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Geographical gradients in boreal forest albedo and structure in Finland

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ABSTRACT

Land surface albedo is an essential climate variable controlling the planetary radiative energy budget, yet it is still among the main uncertainties of the radiation budget in the current climate modeling. To date, albedo satellite products have not been linked to extensive forest inventory data sets due to the lack of ground reference data. Here, we used comprehensive and detailed maps of forest inventory variables to couple forest structure and MODIS albedo products for both winter and summer conditions. We investigated how the relationships between forest variables and albedo change seasonally and along latitudinal gradients in the forest biomes of Finland between 60° and 70° N. We observed an increase in forest albedo with increasing latitude in winter but not in summer. Also, relationships between forest variables and the black-sky albedo or directional–hemispherical reflectance (DHR) at different latitudes were tighter in winter than in summer, especially for forest biomass. Summer albedo was only weakly correlated with the traditional inventory variables. Our findings suggest that the relationships between forest variables and DHR depend on latitude.

1. Introduction

Land surface albedo is one of the essential climate variables (ECV) (Schaaf, 2009) listed by the Global Climate Observing System: it is a key forcing parameter controlling the planetary radiative energy budget and partitioning of radiative energy between the atmosphere and land (GCOS, 2010). Even though land surface albedo is a critical variable affecting the Earth's climate, it is still among the main uncertainties of the radiation budget in the current climate modeling (Liang, 2007). A better understanding of surface albedo for the northern forest biomes will reduce the errors in global energy balances calculated with climate models (Flato et al., 2013).

Local, pointwise measurements of boreal forest albedo have been conducted mainly at flux tower sites by placing a broadband measurement device on a mast above the forest canopy. A synthesis of these data shows that coniferous forests have a lower albedo than deciduous forests: the daily summer albedo of a deciduous forest can be nearly double that of a coniferous or mixed forest (e.g., Betts & Ball, 1997; Davidson & Wang, 2004). These measurements have provided a preliminary understanding of the diurnal and seasonal changes in forest albedo and, for example, of how rapid changes in local surface albedo can be used as an indicator of the start of the thermal growing season (Thum et al., 2009). There may be also a consistent increase in boreal forest albedo throughout the growing season (Kuusinen et al., 2012). However, the measurements have been limited to a few specific forest structures and their temporal cycles, i.e., they do not cover the natural variation of forest structures and species compositions in the northern biomes. Thus, these data sets, even though valuable due to their relatively long record, cannot alone be used to assess the effect of diverse land-use and forest management practices on albedo. In addition, currently, most in situ data have been gathered from North American forests which have different species composition and management regimes than northern European forests.

For large geographical regions, land surface albedo is regularly estimated using coarse and medium-resolution reflectance data from Earth observation sensors such as MODIS on-board Terra and Aqua (Schaaf et al., 2002), MISR on-board Terra (Pinty et al., 2007), SEVIRI on-board Meteosat Second Generation satellites (Geiger, Carrer, Franchistéguy, Roujean, & Meurey, 2008), CERES on Terra (Rutan et al., 2009) and SPOT Vegetation (Lacaze, 2010). Time series of surface albedo based on MERIS on-board ENVISAT and SPOT Vegetation instruments are also available for 15 years (Muller et al., 2012) and a time series based on data from the AVHRR instrument on NOAA and Metop satellites is available for 30 years (Riihelä, Manninen, Laine, Andersson, & Kaspar, 2013). Even though correlations between changes in global albedo products and changes in land cover classes have been established (e.g. Cescatti et al., 2012; Kuusinen, Tomppo, & Beringer, 2013), the biophysical factors causing the albedo changes of forests, especially in the vast boreal zone, have not been identified. Although simulation studies (Lukeš, Stenberg, & Rautiainen, 2013; Rautiainen, Stenberg, Mõttus, & Manninen, 2011) have shown that e.g. forest density and tree species composition have a significant impact on albedo, there is still a poor understanding of the quantitative relationships

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between forest inventory variables and albedo. Forest management procedures, such as thinning and logging, alter the spatial pattern, structure and species composition of forests. Through an altered albedo, these management practices will have implications on the climate. Therefore, links between albedo and routinely measured forest inventory variables (e.g., tree diameter, growing stock volume) must be established.

To date, albedo satellite products have not been linked to extensive forest inventory data sets due to the lack of ground reference data. Data availability has significantly improved very recently; in November 2012, the Finnish National Forest Inventory data (Tomppo, Haakana, Katila, & Peräsaari, 2008) became freely available to the public. In this paper, we used exceptionally large and detailed model prediction maps of forest inventory variables to quantify links between forest structure, land cover and MODIS albedo products. More specifically, we investigated how the relationships between forest variables and albedo change seasonally and along latitudinal gradients in northern forest biomes between 60° and 70° N.

2. Materials and methods

2.1. Study area and national forest inventory data

This study is based on the forests growing in Finland, Europe's most heavily-forested country. Currently, approximately 50% of the growing stock consists of Scots pine (*Pinus sylvestris* L.), 30% of Norway spruce (*Picea abies* (L.) Karst) and 20% of deciduous species such as birches (*Betula pendula* Roth, or *Betula pubescens* Ehrh.) (Metla, 2011). Approximately half of the forest land area is covered by mixed stands. The majority of the forests are used for wood production. The forests are managed in relatively homogeneous compartments which have an average size of less than 2 ha. The typical rotation period of a forest stand is between 60 and 120 years, depending on, e.g. tree species and latitude.

In the National Forest Inventory (MS-NFI) of Finland, a multi-source k-nearest neighbor (kNN) approach is used to generate continuous maps of selected forest variables on the local scale for the entire country. The database includes 26.1 million ha of forests, and in our study, subsets based on specific thresholding conditions are used. Currently two databases for years 2009 and 2012 are available; we used the 2009 data which were downloaded from the Finnish Forestry Research Institute webpage (http://kartta.metla.fi/valinta-en.html). The method combines field forest inventory and satellite data through the non-parametric kNN approach (Tomppo & Halme, 2004). The data are distributed in the ETRS89–TM35FIN coordinate system, and cover all the forest land of Finland at a 20 m spatial resolution. In total 43 different variables, such as species composition, growing stock volume and biomass, describe the forest structure of each pixel (Fig. 1, Table 1).

2.2. MODIS albedo product

The MODIS BRDF/albedo algorithm is based on a semi-empirical kernel-driven bidirectional reflectance model which is used to fit a bidirectional reflectance distribution function (BRDF) to multi-date (multi-angular) MODIS Terra and Aqua satellite images of different observation view angles. The best-fitting BRDF function is integrated over the observation angle and selected spectral intervals to obtain the black-sky (directional–hemispherical, DHR) albedo for local solar noon and further integrated over the incidence angle to calculate the white-sky (bi-hemispherical under isotropic illumination, BHR_{iso}) albedo. The dataset is produced globally for land surface every 8 days in various spatial resolutions and spectral domains (MCD43A3, Schaaf et al., 2002). When sufficient MODIS observations are available, a full retrieval (Strahler & Muller, 1999) is performed. In the case of insufficient number of MODIS observations, a so-called magnitude retrieval based on a priori estimates of BRDF shapes is used as a backup algorithm. In addition to DHR and BHRiso products in the MCD43A3 dataset, the MODIS science team also provides the coefficients for a polynomial

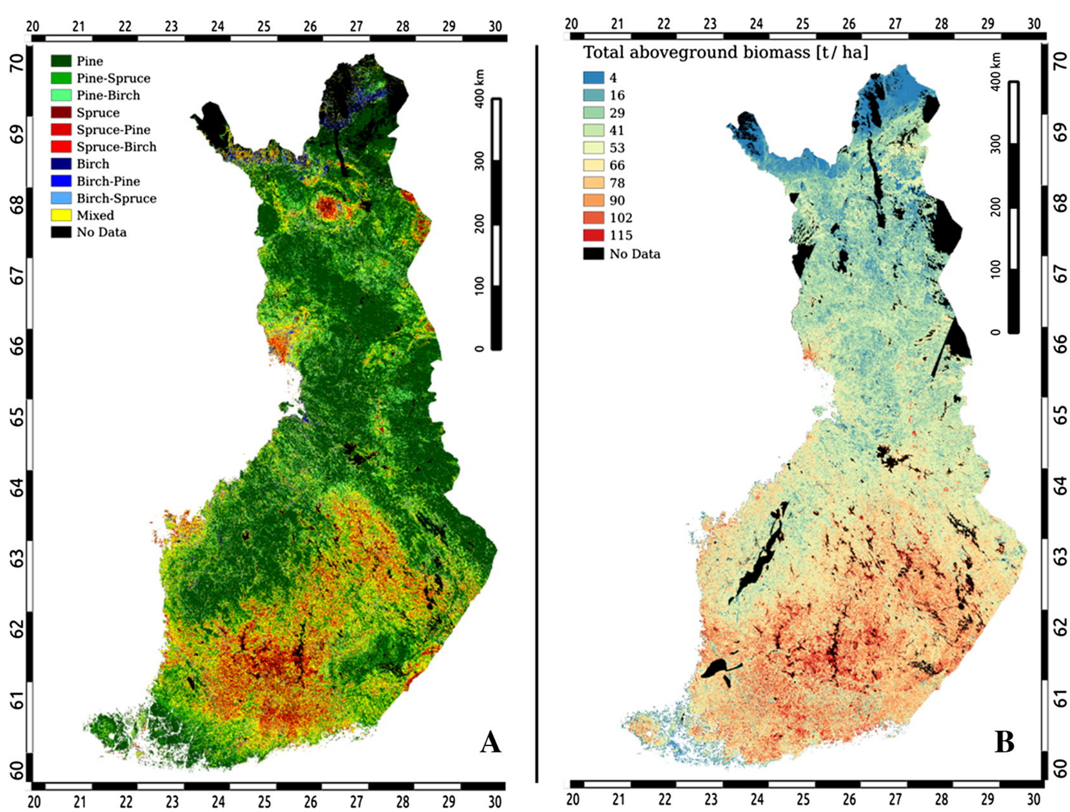

Fig. 1. The Multi-source national forest inventory raster maps of 2009. A. Dominant tree species and their mixtures. B. Total aboveground biomass. Data ©Finnish Forest Research Institute, 2012.