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Spatial scaling of reflectance and surface albedo over a mixed-use, temperate forest landscape during snow-covered periods

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ABSTRACT

Albedo products from the MODerate resolution Imaging Spectroradiometer (MODIS) have been validated extensively over spatially homogeneous sites with snow-cover. This study evaluated the spatial scaling of albedo and related reflectance-based quantities over areas of high spatial heterogeneity in temperate mixed forest, deciduous forest, urban and built-up, and cropland/natural mosaic lands under snow covered conditions. Reflectance-based quantities evaluated included spectral radiance, surface directional reflectance, and spectral and broadband albedo derived from ground- and tower-based measurements and high-resolution (5 m) hyperspectral imagery (HSI) to coarse resolution (~500 m) MODIS satellite data.

Our approach first compared ground- and tower-based spectral and broadband reflectance quantities to HSI data, then to evaluate HSI with MODIS reflectance-based products. Over snow-covered pasture, HSI directional reflectance was biased lower than ground-based measurements collected using a spectroradiometer, and greatly underestimated at wavelengths less than 450 nm. Tower-based shortwave broadband albedo (280–2800 nm) and HSI albedo agreed within ±0.04. HSI directional spectral reflectance agreed well with tower-based measurements of spectral albedo collected using a spectroradiometer and remote cosine receptor above a mixed forest canopy with underlying snow cover. Spectral albedo collected over a dormant deciduous broadleaf canopy increased from 0.10 for snow-free conditions to 0.14–0.18 when snow-cover was present under the canopy. Canopy shortwave broadband albedo was not very sensitive to underlying snowpack depth, indicative of strong vegetation masking.

Next, HSI data were spatially aggregated and averaged to 500 m MODIS grids and compared to two MODIS albedo products: (1) MODIS/Terra and Aqua Combined Bidirectional Reflectance Distribution Function (BRDF) Albedo V005 (MCD43A, magnitude inversion), and (2) MODIS/Terra Snow Cover Daily L3 Global 500 m Grid (MOD10A1). An assessment of surface heterogeneity demonstrated that MODIS products generally perform well for snow-covered landscapes with high spatial heterogeneity, with biases between ±0.04 and RMSEs less than 0.085 for mixed and deciduous broadleaf forested and urban & built-up land cover classes, and less than 0.11 for cropland/natural mosaic. Biases were generally lower for MOD10A1 compared to MCD43A3.

Mean shortwave broadband albedo from MODIS and HSI over deciduous broadleaf and mixed forest with underlying snow cover ranged from 0.14 to 0.28. Albedo over MODIS grids characterized as a mosaic of cropland, forests, grasslands, and shrublands (e.g., cropland/natural mosaic) was substantially higher than forested grids under snow-covered conditions, ranging from 0.39 to 0.43.

1. Introduction

Albedo, the ratio of incoming to reflected solar radiation, plays an important role in climate by regulating the amount of shortwave radiation reflected or absorbed and subsequently reradiated as longwave radiation by a surface. Due to its high albedo, snow cover increases the proportion of solar radiation reflected from the Earth's surface, producing a 1.5 °C to 4.5 °C cooling effect compared to snow-free surfaces (Mote, 2008). The magnitude of cooling depends on a

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variety of factors including snow depth, cloud cover solar zenith angle, and land cover type. Land cover type is particularly important because it limits the maximum snow-covered albedo based on the presence or absence of canopy structure. Forest canopies shield highly reflective snow cover, lowering surface albedo in winter and exerting a positive climate forcing (e.g., warming) relative to non-forested lands covered with snow (Bonan, 2008).

Uncertainties in the climate effects of forest cover can complicate climate model simulations in heavily forested regions, such as the northeastern United States (US). For example, when global climate models were statistically downscaled over the northeastern US region, trends in observed winter warming (+0.7 °C/decade) were greatly underestimated by a CMIP3 model ensemble mean (+0.25 °C/decade) over the period 1970–2000 (Hayhoe et al., 2007). The underestimation of winter temperature trends in the downscaled models may be linked to poor parameterization of surface albedo over forests that contributes to the strength of snow albedo feedback (SAF) in the climate models (Hayhoe et al., 2007), which generally exhibit a three- to five-fold spread in the change in surface albedo associated with a 1 °C change in surface air temperature (Qu & Hall, 2006, 2014). Models with weaker SAF tend to have explicit canopy treatment and either have snow canopy albedos that are too low or have vegetation that excessively shields snow-covered surfaces, while models with stronger SAF generally have a greater contrast between snow-covered and snow-free conditions over forests (Qu & Hall, 2006, 2014).

Snow-covered reflectance and albedo products from satellite measurements have not been assessed for accuracy as extensively for forested landscapes (Wang et al., 2014) as they have for non-forested landscapes (e.g., Jin et al., 2003b; Klein & Stroeve, 2002; Stroeve, Box, & Haran, 2006; Stroeve, Box, Wang, Schaaf, & Barrett, 2013; Wang et al., 2012). Here, we focused on evaluating winter surface reflectance and albedo properties of landscapes in New Hampshire (NH), USA, a region dominated by second growth mixed temperate forest, interspersed with patches of agricultural and other human dominated land cover types. Landscape heterogeneity in the region complicates comparisons of ground-based and satellite albedo because the ground footprint of a tower based measurement may not be representative of the satellite footprint (Román et al., 2009; Wang et al., 2014). In such situations, an intermediate resolution product must be used to connect ground- and tower-based measurements to coarse resolution satellite imagery.

The MODerate resolution Imaging Spectroradiometer (MODIS) bidirectional reflectance distribution function (BRDF) albedo product (Schaaf, Liu, Gao, & Strahler, 2011; Schaaf et al., 2002; Schaaf et al., 2008) has been validated extensively over a variety of land cover types (Jin, Schaaf, Gao, Li, & Strahler, 2003a; Jin et al., 2003b; Liu et al., 2009; Salomon, Schaaf, Strahler, Gao, & Jin, 2006; Wang et al., 2012; Wright et al., 2014). The BRDF provides surface reflectance as a function of illumination and viewing geometry, and accounting for the unique structural and optical scattering, transmittance, absorption, and emission properties of a surface. Validation efforts have included shortwave broadband albedo (300–2800 nm) over the Greenland Ice Sheet (Stroeve et al., 2013), over snow-free (Román et al., 2009) and snow-covered forests (Wang et al., 2014), and spectral albedo over the Greenland Ice Sheet (Wright et al., 2014). These previous studies have demonstrated that MODIS BRDF albedo products perform very well over homogeneous landscapes. However, more research is needed to establish how well they perform over landscapes with high spatial heterogeneity. This is particularly important during periods of snow cover when highly reflective snow-covered fields stand in contrast to adjacent forested areas that mask snow cover with their dark canopies.

The daily MODIS snow albedo product (Hall, Salomonson, & Riggs, 2006) differs from the MODIS BRDF albedo product primarily in its assumption that forested lands are Lambertian reflectors (i.e., no BRDF correction is applied). The Lambertian assumption does not recognize the importance of forest clumping and canopy structure and does not account for shadows cast on adjoining foliage and in gaps in the forest canopy, which significantly alters the surface albedo. These geometric optical effects cause surfaces to appear darker when the source of illumination is opposite the MODIS viewing sensor (forward scattering) or brighter when the source of illumination is behind the sensor (backscattering), significantly impacting the retrieval of accurate snow-covered forest albedo. A higher BRDF could be expected in the viewing direction of forests with wider canopy gaps, where more underlying snowpack would be revealed. It is these shadowing effects that also drive the retention and melt of snow underlying canopy. Nonetheless, daily resolution makes the daily MODIS snow albedo product an ideal dataset for studying rapid changes in albedo as snow surfaces melt or compact. The daily MODIS snow albedo product has been validated over the Greenland Ice Sheet and shown to be biased low (−0.05) relative to ground-based measurements, though the variability in daily snow albedo is greater than that observed at ground-based stations (Stroeve et al., 2006). Daily MODIS snow albedo values were within 10% of ground-based observations collected during the 2004 ablation season in the complex terrain of Karasu Basin, Turkey (Tekeli, Şensoy, Şorman, Akyürek, & Şorman, 2006). A study comparing the MODIS daily snow albedo product to the 16-day MODIS BRDF albedo product over the Greenland Ice Sheet found good correspondence at lower elevations and poorer correspondence at higher elevations (Hall, Schaaf, Wang, & Riggs, 2009a). Hall, Nghiem, Schaaf, DiGirolamo, and Neumann (2009b) note that more work is needed to understand the limitations of daily snow albedo products. To the best of our knowledge, no comparison of the two products over forested and heterogeneous surfaces in the presence of snow-cover has been conducted.

In this study, ground- and tower-based estimates of albedo from surface reflectance quantities collected over snow-covered forest and open pasture were compared to HSI. After a spatial representativeness assessment, the HSI data were spatially aggregated to the resolution of MODIS pixels (~500 m) to assess the accuracy of MODIS BRDF and MODIS daily snow albedo products over heterogeneous landscapes including deciduous broadleaf, mixed forest, mixed forest/cropland/grassland mosaic, and urban & built-up land cover types. This study also examined the spectral albedo over a deciduous broadleaf forest canopy during snow-free dormant conditions and over a range of snow-cover depths using a tower-based field spectroradiometer to evaluate the extent of vegetation masking by forest canopies in the region.

2. Datasets

2.1. Study areas and ground instrumentation

The study focused on two research sites in New Hampshire, USA: (1) Thompson Farm Research Station (TF) in Durham, NH and (2) Bartlett Experimental Forest (BF) in Bartlett, NH (Fig. 1). Ground validation protocols are described in more detail below and summarized in Table 1. Details on the aircraft high resolution hyperspectral flight campaign carried out at the two research sites are provided in Section 2.2.

2.1.1. Thompson Farm (TF) Research Station

The TF Research Station is a 0.83 km^2 mixed use property that includes managed and unmanaged forests, freshwater marshes, and active agricultural fields (Fig. 2). The mixed deciduous and coniferous forest is composed primarily of northern red oak (*Quercus rubra*), white pine (*Pinus strobus*), red maple (*Acer rubrum*), shagbark hickory (*Carya ovata*), and white oak (*Quercus alba*) (Perron, Bennett, & Lee, 2004). The primary agricultural field located east of the canopy tower (Fig. 2) was tilled, manured, and replanted with pasture grass in late October 2012. The TF research station study area included two ground validation sites: (1) a pasture site (TFP) and (2) an above-canopy site (TFC).

At the TFP site, ground validation reflectance-based quantities included spectral radiance, spectral hemispherical conical reflectance factors (HCRF), shortwave broadband bihemispherical reflectance