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Research Paper

Seasonality of albedo and FAPAR in a boreal forest

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ABSTRACT

Satellite data are continuously used to monitor albedo and fraction of absorbed photosynthetically active radiation (FAPAR), which are key components in determining the energy balance and productivity of forests. However, due to the mismatch between spatial resolution of the satellite data and forest stand size, coarse resolution satellite products cannot capture the fine-scale variations in forest structure. Therefore, forest radiation budget models are important tools in quantifying albedo and FAPAR at stand scale. However, due to the lack of suitable input data, simulations are often restricted to summer conditions only and the seasonal patterns are not considered. We modeled the time series of albedo and FAPAR for an entire growing season for 20 forest plots in the boreal zone in Finland (61°50′ N, 24°17′ E) using an exceptional ground reference data set. Canopy gap fractions and the spectra of forest floor were monitored in the plots throughout the growing season. Data on the seasonality of spectra of tree foliage were also available. The modeled albedo and FAPAR were upscaled and compared against albedo and FAPAR derived from MODIS satellite data. We showed that forest radiation budget models capable of adequately taking into account foliage clumping and its effects on multiple scattering are the most appropriate for simulating albedo of boreal coniferous forests. Our results also indicated negative albedo-productivity relations in boreal coniferous forests. In addition, we demonstrated that not only the overall level, but also the seasonal patterns of albedo and FAPAR differ between tree species. Therefore, the use of only peak growing season albedo or FAPAR values when estimating climate impacts of forest management can be misleading.

1. Introduction

Forests have an important role in controlling the albedo of the Earth's surface, and thus also local and global climate (Bonan et al., 1992). Photosynthetically active wavelengths (400–700 nm) have a dual role, because the fraction of absorbed photosynthetically active radiation (FAPAR) influences not only albedo, but also primary productivity and carbon uptake. Forest structure and species composition, in turn, influence both albedo and FAPAR (e.g. Betts and Ball 1997; Eugster et al., 2000; Roujean 1999; Steinberg et al., 2006, Kuusinen et al., 2016). In the boreal region, these interactions are particularly complex, due to seasonality in forest structure and optical properties, as well as in the incoming solar radiation. Despite this, only a couple of studies have analyzed links between boreal forest structure and albedo (Betts and Ball 1997; McCaughey et al., 2006; Kuusinen et al., 2012; Lukeš et al., 2014) or FAPAR (Roujean 1999; Steinberg et al., 2006; Serbin et al., 2013) throughout the growing season.

The studies mentioned above used in situ or satellite data, or their combinations. Another approach to study relations of forest structure to albedo and FAPAR is through forest radiation budget simulation models (Ni and Woodcock 2000; Lukeš et al., 2013a; Hovi et al., 2016). These models are potentially useful tools also in quantifying the seasonal trends, particularly because satellites used for deriving albedo and FAPAR estimates in high temporal resolution have only coarse spatial resolution (see e.g. He et al., 2014 and Yan et al., 2016 for review of available albedo and FAPAR products). Thus it is difficult to link fine-scale variations in forest structure with albedo and FAPAR. The performance of simulation models depends, however, on the availability and quality of measurements used for their parameterization. Particularly, measurements of seasonal time series of required input parameters have rarely been conducted (Rautiainen et al., 2011; Rautiainen et al., 2012; Heiskanen et al., 2012; Mõttus et al., 2014). As a consequence, simulations of forest albedo and FAPAR have until now been restricted to summertime only, although some studies have compared general summer and winter conditions (Ni and Woodcock 2000). However, to our knowledge no albedo or FAPAR time series for forests

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in high temporal resolution has been simulated to date.

Adequate representation of forest structure is essential in radiation budget simulations. An important structural parameter is clumping i.e. aggregation of the foliage and branches into grouped structures. Previous studies have shown that there are at least two significant levels of clumping in boreal coniferous forests: clumping of needles into shoots (Norman and Jarvis 1975; Oker-Blom and Smolander 1988), and clumping of foliage into tree crowns (Nilson 1999). The high degree of clumping of foliage into shoots in coniferous forests has also been shown to be the main reason behind low bidirectional reflectance in near infrared when compared to broadleaved forests (Rautiainen and Stenberg 2005). However, the impact of shoot and crown level clumping on forest albedo or FAPAR has not yet been quantified in boreal forests.

In this study, we present field measurements of seasonal courses of canopy gap fractions and forest floor reflectance spectra in a test site in southern Finland. The measurements span over a growing season starting in early May and ending in October. The dataset is complemented with seasonal courses of leaf and needle optical properties measured in close surroundings. We use these data as input in simulating forest albedo and FAPAR over growing season (i.e. snow-free period from bud-burst to senescence), using two different models. One of the models (PARAS) is based on photon recollision probability theory, and the other (FRT) is based on geometric optics and radiative transfer theory. We compare model simulations against each other, and against MODIS satellite data. The results quantify the effect of foliage clumping on albedo and FAPAR and show the importance of taking into account species-specific seasonal courses of albedo and FAPAR when evaluating the climate impacts of forests. Finally, the simulated data are used to demonstrate negative albedo-productivity relationships in boreal coniferous forests.

2. Materials and methods

Field and laboratory measurements are presented in Sections 2.1–2.2, followed by description of methods for deriving true plant area index from field measurements of canopy gap fractions (Section 2.3). Data presented in these three sections are used as input in albedo and FAPAR simulations, which are elucidated in Section 2.4. Finally, Section 2.5 describes the satellite data and how it was compared to the simulation results.

2.1. Canopy gap fractions and forest floor optical properties

2.1.1. Study area

Field data were collected in year 2010 in the vicinity of Hyytiälä Forestry Field Station which is located in southern Finland (61°50′ N, 24°17′ E). The area belongs to the southern boreal zone, and the forests are dominated by Norway spruce (*Picea abies* (L.) Karst), Scots pine (*Pinus sylvestris* L.) and birches (*Betula pendula* Roth, *Betula pubescens* Ehrh). The forest floor vegetation comprises at least mosses, and depending on site fertility, also grasses, herbs, dwarf shrubs or lichens. Based on air temperature observations from nearby SMEAR (Station for Measuring Ecosystem-Atmosphere Relations), growing season in 2010 started on Julian day-of-year (DOY) 130 (May 10) and ended on DOY 284 (Oct 11). The start was defined as the day when mean daily temperature permanently exceeded +5 °C and the end as the day when mean daily temperature permanently fell below +5 °C. "Permanently" here means that the above criteria were met for at least 10 consecutive days. The first snow in the area usually falls between mid-October and mid-November.

2.1.2. Canopy gap fractions

Seasonal measurements of canopy gap fractions were carried out in 20 plots during the growing season in 2010. In addition, a regular stand inventory was conducted in the plots to provide ancillary information on forest structure (Table 1). The plots represented different age classes (stand age approximately 25–100 years), species compositions, and site fertility types that are typical to the area.

Table 1
Mean (and range: min–max) forest variables in the study plots. Dominant tree species = tree species which comprised > 80% of stand total basal area.

	Pine-dominated	Spruce-dominated	Birch-dominated	All
Diameter at breast height i.e. 1.3 m (cm)	18.1 (9.4–25.1)	14.0 (8.8–18.9)	11.0 (1.2–16.3)	15.4 (1.2–25.1)
Tree height (m)	15.0 (7.8–18.6)	12.0 (7.5–15.2)	12.9 (2.4–19.1)	14.2 (2.4–23.1)
Basal area ($m^2\ ha^{-1}$)[a]	19 (10–24)	21 (10–32)	16 (4–27)	20 (4–32)
Crown ratio (%)[b]	41 (19–56)	70 (55–92)	55 (41–79)	56 (19–92)
Stem volume ($m^3\ ha^{-1}$)	140 (43–200)	136 (40–211)	107 (10–156)	146 (10–243)
Number of plots representing each site type				
Herb-rich	0	0	3	4
Mesic	2	3	4	13
Sub-xeric	1	0	0	2
Xeric	1	0	0	1

[a] Total cross-sectional area of stemwood at breast height (1.3 m).
[b] Ratio of height of living crown to tree height.

The canopy gap fraction measurements were repeated in exactly the same locations approximately every two weeks i.e. a total of 11–12 times between May 3 and October 20. LAI-2000 Plant Canopy Analyzer (PCA) was used to measure angular distribution of canopy gap fractions, effective plant area index (PAI_{eff}) and diffuse canopy non-interceptance (DIFN) in all study stands. A total of 12 measurement points were located in each stand in a cross scheme (i.e. 3 points in each cardinal direction at 4 m intervals, see e.g. Majasalmi et al., 2012). Two LAI-2000 PCA units were operated simultaneously so that one sensor (sensor "B") was manually operated in the study stand (at a height of approximately 70 cm) and the reference sensor (sensor "A") was logging above the forest canopy at 15 s intervals. The LAI-2000 PCA measurements require diffuse illumination conditions. This was achieved by carefully selecting the measurement periods to overcast days or in early morning or late evening when the sun was clearly below the last zenith ring of LAI-2000 (i.e. sun-zenith angle larger than 74°). The measurement points were marked with sticks so that the same measurement points were used throughout the growing season.

2.1.3. Forest floor optical properties

Seasonal courses of forest floor reflectance spectra were also measured throughout the growing season in 2010 in four plots representing the most common site fertility types in the study area: mesic, xeric, sub-xeric and herb-rich. In each study plot, a 28-m long transect was marked with sticks and measurements were made at approximately 70 cm intervals under the diffuse light conditions. The instrument was a FieldSpec Hand-Held UV/VNIR (325–1075 nm) Spectroradiometer manufactured by Analytical Spectral Devices (ASD). No fore-optics were attached i.e. the field-of-view of the instrument was 25°. Three spectra above a white Spectralon panel (nominal reflectance of 99%) were measured at the beginning and end of the transect, and additionally between every three measurements along the transect. The raw data (DN readings) were processed to correspond to hemispherical-directional reflectance factors and averaged for all measurement points in each transect. In addition to the seasonal measurements in 2010, HDRF data were measured with a FieldSpec 3 PRO Spectroradiometer (with a full-range detection capacity from 350 nm to 2500 nm) for the same forest floor types during June 2–3 in 2009. These data were used to form the spectra for the shortwave infrared region (> 1075 nm). The forest floor types and seasonal measurements have been described in