caused by leaves, stems, and other elements comprising the tree
Geometric shade	Darkening due to changes in incidence angle across the surfaces of the individual elements of the tree