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Multidecadal analysis of forest growth and albedo in boreal Finland

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ABSTRACT

It is well known that forests serve as carbon sinks. However, the balancing effect of afforestation and increased forest density on global warming due to carbon storage may be lost by low albedo (thus high absorption) of the forests. In the last 30 years, there has been a steady increase in the growing stock of Finnish forests by nearly a quarter while the area of the forests has remained virtually unchanged. Such increase in forest density together with the availability of detailed forest inventories provided by the Multi-Source National Forest Inventory (MS-NFI) in high spatial resolution makes Finland an ideal candidate for exploring the effects of increased forest density on satellite derived estimates of bio-geochemical products e.g. albedo (directional-hemispherical reflectance, DHR), fraction of photosynthetically active radiation absorbed by canopies (fAPAR), leaf area index (LAI) and normalized difference vegetation index (NDVI) in both current and long-term perspective.

In this study, we first used MODIS-based vegetation satellite products for Finnish forests to study their seasonal patterns and interrelations. Next, the peak growing season observations are linked to the MS-NFI database to yield the generic relationships between forest density and the satellite-derived vegetation indicators. Finally, long-term GIMMS3g datasets between 1982 and 2011 (2008 for DHR) are analyzed and interpreted using forest inventory data. The vegetation peak growing season NIR DHR and VIS DHR showed weak to moderate negative correlation with fAPAR, whereas there was no correlation between NIR DHR and fAPAR. Next, we show that the spectral albedos in the near-infrared region (NIR DHR) showed weak negative correlation with forest biomass, basal area or canopy cover whereas, as expected, the spectral albedo in the visible region (VIS DHR) correlated negatively with these measures of forest density. Interestingly, the increase in forest density (biomass per ha) of Finnish forests during the last 30 years was not accompanied by trends in the indicators of vegetation 'greenness' and photosynthetic productivity (fAPAR, LAI and NDVI) or in forest albedo (DHR). Even though there were small increases in both DHR, fAPAR, LAI and NDVI and from the start to the end of the study period (1982–2011), the pattern and magnitude of change in these variables did not follow the development of forest biomass in the different NFI inventories.

1. Introduction

The black-sky albedo or directional-hemispherical reflectance (DHR) is one of the surface properties that controls the radiative energy budget of the Earth and it has been specified by the Global Climate Observation System (GCOS) as one of the products required for global climate observation and modeling purposes (GCOS, 2004). It is formed of reflectance factors integrated hemispherically over view direction and averaged over a selected range of wavelengths (e.g. broadband shortwave DHR from satellite observations is typically averaged between 400 and 2500 nm), while assuming a point source of illumination (Schaaf et al., 2002). Various complex positive and negative feedbacks associated with global change may alter surface albedo, thus changing the Earth's radiation budget. For example a typical positive feedback concerning surface albedo is

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the melting of glaciers and snow covered ground of Greenland and the Antarctic. With the increase in surface temperatures, the originally high albedo decreases due to the melting of snow and ice, which further accelerates the rise of surface temperatures because of increased absorption of incoming solar radiation by the surface with lower albedo (Flanner et al., 2011). However, more favorable environmental conditions may stimulate growth of vegetation (e.g. afforestation of previously non-forest land, advancement of the treeline further north), and an increase in forest density. Since growing forests serve as carbon sinks (i.e. remove the CO_2 from the atmosphere), and this counterbalances the effect of decreased surface albedo on global climate. As noted by Betts (2000), the balancing effect of afforestation and increased forest density on global warming is, however, yet more complex: the positive effect of increased carbon fixation may be lost due to very low albedo of the forests. It is yet unclear whether surface radiation budget or carbon fixation of vegetation (i.e. biomass) plays a more significant role in Earth's climate. As shown in previous studies (Lukeš et al., 2014; Kuusinen et al., 2014, 2016; Rautiainen et al., 2011), the link between the broadband albedo and stand variables is not straightforward and many uncertainties regarding e.g. the sensitivity of forest albedo on the density and productivity of the forest remain.

Satellite products of Normalized difference vegetation index (NDVI), fraction of photosynthetically active radiation absorbed by canopy (fAPAR) and Leaf area index (LAI) serve as an indicators of vegetation density ('greenness') and photosynthetic productivity. These products are closely interrelated and thus, for example, the NDVI has been successfully used for the retrieval of LAI (Chen and Cihlar, 1996; Colombo et al., 2003; Wang et al., 2005) and fAPAR (Myneni et al., 1997; Fensholt et al., 2004) at various spatial scales.

Although useful information about forest productivity and structure may be retrieved from a single satellite observation, the great advantage of satellite remote sensing originates from the repetitive systematic observations of the same target over a long time period. Currently available datasets of seasonal and multi-decade trends of vegetation structure and phenology help us to better understand our changing Earth (Zhang et al., 2003; Jin and Sader, 2005). The systematic repetitive acquisition of Earth surface reflectances in visible (VIS) and near-infrared (NIR) wavelengths started with the launch of the series of AVHRR satellites by the National Oceanic and Atmospheric Administration (NOAA) in the late 1970's and early 1980's (Gutman, 1991; Moulin et al., 1997). Despite its relatively coarse spatial and spectral resolutions, AVHRR provides an invaluable source of continuous NDVI observations from the last 30 years. From 2000 onwards, new data from the MODIS instruments onboard Terra (launched in December 1999) and Aqua (launched in May 2002) platforms are available. With significantly better spatial and spectral resolutions, numerous products have been developed, including DHR, fAPAR and LAI (Justice et al., 2002).

In the last 30 years, there has been an increase by 23% in the growing stock of Finnish forests (classified as forest land and low productive forests) while the area of the forests has remained virtually unchanged and decreased by only 0.2% (Metla, 2011). The steady increase in forest density together with the availability of detailed forest inventories for the entire country provided by the Multi-Source National Forest Inventory (MS-NFI) data (Tomppo, 2008) makes Finland an ideal candidate for exploring the effects of increased forest density on satellite derived estimates of DHR, fAPAR, LAI and NDVI in a long-term perspective.

In this study we first use the datasets of satellite products for Finnish forests to study their seasonal patterns and interrelations. Next, the peak growing season observations are linked to the MS-NFI database to yield the relationships between forest density and the satellite-derived vegetation indicators. Finally, long-term datasets of the satellite products between 1982 and 2011 (2008 for DHR) are analyzed and interpreted using the MS-NFI data.

The specific research questions of this paper are: (1) how is the forest shortwave DHR related to fAPAR? (2) what are the generic relationships between forest density and the vegetation parameters and DHR retrieved from space? (3) using the historical forest inventory data, can we identify the observed trends in forest density from the long-term satellite observations?

2. Material and methods

2.1. Identification of the start and end of the growing season

First, we focused on exploring the patterns and relationships for the vegetation growing season only, i.e. the snow-free period with forest in its growing stage. Since Finland is located between 60°N and 70°N and thus exhibits a strong latitudinal gradient in climate, the start and end of the vegetation growing season vary between different locations. To identify the day of year (DOY) for the start and end of vegetation growing season across Finland, we analyzed the time series of NDVI observations retrieved from the GIMMS3g dataset (Tucker et al., 2005). This dataset consists of AVHRR observations and is corrected for various deleterious effects such as orbital drift and sensor inter-calibration artifacts (Pinzon et al., 2005). The extraction of the DOY's of the start and end of the growing season were calculated using TIMESAT software (Jönsson and Eklundh, 2002; Jönsson and Eklundh, 2004). In TIMESAT, we fitted the logistic function with adaptation to the upper envelope on a temporally smoothed time series of NDVI observations between 1982 and 2011. Next, the start and end of the vegetation growing season were identified based on the amplitude of the curve as suggested by Eklundh and Jönsson (2012). For both the DOY of the start and the end of the vegetation growing season we calculated country-wise average values and also latitudinal-averaged values.

2.2. Seasonal trends in DHRs, NDVI, fAPAR and LAI

To identify the average DOY of the peak-growing season for the country of Finland, we analyzed the seasonal patterns of Finnish forests using the medium resolution MODIS products of DHR, LAI, fAPAR and NDVI for the years 2000–2010 with the spatial resolution of 1000 m (see Table 1). For each of the products, detailed quality information is provided. In this study, we used only the high quality retrievals. These comprise product retrievals using the main MODIS algorithms with no saturation (i.e. loss of sensitivity of product on input observation).

Next, we derived a raster mask of the fraction of forest area within the MODIS pixels from the high resolution MS-NFI of Finland for the year 2009 (for more details see Lukeš et al., 2014; Tomppo,

Table 1
Datasets of MODIS products used for decadal averages of vegetation growing season trends across Finland.

MODIS product and time frame	Name	Spatial resolution	Temporal resolution	Reference
DHR (2000–2010)	MCD43B2 MCD43B3	1 000 m	8 days	Schaaf et al., 2002
fAPAR (2000–2010)	MCD15A2			Knyazikhin et al., 1999
LAI (2000–2010)				
NDVI (2000–2010)	MOD13A2		16 days	Huete et al., 2002