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Structural factors driving boreal forest albedo in Finland

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ABSTRACT

Understanding the influence of forest structure on forest albedo, and thus on the energy exchange between the forest and the atmosphere, is urgently needed in areas with large forest cover and active forest management. Fine resolution albedo retrievals enable quantifying the relationships between forest variables and albedo also in patchy landscapes, such as in the managed forests in Fennoscandia. In this study, field plot data, airborne laser scanning (ALS) data and high resolution satellite albedo retrievals from Landsat were used to investigate the main factors influencing forest albedo in Central Finland in midsummer. Tree species, forest structure and understory (ground) vegetation composition all influenced forest albedo. The tree species-specific models were estimated on a subpixel scale by utilizing information on the proportions of each species within a plot. Tree species considerably improved the albedo prediction when added to a model containing only a structural variable, whereas a further addition of the site fertility class as a proxy of understory vegetation composition only slightly improved the model. Albedo decreased with increasing volume of growing stock, but the decrease leveled off at high volumes. The albedo of plots with high volume was instead mainly governed by tree species and was the lowest for Norway spruce, intermediate for Scots pine and highest for broadleaved species. Norway spruce albedo decreased almost linearly with increasing mean tree height. ALS-derived canopy cover explained fairly well the variation in albedo in the visible region, but the total shortwave albedo was better predicted by ALS-derived tree height.

1. Introduction

Forest utilization and management has altered the structure and tree species composition of Northern European boreal forests. The shift to even-aged forest structure by clear-cuttings and thinnings has altered the diameter and age distribution of the individual forest stands (Uotila, Maltamo, Uuttera, & Isomäki, 2001; Axelsson & Östlund, 2001), and changed the understory vegetation composition (Vanha-Majamaa & Reinikainen, 2001). Tree species composition has changed to favor commercially used species (Tomppo et al., 2011).

Altering the structure and species composition of forests may change the local energy balance and, hence, the climatic conditions. For example, tree species composition may affect the proportion of global radiation reflected by the forest (i.e. the albedo) and therefore the amount of available energy, as well as the partitioning of available energy into sensible and latent heat fluxes (Baldocchi, Kelliher, Black, & Jarvis, 2000). Eugster et al. (2000) found that deciduous boreal forests typically have a lower Bowen ratio (the ratio of sensible to latent heat flux) compared to coniferous boreal forests.

Forest albedo is determined by factors related to the forest structure and spectral properties of the forest elements, as well as to the spectral and directional properties of the incident solar radiation. Forest structure, i.e. the arrangement and size of the trees, branches and foliage, influences the pathways of radiation within the forest and therefore its directional reflectance (Kimes, Newcomb, Nelson, & Schutt, 1986). Spectral properties of leaves, needles, stems, branches, understory vegetation or bare soil differ among species and geographical areas. For example, the leaves of broadleaved deciduous tree species often have a higher single scattering albedo than the needles of coniferous species (e.g. Roberts et al., 2004; Lukeš, Stenberg, Rautiainen, Mõttus and Vanhatalo, 2013). In Finnish boreal forests, the ground is usually covered by understory vegetation, such as dwarf shrubs, mosses, graminoids, herbs and lichen. Spectral properties of boreal forest understory vegetation have been measured by, for example, Miller et al. (1997); Peltoniemi et al. (2005) and Rautiainen, Mõttus, et al. (2011). Pisek and Chen (2009) estimated understory reflectance from Multi-angle Imaging SpectroRadiometer (MISR) data. However, to our knowledge no studies exist in which the understory albedo has been extensively assessed (but see Kuusinen, Lukeš, et al., 2014 for measurements of a few plots). Seasonal variation in vegetation, snow cover, soil

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moisture and solar angle has also been observed to affect forest reflectance or albedo (Betts & Ball, 1997; Nilson, Suviste, Lükk, & Eenmäe, 2008; Niemi et al., 2012; Kuusinen et al., 2012).

Empirical research on boreal forest albedo has been based on permanent radiation measurements on meteorological towers (e.g. Betts & Ball, 1997; Beringer, Chapin, Thompson, & McGuire, 2005; Amiro et al., 2006; Riihelä & Manninen, 2008; Hollinger et al., 2010; Kirschbaum et al., 2011; Kuusinen et al., 2012), movable masts or towers equipped with radiation sensors (Kuusinen, Lukeš, et al., 2014), airborne measurements using pyranometers mounted on airplanes (Manninen et al., 2012) or estimation of albedo from satellite data (e.g. Lyons, Jin, & Randerson, 2008; Bernier et al., 2011; Bright, Astrup, & StrØmman, 2013; Kuusinen, Tomppo, et al., 2014; Lukeš, Rautiainen, Manninen, Stenberg, & Mõttus, 2014). Despite these efforts, research on the impact of forest structure on the albedo using empirical data has been restricted by the sparse spatial coverage of in-situ measurements of albedo and by the relatively coarse spatial resolution of available satellite-based albedo products. In particular, not many empirical studies have investigated the relationships between forest structure and albedo in boreal forests. Kuusinen, Lukeš, et al. (2014) used a movable telescopic mast to study the albedo variation in forest stands in Southern Finland during growing season. They reported that in middle-aged or mature forests, tree species composition might be more important than, for example, the leaf area index (LAI) or canopy cover in determining forest albedo. Kirschbaum et al. (2011) used permanent tower based albedo measurements and satellite data to study the long term albedo change of a pine forest in New Zealand. They noticed that the initially high albedo of a former pasture land first declined as the forest matured, and then stabilized. Similar results of an initial decline and thereafter a stabilization of the albedo of a maturing boreal forest have been obtained from in-situ measurements of Amiro et al. (2006) and remote sensing based studies of Bright et al. (2013) and Kuusinen, Tomppo, et al. (2014). In a modeling study, Lukeš, Stenberg and Rautiainen (2013) found that albedo decreased with increasing aboveground biomass, LAI and canopy cover, although at high values of canopy cover the albedo again increased. On the other hand, Ni and Woodcock (2000) based on results using a forest reflectance model, concluded that during the snow-free time canopy cover affects the forest albedo only marginally. They suggested that this is a result of the similar spectral properties of the moss understory and canopy overstory. Bernier et al. (2011) used MODIS data to study the albedo of Canadian black spruce forests with lichen dominated ground cover, and noticed that decreasing canopy cover increased albedo. Overall, it has been noticed in many studies that the change in forest albedo along with forest structural variables is larger in winter with snow on the ground than during the snow-free season (Ni & Woodcock, 2000; Amiro et al., 2006; Bright et al., 2013; Lukeš et al., 2014; Kuusinen, Tomppo, et al., 2014).

Considering the patchiness of landscape and forests and the small stand size of forests in countries with dense population, intensive forest management, or both, the moderate or coarse spatial resolution satellite albedo products may not be appropriate for studying dependencies between forest structure and albedo. Albedo cannot in principle be estimated from single-view-angle remote sensing data. However, Shuai, Masek, Gao, and Schaaf (2011) introduced a method that utilizes estimates of the bidirectional reflectance distribution function (BRDF) from moderate resolution MODIS data to approximate the ratio of total to nadir reflectance and apply this to estimate the albedo from Landsat ETM+ images.

Accurate information on forest structural properties is traditionally derived from field inventories, but airborne laser scanning (ALS) data have become increasingly popular in stand-level forest management inventories and even in national forest inventories (NFIs) (Vauhkonen, Maltamo, McRoberts, & Næsset, 2014). The ALS variables which are most useful in practical forest inventories are based on the XYZ-coordinates of canopy echoes. Commonly derived ALS variables include different canopy height and density metrics which can be used to predict stand volume (e.g. Næsset, 1997). However, information on tree species cannot be reliably extracted from the structural ALS data. Discrete return ALS sensors also record the intensity of the returning echo as an 8-bit integer, which approximates the target's surface reflectance. Intensity can be useful for species classification (Ørka, Næsset, & Bollandsås, 2009), but it requires empirical corrections that can change considerably in different acquisitions (Korpela, Ørka, Hyyppä, Heikkinen, & Tokola, 2010). Thus multispectral aerial image data that describes the species better are needed as auxiliary data in practical ALS inventories (Maltamo & Packalen, 2014).

In this study, we identified the main field measured and ALS-based variables influencing boreal forest albedo at plot-level. Our study is based on field measurements from 1005 forest plots located on both managed and unmanaged forest land, ALS data and albedo data estimated from Landsat-5 TM images in Central Finland. The study is motivated by the possibility to use an extensive field plot data set as well as fine resolution satellite albedo data to improve our understanding of the influence of boreal forest structure, and therefore also management decisions, on forest albedo. Because the field plots are often mixtures of more than one tree species, we use the unmixing approach to estimate the species-specific models based on each species' proportion of volume of growing stock or stem number.

2. Material and methods

2.1. Field plot data

The study area was located in Central Finland with the center of the area approximately at 62°3′N and 24°5′E and reaching about 50 km in each direction. Main tree species in the area are Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* (L.) Karsten) and broadleaved species, mainly birch (*Betula pendula* Roth. and *Betula pubescens* Ehrh.) and aspen (*Populus tremula* L.). From here on, we will refer to these species simply as pine, spruce and broadleaved species. The field plot data were measured during the growing season of 2013 by the Finnish Forest Research Institute (currently Natural Resources Institute Finland) and the Finnish Forest Centre. The data were collected to study the influence of different sampling strategies on ALS-based forest resource estimates (Tomppo, Kuusinen, Mäkisara and Katila, manuscript). Systematic sampling with L-shaped clusters of eight sample plots was employed. The distance between the clusters was 4.3 km and that between the plots 250 m. The plots were located using accurate GNSS receivers with 95% of the errors less than one meter under tree canopy when the receiving time is not more than 35 min. Trees with a breast height (1.3 m) diameter (DBH) of at least 4.5 cm were measured within a circle with a radius of 9 m, or 5.64 m in seedling stands. Additionally, all trees belonging to an angle count (relascope) plot with a basal area factor of 1.5 and a maximum distance of 9 m were measured. Trees with DBH smaller than 4.5 cm were also measured from three sub-plots with a radius of 1.05 m per plot. In seedling stands, stem number and mean tree height were estimated from trees measured in tree density plots with a radius of 2.82 m. The plot data, either measured or derived, included e.g. land class, main site class, site fertility class, distance from the plot center to nearest stand boundary, mean height of trees, mean DBH, mean volume of growing stock per species, basal area, stem number and harvesting history. The study area comprised a total of 2468 plots. From these plots, 1005 plots were selected for our study based on the following criteria: the plot must be situated completely within one stand, the nearest stand boundary must be at least 15 m from the plot center, the plot must be on forest land (both productive mineral and peatland soil plots included), plots in seedling stands with retention trees for natural regeneration are excluded. In addition, no plots were included where major cuts had been done during the time between the Landsat albedo retrieval and field plot measurements (Table 1).