Ecological Modelling 284 (2014) 10–18

Contents lists available at ScienceDirect

Ecological Modelling

journal homepage: www.elsevier.com/locate/ecolmodel

Measured and modelled albedos in Finnish boreal forest stands of different species, structure and understory

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ARTICLE INFO

Article history:
Received 12 October 2013
Received in revised form 4 April 2014
Accepted 9 April 2014
Available online 4 May 2014

Keywords:
Albedo
Boreal forest
Forest albedo model
Understory reflectance
Thinning

ABSTRACT

Total shortwave and photosynthetically active radiation (PAR) albedos of eight boreal forest stands of different species (pine, spruce and birch) and structure were measured, and the results were compared to albedos simulated with an existing forest albedo model. The measured shortwave and PAR albedos were rather insensitive to leaf area index (LAI), the largest differences in albedo occurring between tree species. A thinning operation in one of the pine stands caused a short term increase in the PAR albedo but did not affect the total shortwave albedo, probably due to a low understory albedo in the near-infrared (NIR). In the coniferous stands, the white-sky albedos simulated using the PARAS albedo model ranged from 0.071 to 0.101 and were on average about 10% lower than the measured daily coniferous forest albedos in overcast conditions (0.075–0.120). However, the modelled PAR albedos (0.009–0.025) were clearly lower (by 49%) than the measured ones (0.026–0.037) in the coniferous stands. In the single birch stand, on the other hand, the modelled and measured PAR albedos were similar, but the modelled shortwave albedo was notably higher (0.237) than the measured one (0.167) in overcast conditions. The modelled albedos showed a much weaker trend along the diurnal course of solar zenith angle (SZA) than did the measured ones. A sensitivity analysis was conducted in order to find out possible reasons for the differences between the modelled and measured albedos.

1. Introduction

Net radiation (R_n) is the radiation energy available at the earth's surface and is composed of the net shortwave and net longwave radiation. Net shortwave radiation is determined by the amount of incoming solar radiation and the surface albedo, which is the fraction of solar radiation that is reflected by the surface. The longwave radiation balance is dependent on the temperature and emissivity of the ground and the atmosphere. R_n is partitioned into latent and sensible heat fluxes and to the heat flux to the soil. A small part of the solar energy can also be converted into carbon compounds in the photosynthesis of living vegetation. The magnitude of R_n determines the amount of radiation energy retained to the earth's surface, and thus directly influences the climate. Also the partitioning of R_n into latent and sensible heat fluxes may change the local to regional scale climate by affecting the boundary layer conditions and mesoscale circulations (Pielke and Vidale, 1995; Pielke et al., 2011).

Surface characteristics, such as the structural arrangement and optical properties of the surface elements, affect the surface albedo and also the partitioning of the convective heat fluxes. For example, coniferous forests generally have a lower albedo and a higher R_n compared to short vegetation (Betts and Ball, 1997). In addition, sensible heat flux may be higher and latent heat flux lower in coniferous boreal forests as compared to deciduous broadleaved forests or some well-drained short vegetation types (Lafleur and Rouse, 1995; Baldocchi et al., 2000; Eugster et al., 2000; Beringer et al., 2005). This has been explained by on one hand the low aerodynamic resistance and thus a high turbulent transport of heat fluxes, but on the other hand the low intrinsic transpiration rate of boreal coniferous forests (Baldocchi et al., 2000; Beringer et al., 2005).

In this study, our interest lies in the shortwave radiation balance, as quantified by the surface albedo, of typical managed boreal forests in Finland. Particularly, we are interested in the differences in albedo between tree species, and in the variation of albedo with canopy structure within a single species. Differences in albedo between tree species can be caused by different optical properties of the canopy elements and understory, as well as different canopy structure. In addition, the albedos in different spectral regions may have different responses to the above mentioned factors.

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http://dx.doi.org/10.1016/j.ecolmodel.2014.04.007
0304-3800/

For example, the difference in albedo between coniferous and broadleaved forests is pronounced in the near-infrared (NIR) wavelengths. This is caused by a higher leaf albedo of deciduous broadleaved species in NIR and a less clumped foliage structure, as compared to those of conifer species (Gates et al., 1965; Williams, 1991; Roberts et al., 2004; Lukeš et al., 2013a). The clumping of needles in coniferous shoots increases multiple scattering of NIR within the shoot and, thus, the probability of absorption (Smolander and Stenberg, 2005). The effect of understory on forest albedo is higher the lower is the canopy cover and the more the understory reflectance deviates from that of the canopy (Spanner et al., 1990; Ni and Woodcock, 2000; Rautiainen et al., 2007). In addition, the effect of understory species composition on forest albedo varies with wavelength. For example, Rautiainen et al. (2007) noticed that forest stands with lichen understory could be separated from stands with dwarf shrub dominated forest floor vegetation in the visible but not in the NIR spectral region.

The effect of forest structure on forest albedo is laborious to quantify using in situ albedo measurements only. Therefore, studies examining the effect of, e.g. leaf area index (LAI), forest age or biomass on albedo are usually simulation studies making use of forest reflectance models (Ni and Woodcock, 2000; Lukeš et al., 2013b) or remote sensing data (Bernier et al., 2011; Bright et al., 2013; Kuusinen et al., 2014). Only a few studies have empirically assessed the impact of forest structure on albedo. Kirschbaum et al. (2011) examined the effect of afforestation of a former pasture land with Monterey pine (*Pinus radiata*) in New Zealand and reported a decrease in albedo from 0.2 to 0.13 at about 8 years age and saturation thereafter. Also Amiro et al. (2006), based on data on mast measured albedos on different boreal forest sites, found that the albedo, after an initial increase following a stand replacing fire, generally decreased both in summer and winter conditions as the forest age increased.

The observed variation in forest albedo due to differences in stand structure has brought about an interest in the possibility of altering the albedo and radiative forcing of forests by management practices parallel to controlling the CO_2 fluxes. The commonly used silvicultural practises that could have an impact on forest albedo are those that change the tree species composition or forest structure, such as the selection of tree species, rotation length, removal of broadleaved trees during seedling stand treatment or during thinnings, and the intensity of thinnings. Such effects naturally depend on the local tree species, climate (e.g. snow conditions), and forest background properties, and should be evaluated separately for different forest types in the boreal zone. In this study, we concentrate on forests dominated by tree species typical for Fennoscandia; namely Scots pine (*Pinus sylvestris* (L.)), Norway spruce (*Picea abies* (L.) Karsten) and silver birch (*Betula pendula* Roth.). In Finland, 66% of the combined forest land and poorly productive forest land is dominated by Scots pine, 22% by Norway spruce and 12% by broadleaved deciduous species, mainly birches (Tomppo et al., 2011). Comprehensive albedo measurements of the vast boreal forests for all possible combinations of canopy structure, species composition and understory are not practical, but a sampling scheme covering forests with the regionally most typical tree species and canopy structures could be viable. Such measurements could be used to calibrate forest albedo models and to evaluate the albedo estimates derived from remotely sensed data. In addition, using information on the abundances of the different forest types, approximate regional albedo values could then be computed.

The specific aims of this study are twofold: the first objective is to use in situ measurements to study the albedo in Finnish boreal forest sites with different tree species and forest structure. For this purpose, a portable telescopic mast was used to measure the albedo in one birch stand, four pine stands and three spruce stands with variable LAI and canopy cover. Secondly, the PARAS forest albedo model (Manninen and Stenberg, 2009) was used to simulate albedos for the measurement sites. This was done in order to evaluate the model against measured albedos and to better understand the influence of stand structure on the measured albedos. The PARAS albedo model is based on the spectral invariants theory (Knyazikhin et al., 2011) and provides a simple approach to simulate the forest albedo with only a few required input parameters (Stenberg et al., 2013), facilitating its use for larger areas. In the model, the spectrally invariant parameter *p* (photon recollision probability) quantifies the canopy structure without a need for a detailed canopy description.

2. Materials and methods

2.1. Albedo definitions

In the following text, the terms “albedo” and “shortwave albedo” refer to the ratio of reflected to incoming solar radiation in the total shortwave region (0.3–3.0 μm), whereas when talking about albedo in the visible or PAR region (0.4–0.7 μm), the term “PAR albedo” is used. Albedos in the near-infrared (NIR, 0.7–1.3 μm) and mid-infrared (MIR, 1.3–3.0 μm) regions were not measured or modelled separately, but the variation in the total shortwave albedo that is not explained by the PAR albedo can be attributed to these spectral regions. In the context of albedo modelling, definitions similar to those used in the MODIS albedo product (Lucht et al., 2000) are used: “Black-sky albedo” describes the albedo under direct illumination conditions (i.e. sun as a point source of illumination), while the diffuse radiation from the sky is ignored. In contrast, “white-sky albedo” refers to the albedo in completely isotropic illumination conditions.

2.2. Field measurements of albedo

The albedo measurement sites were located within a few kilometres of each other in the area of the Hyytiälä field station of the University of Helsinki in southern Finland (61°51′N, 24°17′E). Monospecific stands on flat terrain, representing different stand structures were chosen for the measurements (Table 1). Altogether, four Scots pine (P1, P2a, P2b, P3), three Norway spruce (S1–S3) and one silver birch (B) stands were measured. Measurements were conducted using a portable telescopic mast in summers 2011, 2012 and 2013. Pairs of factory calibrated cosine corrected Middleton SK08 pyranometers and Apogee quantum sensors were placed on a circa 1 m long boom on top of the telescopic mast to measure the incoming and reflected total shortwave radiation and PAR radiation, respectively. The measuring height was 4–5 m above the canopy top. In addition, a pair of Middleton SK08 pyranometers was used to measure the incoming and reflected shortwave radiation beneath the canopy at about 1 m height above the ground on a boom attached to a tripod. Instantaneous radiation data were recorded once a minute. 95% of the pyranometer signal came from an area within a field a view of circa 144. Assuming the sensor to be located 4 m above the canopy top, this would correspond to a radius of 12.17 m and plot area of 465 m^2. The downward facing pyranometer situated on the tripod received 95% of the signal from an area of about 29 m^2.

The stands P1, B, S1 and S2 were measured in June–August 2011 and P2a, P2b and S3 in June–August 2012. The young pine stand P3 was measured in July 2013. The Scots pine stand P2 was measured before (P2a) and after (P2b) a thinning procedure during which about 42% of the dominant trees were removed. After the thinning, most of the large logging residues were removed from the site but the smaller branches were left. Each stand was measured for about three weeks, except for P2a where the measurements lasted only