BRIEF REPORT

Albedo of the Forested Landscape at the SMEAR-Estonia Research Station

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Abstract

Spectral and integrated albedo (photosynthetically active radiation and total) of the forested landscape surrounding the SMEAR-Estonia research station is estimated using airborne measurements of reflectance spectra and MODIS land products. Airborne reflectance measurements were carried out during the stable period of phenology in the middle of growing season in 2006-2015. MODIS Collection 5 products are available since autumn 2006. The directional canopy reflectance models FRT and ACRM are used for the integration of directional reflected radiance over hemisphere. Spectral black sky albedo is found for 18 visible-near infrared spectral bands which correspond to the Mode 3 bands of the Proba/CHRIS imaging spectrometer. Year-to-year variations of albedo are small, therefore, the mean albedo values are provided which could be used in the studies of energy fluxes and net primary production at the test site. MODIS estimates of albedo are systematically higher and more variable than estimates using airborne spectral measurements.

Keywords: Forest albedo, MODIS albedo product, Airborne measurements.

Introduction

A research station for measuring ecosystem-atmosphere relations SMEAR-Estonia was established in southeastern Estonia, at the Järvselja Experimental Forestry station, 58º 16’ N, 27º 18’ E in 2013-2015. The Järvselja SMEAR station completes the network of Finnish SMEAR stations (SMEAR 2015). In order to estimate absorbed photosynthetically active radiation (PAR) and absorbed spectral and total radiation in forests, from where air arrives to the instruments at the SMEAR tower, incident radiation fluxes and albedo of the landscape surrounding the SMEAR station are needed.

The albedo of a surface describes the ratio of radiant energy scattered upward and away from the surface in all directions to the downwelling irradiance incident upon the surface. Uncertainties in albedo may induce significant uncertainties in the estimation of surface energy fluxes required to estimate evapotranspiration and photosynthesis. Monitoring of forest albedo allows detecting insect defoliation of forests (Eklundh et al. 2009).

Albedo estimates based on satellite measurements of reflectance spectra are provided by MODIS Land Team (LPDAAC 2015). MODIS land products provide spectral albedo at 500 m spatial resolution in seven reflective bands (LPDAAC 2015). The MODIS Collection-5 products are available since autumn 2006.

There have been attempts to validate MODIS albedo estimates using ground-based and airborne data. Point-based measurements at the ground level are not suitable for direct comparisons with moderate spatial resolution satellite data over heterogeneous landscapes. Knobelspiesse et al. (2008) compared MODIS albedo to airborne estimates using measurements of spectral directional reflectance over a typical rural mid-west of the United States in the fall. Data from two flights at the altitude of about 200 m above ground were used having ground resolution about 3 m. Retrieved data were classified into two classes, soil and vegetation ones. Albedo was estimated using the same computational scheme as in the MODIS land product. The general conclusion was that there is good agreement between MODIS and airborne albedo estimates, however, the MODIS visible-near infrared (Vis-NIR) albedo estimates were higher than airborne estimates in both ground cover types. The validation effort was hindered by the small quantity of data available for comparison.

Mira et al. (2015) performed two-stage validation of MODIS albedo product over a Mediterranean agricultural area. First, local ground measurements were used to validate albedo estimates using high spatial and temporal resolution images of Formosat-2 sensor, which were then aggregated to evaluate collocated coarser resolution images of MODIS. The comparison revealed the ability of the MODIS albedo product to estimate with high accuracy and low uncertainty the albedos from an agricultural region, however some bias was observed over dark targets.

Remote sensing studies at Järvselja have been carried out for several years in the frame of the VALERI project (Validation of Land European Remote Sensing Instruments) (VALERI 2005), for the support of satellite remote sensing of forests (Kuusk et al. 2007, Rautiainen et al. 2008), and for the validation of theoretical models of radiative transfer in vegetation canopies (Kuusk et al. 2013). Measurements of top-of-canopy reflectance spectra in these studies allow estimating landscape spectral albedo at the study area and its year-to-year variability. The estimates of mean albedo of the forested landscape based on top-of-canopy measurements of reflectance spectra onboard a low flying helicopter are compared to the albedo estimates of the study area in MODIS land products (LPDAAC 2015).

Material and Methods

The surroundings of the SMEAR-Estonia are mixed forests, which belong to the hemiboreal zone with moderately cool and moist climate and can be characterized as remote and rural with low anthropogenic disturbances. Stands are pure or mixed and composed mainly of silver birch (*Betula pendula* Roth), Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* (L.) Karst.), common alder (*Alnus glutinosa* (L.) Gaertn.), aspen (*Populus tremula* L.), grey alder (*Alnus incana* (L.) Moench) and small-leaved lime (*Tilia cordata* Mill.). Growth conditions range from poor, where the site index H_{100} (estimated stand height at the stand age of 100 years) is less than 10 m, to very good, where H_{100} can be over 35 m. About 75% of the site area is covered by forests, natural grasslands, and pastures. A more detailed description of the test site is provided by Kuusk et al. (2005).

Helicopter measurements of reflectance spectra in the spectral domain 350-1,050 nm over the study area have been carried out since 2006 using UAVSpec series of spectrometers. These are fully autonomous lightweight spectrometers based on the 256-band NIR enhanced variant of the miniature Vis-NIR spectrometer module Monolithic Miniature Spectrometer 1 (MMS-1) manufactured by Carl Zeiss Jena GmbH (Kuusk 2011). The spectrometers were mounted on the chassis of a Robinson R22 helicopter so that they were looking in the nadir direction during straight flight at constant speed. Average flight altitude was about 80-100 m above ground level in order to minimize the influence of the underlying air layer. The footprint of the field-of-view (FOV) on the ground was about 2.5-3 m. An average measurement campaign comprised approximately one-hour flight over the forests, during which more than 20 000 spectra over more than 400 forest stands were acquired. Recorded spectra were geo-located with the GPS receiver of the UAVSpec instrument. Measurements were carried out in 2006-2011, 2013, and 2015 in direct sunlight at solar zenith angle (SZA) of approximately 40º. Measurements were carried out in July, except of 2007, when there was no weather for measurements in July and measurements were done on 8th August.

The measured hyperspectral reflectance was reduced to 18 spectral bands, which correspond to the Proba/CHRIS Mode 3 bands (Barnsley et al. 2004). This selection of bands is intended for studies of land surface and vegetation, and has been used in several previous studies of spectral signatures and directional properties of reflectance at the test site (Kuusk et al. 2007, 2013, 2014, 2015, Rautiainen et al. 2008). Spectral albedo in these spectral bands was estimated: (a) using the modified version of the two-layer homogeneous canopy reflectance (CR) model ACRM (Kuusk 2001, Kuusk et al. 2015), and (b) using the forest reflectance model FRT (Kuusk and Nilson 2000, Kuusk et al. 2014). In the first case, the CR model was fitted to the mean spectrum of the whole test area in 18 CHRIS bands and the modelled directional reflectance was integrated over the upper hemisphere via view zenith and azimuth angles. All the spectra registered at less than 6º view nadir angle (VNA) were involved. This way the black sky albedo (directional-hemispherical reflectance, (Liang 2004)) of the landscape for the SZA = 40º was calculated using:

$$A_\lambda(\theta_0) = \int_{2\pi} \rho_\lambda(\theta, \theta_0, \varphi) \cos\theta \sin\theta \, d\theta \, d\varphi, \qquad (1)$$

where: $\rho_\lambda(\theta, \theta_0, \varphi)$ is the spectral bidirectional reflectance;

θ is the view zenith angle;

θ_0 is the SZA; *and*

φ is the view azimuth relative to the solar azimuth.

In the second case, average spectral signatures of spruce, pine and broadleaf forests, and grasslands were found separately. Involved were forest stands, where at least 10 registered spectra with the VNA < 6º were collected. The forest reflectance model FRT was fitted to mean spectrum in 18 CHRIS bands varying some model input parameters (the overstorey and understorey LAI, leaf chlorophyll content, soil reflectance). The modelled directional reflectance was integrated over view directions. The mean landscape albedo was calculated as a weighted sum of the albedos of the landscape components. Respective weights were estimated using the classification of CHRIS spectral images of the test site (Kuusk et al. 2015) and the land use map of the test site (Kuusk et al. 2005).

MODIS land products provide spectral albedo at 500 m spatial resolution in seven reflective bands (LP-DAAC 2015). Four MODIS bands fall into the sensitivity range of UAVSpec, therefore, these four bands are used in the following analysis. The MODIS Collection-5 products are available since autumn 2006. A 7 km × 7 km subset was extracted, which includes both the Järvselja VALERI site and the SMEAR-Estonia. Most of the helicopter measurements are also inside this subset. The MODIS albedo product supplies the weighting parameters f_{iso}, f_{vol}, f_{geo} for each of the MODIS spectral bands as well as for three broad bands (0.3-0.7 µm, 0.7-5.0 µm, and 0.3-5.0 µm). These parameters are used with a simple polynomial to easily estimate the directional-hemispherical reflectance (black-sky albedo) for any desired solar zenith angle (MODIS Land Science Team 2015), i.e.:

$$\begin{aligned} A_{\lambda}(\theta_0) = {} & f_{iso}(\lambda)(g_{0,iso} + g_{1,iso}\theta_0^2 + g_{2,iso}\theta_0^3 \\ & + f_{vol}(\lambda)(g_{0,vol} + g_{1,vol}\theta_0^2 + g_{2,vol}\theta_0^3 \\ & + f_{geo}(\lambda)(g_{0,geo} + g_{1,geo}\theta_0^2 + g_{2,geo}\theta_0^3, \end{aligned} \tag{2}$$

where: g_{xcxx} are given constants; θ_0 is the solar zenith angle.

The MODIS albedo is not available for every day; there are gaps due to weather conditions. For the comparison of albedo from airborne measurements and MODIS data, MODIS albedo values of every pixel in the subset are interpolated to the date of helicopter measurements using the previous and following MODIS values. Visible and NIR spectral albedos are calculated using MODIS albedo product for every pixel in the subset of 196 pixels. Mean value and standard deviation of spectral albedo values over the subset are found. Spectral bands of MODIS/Terra and MODIS/Aqua, which are used in this study, and the respective CHRIS Mode 3 bands are listed in Table 1.

Table 1. Spectral bands of MODIS/Terra and Proba/CHRIS

Band	MODIS	CHRIS
Blue	459–479	437-442
		483-495
Green	545–565	543-556
		563-574
Red	620–670	622-636
		651-667
		667-678
NIR	841–876	767-789
		855-882

Results

In Figure 1, the spectral albedo of the study area is estimated using UAVSpec data in CHRIS bands, and the MODIS albedo in the respective spectral bands. The red albedo $\lambda = 622 - 636$ nm (CHRIS band 8) is omitted in Figure 1c in order to avoid overloading the graph. Error bars of the MODIS albedo show the standard deviation of the MODIS estimate over 196 pixels.

We can see rather small changes of spectral albedo from year to year estimated from the UAVSpec data. There are some systematic differences between the two estimates using ACRM or FRT in all spectral bands. On average, over all years and all spectral bands the ACRM estimates are 0.01 higher. Relative difference is the highest in the CHRIS band 11 (701 nm), where the ACRM estimate is 30 % higher. In other bands, the differences are less than 10 %. The year-to-year variations are about 10 % in blue bands, 10-15 % in NIR bands, 15-25 % in green and red bands. The difference in the spectral shape of black sky albedo using ACRM or FRT is caused by the ability to simulate reflectance spectra by these CR models. The spectral behaviour of the ACRM results are controlled by the optical properties of foliage. In the wavelength range 750–1,000 nm leaf reflectance and transmittance are almost constant; therefore, the albedo estimate is almost constant as well. The forest model FRT accounts for the contribution of tree stems and bark. Stem and bark reflectance is increasing with increasing wavelength in this spectral interval; hence the forest reflectance is increasing with wavelength in this spectral range.

The MODIS estimates are systematically higher in all spectral bands (Figure 2). The variability of estimates is rather large in visible bands. In NIR the MODIS albedo is stable and close to the airborne estimate using the forest model FRT. The exception is year 2007, when weather conditions for satellite measurements were poor. There is a long gap in the MODIS albedo data, and the first available data after the airborne measurements are probably affected by clouds. Therefore, the 2007 MODIS data are ignored in Figure 2.

To some extent the uncertainty of the mean albedo based on MODIS data is characterized by the statistical variability of pixel values over the study area. It is difficult to estimate the uncertainty of airborne albedo for several reasons. While the radiometric calibration errors are mainly determined by the errors in the measured incident radiation and errors in the calibration of field reference (Kuusk 2011, Kuusk et al. 2014), the statistical error of albedo estimates depends on several factors. The field of view of the UAVSpec spectrometer is very small, therefore, the standard deviation of the UAVSpec signal characterizes the variability of reflected radiance in the scene (sunlit and shaded tree crowns, secondary growth,

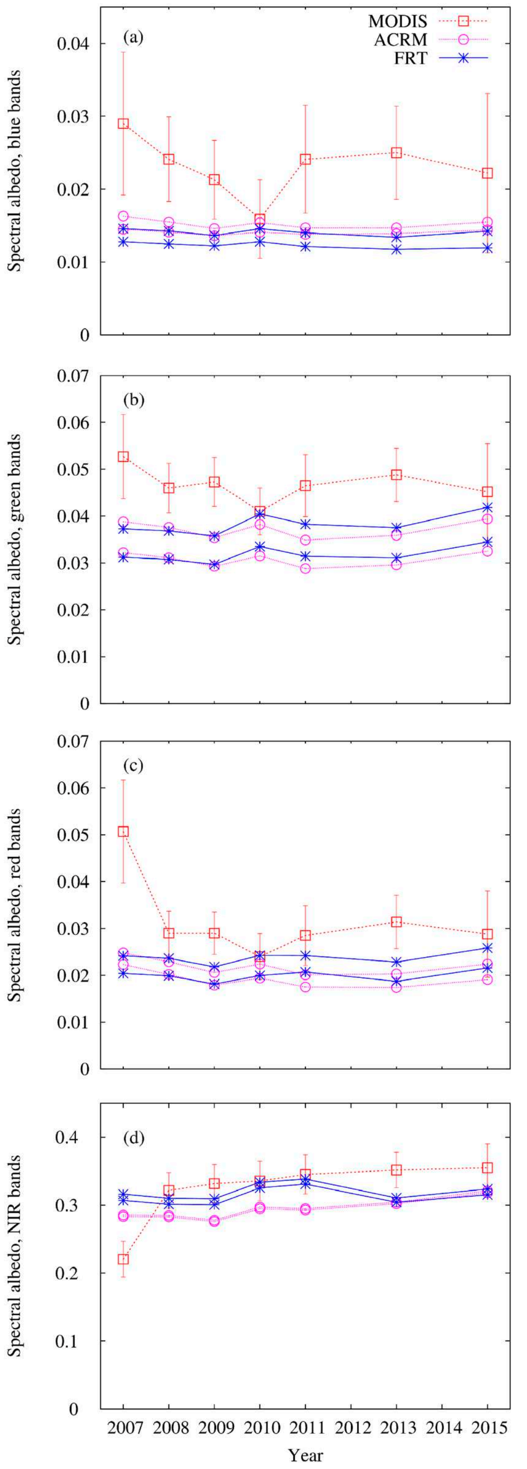

Figure 1. Spectral albedo of the study area, estimated using UAVSpec data and the ACRM model or the FRT model, and the MODIS land product: (a) blue spectral bands, (b) green spectral bands, (c) red spectral bands, (d) NIR spectral bands. Two lines marked as ACRM or FRT in every subfigure correspond to the respective CHRIS bands, see Table 1

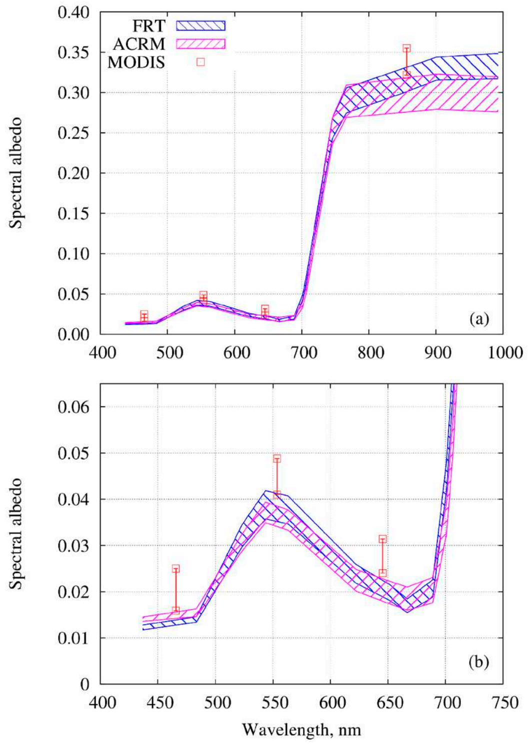

Figure 2. The range of the estimated spectral albedo values in 2007–2015

Table 2. The average black sky albedo of the study area for SZA = 40

Band, nm	FRT		ACRM	
	Mean	STD	Mean	STD
437	0.0123	0.0004	0.0141	0.0003
484	0.0142	0.0003	0.0152	0.0006
523	0.0327	0.0026	0.0307	0.0015
544	0.0395	0.0034	0.0372	0.0018
563	0.0383	0.0031	0.0357	0.0018
622	0.0241	0.0014	0.0219	0.0017
651	0.0200	0.0010	0.0191	0.0018
667	0.0169	0.0010	0.0177	0.0018
689	0.0208	0.0011	0.0196	0.0019
701	0.0456	0.0025	0.0353	0.0025
707	0.0684	0.0036	0.0543	0.0030
732	0.1926	0.0093	0.1810	0.0069
746	0.2567	0.0131	0.2482	0.0109
767	0.2906	0.0147	0.2849	0.0139
855	0.3165	0.0143	0.2927	0.0143
882	0.3251	0.0139	0.2950	0.0145
901	0.3310	0.0135	0.2967	0.0146
993	0.3346	0.0132	0.2938	0.0141
PAR	0.0226	0.0010		
Total	0.1520	0.0059		

and ground vegetation). However, the number of recorded spectra is huge and the small-scale variability of scene radiance is filtered out by averaging. The uncontrolled variance of measurement results is mainly due to the different set of measured stands and changes in the flight track position in stands in different years. Therefore, the observed variations of the site albedo from year to year cannot be considered the measure of real albedo variations. The mean albedo spectrum and integrated albedo values are listed in Table 2. The integrated albedos expressed as:

$$A_{\Delta\lambda} = \int_{\Delta\lambda} a(\lambda) Q(\lambda)\, d\lambda \Big/ \int_{\Delta\lambda} Q(\lambda)\, d\lambda, \qquad (3)$$

are for the wavelength range Δλ = 400 – 700 nm (PAR) and *Δ*λ = 400 – 2200 nm (total). Here, *a*(λ) is the spectral albedo and *Q*(λ) is the spectral incident flux. Two albedo estimates are the results of integrating the forest model FRT or homogeneous model ACRM over view angles. The standard deviations in Table 2 cannot be considered as the measure of uncertainty of albedo estimates, these describe the variation of estimated albedo in the time frame 2007–2015.

Conclusions

Mean black sky albedo of the forested landscape surrounding the SMEAR-Estonia research station is estimated using airborne measurements and MODIS land product. Results are presented for the CHRIS Mode 3 spectral bands, photosynthetically active radiation and integrated Vis-NIR spectral domain. Top of canopy results from helicopter measurements are compared to respective albedo estimates in the MODIS land product. Previous extensive studies both of angular distribution and high spectral resolution of forests at the study area, and applying carefully validated models of forest directional reflectance allowed to get the best possible estimates of landscape albedo during the stable period of forest phenology in mid-summer in the time frame from 2006 to 2015. Year-to-year variations in the estimated albedo are so small that in the studies of energy fluxes and net primary production the average estimates could be used. The obtained albedo spectra can be used as a reference for detecting forest damages caused by insects, diseases or other natural disturbances. The albedo estimates using the MODIS land product systematically overestimate the albedo of the study region and have random variations, which could be caused by small clouds indistinguishable at the 500 m resolution of the MODIS land products.

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