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Relationship between forest density and albedo in the boreal zone

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ABSTRACT

The relationship between albedo and forest areas is complex. Little is known about the driving factors of albedo in the boreal zone. Using a radiative transfer model and an extensive forest inventory database, we simulated albedo of forest stands composed of the most abundant tree species of Fennoscandia – Scots pine, Norway spruce and Silver birch. The physically-based radiative transfer model allowed us to uncouple the driving factors of the forest albedo. We analyzed separately how biomass, canopy cover, and species composition influence the shortwave albedo of a boreal forest. The albedos differed significantly between species and increased with solar zenith angle. The lowest values were observed for spruce stands, followed by pine stands and the highest values were observed for birch stands. Diurnal courses of albedo were tightly related to forest density as quantified by biomass or canopy cover. The albedos generally decreased with increasing stand biomass and canopy cover whereas the sensitivity to solar angle increased as the stands became denser. The sharpest decrease in albedo was observed at low biomass values, after which the albedo remained relative stable. The strength of the relationships was weaker for larger solar zenith angles.

1. Introduction

Changes in the amount of forest cover and biomass can have diverse effects on global climate and carbon sequestration via various feedback mechanisms, such as fluctuations in the land surface albedo and effects on the global water cycle. On the other hand, changes in climate directly affect the functioning of forests via the frequency of occurrences of natural disturbances, CO_2 fertilization, and alterations in the length of the growing season (Betts et al., 2007).

Among terrestrial biomes boreal forests have the greatest effect on annual mean global temperature (Snyder et al., 2004). The on-going increase in boreal forest biomass in Europe and parts of Asian Russia can influence the global climate not only through carbon fixation but also through altering the albedo. However, the link between forest land and its albedo is complex: very little is known about the influence of natural disturbances and human activities (such as forest management procedures) on albedo. Albedo perturbations due to natural forest disturbances can either enhance or reduce the positive radiative forcing from CO_2 efflux (O'Halloran et al., 2012; Bernier et al., 2011). In regions seasonally covered by snow such as the boreal zone, removal of forest canopy will lead to an increase in albedo in winter; snow covered forest floors significantly affect the total canopy albedo (Manninen and Stenberg, 2009). Furthermore, the effects of stand age and development stage on albedo need to be considered (Bonan, 2008). In managed boreal forests, forestry practices affect the albedo not only through changes in biomass and canopy cover but also by altering the stand structure (Rautiainen et al., 2011a). A similar canopy cover or biomass can result from a range of forest structures, which cause different albedos.

Whereas the general difference in the albedo of coniferous and deciduous forests has been long established (e.g. Betts and Ball, 1997), the reasons behind this are still partly unknown. Moreover, as there are indications that the currently conifer-dominated boreal forests are gradually shifting towards including more deciduous tree species, it is ever more important to understand the role of species composition on forest albedo. As the global forest area and biomass change independently (Rautiainen et al., 2011b), their effects on forest albedo need to be analyzed separately.

Neither local albedo measurements nor satellite-based albedo products can explain the causality between small-scale environmental management scenarios and changes in albedo. Thus, forest reflectance models validated with satellite remote sensing data is the only possible method for linking quantitative changes in vegetation structure to albedo for large geographical regions. Forest reflectance models are parameterized using mathematical descriptions of canopy structure (e.g. leaf area index, tree height, crown dimensions, stand density), optical properties of leaves and forest floor, and spectral and angular properties of incoming radiation.

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Table 1
Tree species composition and understory types for the study sites Puumala, Saarinen and Hyytiälä.

	Puumala	Saarinen	Hyytiälä
Number of stands	361	326	8
Dominant species (%)			
Pine	67	28	4
Spruce	26	53	43
Birch	7	19	53
Understory type (%)			
Mesic	89	96	50
Herb-rich	0	3	38
Xeric	11	1	12

Using these models, the spectral and broadband albedos of a forest can be calculated from more readily measurable variables such as forest structure and leaf optical properties.

Here, we investigate the influence of forest biomass, canopy cover and species composition on the shortwave albedo of boreal forests using a forest reflectance model which uses routine forest inventory variables as input. We use an extensive forest inventory database collected in Finland covering the natural variation in stand structures.

2. Materials and methods

2.1. Study stands

We simulated the albedo for 695 boreal forest stands located in three sites in Central and Eastern Finland, named Puumala, Saarinen and Hyytiälä. The stands represent the typical range in stand structures, development classes and site fertility types of managed boreal forests in Finland, and are dominated by the most abundant tree species in Northern Europe i.e. Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* (L.) Karst) and birches (*Betula pendula* Roth or *Betula pubescens* Ehrh.) (Table 1). The forest inventory database available as input for the albedo simulations included leaf area index (LAI) and species-specific values of stand density (N), and medians of diameter at breast height (DBH), tree height (H) and crown length (L_{CROWN}). The understory type was assigned to each forest stand based on its site fertility class. The stands and measurements are described in more detail by Stenberg et al. (2004) and Korhonen et al. (2011).

The two inputs for albedo simulations which were not directly measured were the crown radius (C_R) and total aboveground biomass. C_R was calculated using an allometric relationship between DBH and C_R developed by Jakobsons (1970) for pine, spruce and birch of northern Sweden (latitudes > 60°). Total aboveground biomass of simulated stands was estimated using the recently developed Finnish national multivariate models for birch (Repola, 2008), pine and spruce (Repola, 2009). Basic structural parameters of all forest stands (N = 695) are given in Table 2, and the structural parameters of monospecific stands (N = 291) in Table 3.

The optical properties (directional-hemispherical reflectance and transmittance factors) of needles and leaves for the three species were obtained from a spectral database measured by Lukeš et al. (2013) in boreal Finland (Fig. 1a). For the two coniferous species, the shoot was chosen as the basic scattering element (Nilson and Ross, 1996), i.e. we used shoot spectra (instead of needle spectra) as input in the albedo simulations. Species-specific shoot spectra were obtained from needle spectra according to a previously published methodology (Rautiainen et al., 2012; Smolander and Stenberg, 2003) using average values of the shoot to total needle area ratio, STAR (Oker-Blom and Smolander, 1988). The STAR values used were 0.147 for pine (Smolander et al., 1994) and 0.161 for spruce (Stenberg et al., 1995).

Optical properties of the forest understory were based on a database collected in Finland (Rautiainen et al., 2011c) covering typical forest understory types from herb-rich green understories to xeric lichen types (Fig. 1b). For each study stand, we assigned an understory spectrum (xeric, mesic or herb-rich) according to its site fertility class. Also bark and trunk optical properties were based on a previously published database (Lang et al., 2001).

2.2. Albedo simulations

Albedo simulations for different solar zenith angles (SZA) were performed using the recently modified version (Mõttus et al., 2007) of the Forest Reflectance and Transmittance Model (FRT) (Kuusk and Nilson, 2000). FRT is a hybrid type of radiative transfer model, i.e. it includes properties of both geometric-optical and radiative transfer equation based models. The forward simulations of albedo for a large number of stands with a complex structure are relatively fast with the FRT because the model is computationally efficient and its parameterization is based on standard forest inventory data. More importantly, it is able to accurately simulate the spectral fluxes of a forest (Widlowski et al., 2007).

Several tree classes with different structure, density and optical properties of foliage can be defined in FRT in order to simulate mixed stands. We simulated either one, two or three tree classes depending on the species composition of the study stand. Tree crowns were simulated with ellipsoid crowns which have been found to represent well crown shape and volume in our study species (Rautiainen et al., 2008; Mõttus et al., 2006). As described previously, the input parameters by species were obtained directly from the inventory database or derived using allometric equations (Table 4).

The optical properties of leaves, shoots and bark were parameterized according to measured values (see Section 2.2) (i.e. one average spectrum of foliage and bark for each tree species). The forest floor was considered a Lambertian surface with a mesic, herb-rich or xeric type spectrum.

In this study, we simulated the black-sky albedo, also known as directional-hemispherical albedo which has been specified as the product required for climate change purposes (GCOS, 2004). Forest albedo was simulated for two extreme solar zenith angles (40° and 70°) during midsummer at latitudes corresponding to the study sites (around 61°). In addition, the hourly diurnal course of albedo during summer solstice (DOY = 172) was simulated for hourly solar zenith angles between 6 am and 6 pm of apparent solar time. The albedo simulations were run at a 5 nm spectral resolution from 400 nm to 2400 nm. A 12 × 12 quadrature was used to integrate over all the viewing zenith and azimuth angles in the hemisphere.

The broadband shortwave albedo was approximated as a sum of spectral albedos weighted by the incoming solar irradiances at the corresponding wavelengths. We used solar irradiance measurements which are recommended as the reference exo-atmospheric solar irradiance spectrum by the Committee on Earth Observation Satellites (CEOS) (Thuillier et al., 2003). Although our simulated spectral range (400–2400 nm) is somewhat narrower than the theoretical definitions of total shortwave broadband albedo (300–4000 nm), it covers the bulk part (ca. 98%) of the solar irradiance and thus gives a good approximation of total broadband albedo.

3. Results

3.1. The influence of species composition on albedo

First, we focused on monospecific forest stands, i.e. stands with a 100% composition of pine, spruce or birch. From the original 695