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# Linear unmixing of MODIS albedo composites to infer subpixel land cover type albedos

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ABSTRACT

We use a linear unmixing approach to test how land use and forestry maps, in combination with the MODIS BRDF/albedo product, can be used to estimate land cover type albedos in boreal regions. Operational land use maps from three test areas in Finland and Canada were used to test the method. The resulting endmember albedo estimates had low standard errors of the mean and were realistic for the main land cover types. The estimated albedos were fairly consistent with albedo measurements conducted with a telescope mast and pure pixel albedos. Problems with the method are the possible errors in the land cover maps, lack of good quality winter MODIS albedo composites and the mismatch between the MODIS pixels and the true observation area. The results emphasize the role of tree species as determinant of forest albedo. Comprehensive spatial and temporal measurements of land cover albedo are usually not possible with in situ mast measurements, and the spatial resolution of MODIS albedo product is often too low to allow direct comparison of pixel albedos and land cover types in areas with heterogeneous vegetation. Hence, and since local forestry maps exist for most temperate and boreal regions, we believe that the proposed method will be useful in estimating average regional land cover type albedos as well as in tracking changes in them.



## 1. Introduction

Surface albedo determines the fraction of incident solar radiation that is reflected back to the atmosphere and is thus a key parameter in the earth's radiant energy budget. Changes in vegetation cover and surface albedo lead to changes in net radiation and thus modify the local heat and water fluxes, which in turn affect the boundary layer conditions and the local to larger scale climate (Sellers et al., 1997). Lately, effort has been made to understand the impacts of land use change on radiative forcing when both the biophysical and carbon cycling effects are accounted for (Betts et al., 2007). For example, many studies concluded that the deforestation of the seasonally snow covered northern coniferous forests might actually cool the climate because of the higher albedo and therefore lower net radiation of open vegetation compared to forests (Thomas and Rowntree, 1992; Otterman et al., 1984; Bonan et al., 1995). The reduced radiative forcing caused by the increase in albedo could even offset the increased longwave forcing caused by the reduced carbon sequestration in biomass (Betts, 2000; Bala et al., 2007). Within functional vegetation types, many ecological and climatic factors, such as snow cover (Betts and Ball, 1997), canopy closure (Davidson and Wang, 2005; Bernier et al., 2011), and stand age through forest structure (Roberts et al., 2004) are reported to affect albedo. However, long-term in situ measurements of forest albedo are constrained to measurements from masts and are therefore rather sparse and hardly representative regarding the variability in albedo in vegetated areas.

Satellite observations are the only feasible means of monitoring changes in surface albedo extensively over time and space. However, although global satellite products of surface albedo are available at variable temporal, spectral and spatial resolutions (e.g. MODIS, MISR, and Meteosat), their coarse spatial resolution often precludes the direct comparison of the albedo of a single pixel and the land cover type. For example, in the heavily managed and fragmented forests in Europe, the uniform forested areas are usually not larger than a few hectares while the MODIS albedo product has a spatial resolution of about 25 ha.

Some researchers have used a method called spectral unmixing (Settle and Drake, 1993) to infer subpixel land cover type fractions from satellite or aerial images. The approach has been used for example to map vegetation cover (Foody et al., 1997; Roberts et al., 1998; Asner et al., 2005; Song, 2005) or to track changes in it (Okin, 2007), to estimate subpixel snow cover (Vikhamar and Solberg, 2003; Painter et al., 2009) and to infer structural parameters of

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black spruce stands (Hall et al., 1995). The literature on spectral unmixing is shortly reviewed in Plaza et al. (2011). Although this method is usually used to estimate subpixel proportional coverage of desired targets by defining their endmember spectra, it is as well useful to estimate the reflectance of a priori known land cover classes.

While the influence of forest management practices on carbon sequestration has gained a lot of attention, it would also be important to understand the biophysical effects of forest management on climate through albedo. The use of local forestry maps and linear unmixing approach to infer albedos for local vegetation and forest types under different management options could help to estimate the whole effect of forestry on climate and, more broadly, specify the albedo parameterizations in land surface models and thus improve climate change scenarios (Lohila et al., 2010).

The advantage of the unmixing approach over the use of pure pixels only in deriving endmember albedos would be ability to estimate albedos of land cover types in areas with fragmented land cover and vegetation. In this paper, we examine the possibility to derive reliable subpixel albedo values for different land cover and forest types using the MODIS MCD43A3 albedo products and local land cover and forestry maps from three different locations with the linear unmixing approach. Furthermore, we compare the estimated forest albedos with the ones measured in the field and, wherever possible, to albedos of pure pixels.

## 2. Materials and methods

### 2.1. Satellite data

The albedo products used were the Moderate Resolution Imaging Spectroradiometer (MODIS) MCD43A3 (collection 5) composites with a spatial resolution of ca. 500 m. The subsets were downloaded from the NASA Oak Ridge National Laboratory Distributed Active Archive Centre (ORNL DAAC) (http://daac.ornl.gov/cgi-bin/MODIS/GLBVIZ_1_Glb/modis_subset_order_global_col5.pl). The MODIS BRDF/albedo product is generated using clear-sky atmospherically corrected surface reflectance observations over 16-day aggregating periods and a bidirectional reflectance model to characterize the surface reflectance anisotropy (Schaaf et al., 2002). The subsets included the quality information about whether, depending on the availability of clear sky acquisitions during the period and the fit of the observations to the BRDF model, a full or a magnitude BRDF inversion was used for each pixel and band as well as the information if a snow or a snow free albedo was retrieved. The black-sky albedo in the MCD43A3 product is calculated for the local solar noon zenith angle (Schaaf et al., 2002). The albedos used here were the broadband shortwave actual sky albedos. Only pixels with band quality 0 (best quality, full inversion), 1 (good quality, full inversion) or 2 (magnitude inversion, number of observations greater than 7) were used. In other words, if any of the seven pixel bands used in the inversion had a worse quality class than 2, the pixel was not included in the calculation. In addition, a composite was only used if more than 70% of the pixels in the study area were of best or good (0 or 1) quality in the snow free time and more than 40% in the snow covered time. The requirement for the amount of best or good quality pixels was lower during snow covered time since the quality of composites in times of low Sun elevations is usually low. However, we were still interested on how the albedos of the winter composites are estimated by the model. The approach of using as many pixels of each composite as possible but to select the composites with strict criteria (rather than to use all composites but only the best quality pixels) was chosen because the method used requires as many pixels at each composition date as possible.

### 2.2. Study areas and data processing

#### 2.2.1. Hyytiälä, Finland

The first study area, hereafter called Hyytiälä, is located around a SMEAR II measurement station in southern Finland (61°51′N and 24°17′E). The area belongs to the southern boreal zone and is a mosaic of managed forest, agricultural land, open/forested peatland, lakes and sparse human settlement. The forests are mainly consistent of coniferous species (Norway spruce (*Picea abies* (L.) Karsten) and Scots pine (*Pinus sylvestris* (L.))), but also some deciduous species (e.g. birches, *Betula pendula* Roth. and *Betula pubescens* Ehrh.) are usually present as a mixture in the forest stands. In this region we used a multisource land cover map on a 20 m grid, covering an area of 1272 km$^2$ of which about 75% was covered by forests. The map includes, in addition to the basic land cover classes (water, agricultural land, and infrastructure), predictions of forest attributes, e.g. growing stock per species, age, basal area and site fertility that are produced in the multisource national forest inventory project of Finland at the Finnish Forest Research Institute (Tomppo et al., 2008; Tomppo and Halme, 2004). The ground data employed originates from the field measurements of the 10th National Forest Inventory. Map predictions are constructed using an improved version of the non-parametric *k*-NN method, called *ik*-NN. In addition to ground measurements, the method relies on Landsat TM or ETM+ images and digital map data (Tomppo and Halme, 2004; Tomppo et al., 2008).

The multisource land cover map was from 2007 (Tomppo et al., 2012) and the MODIS albedo subsets were derived for the four closest years (2005–2008) in order to avoid the effects of new clear cuts. After quality filtering we retained 77 MODIS albedo subsets. Due to low quality, no composites from November to January were used.

The non-forested land cover endmembers for the Hyytiälä area were the same as in the land cover map: water, cropland, road, settlement and other infrastructure. To estimate the albedo for each tree species, we used the average proportions of growing stock represented by each tree species in the pixel area as the endmembers. More precisely, the proportion of each tree species (pine, spruce, and deciduous) was calculated for each 20 m × 20 m land cover pixel and the average of these proportions in the MODIS pixel area was used as the endmember fraction in the analysis explained in Section 2.5. However, if there were altogether less than 25 m$^3$ ha$^{-1}$ of growing stock in a land cover pixel, it was assigned to a category "young stand". There were no significant changes in the model performance or in the distribution of residuals when testing different growing stock limits for determining the young stand and stratification of stands by volume or age did not improve the results. Peatland area was identified by using a mask from a land cover map produced by the National Land Survey of Finland in 1997. Note that the cover fractions always sum up to 1 within each MODIS pixel. The proportion of each land cover class of the study area is shown in Table 1. The land cover data were converted to the sinusoidal projection of the MODIS albedo composites in all three test areas. Fig. 1 illustrates the procedure by presenting the volume maps by tree species, other land cover classes and two examples of the MODIS albedo subsets in the Hyytiälä area.

#### 2.2.2. Värriö, Finland

The second Finnish study area (hereafter Värriö) is located in Eastern Finnish Lapland (67°48′N, 27°52′E). The forestry/land cover map was derived from the Finnish state forest enterprise (©Metsähallitus, 2012). The forest map is originally derived from ground measurements after stratification of the polygons from aerial photographs. Ground measurements were done by forest planners and present an "expert judgement" of forest stands rather than an unbiased estimate of forest attributes using a formal sampling scheme. The maps are updated after forestry operations.