

Radiative transfer simulations link boreal forest structure and shortwave albedo

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Vegetation cover and land-use changes induced by human activities have changed the global surface albedo, or the extent to which incoming solar radiation is reflected back to the atmosphere. Forest albedo is a critical variable affecting the Earth's climate, and is still among the main uncertainties of the radiation budget in climate modelling. A synthesis of current research results clearly indicates a need for more reliable quantitative predictions of the effect of forest structure on the global albedo. This paper reports a case study on the application of a forest radiative transfer model in shortwave albedo simulations: we simulate the blue-sky and black-sky albedos of coniferous stands in Finland, and link forest albedo to stand structure and management practices. Our results indicate that boreal forest albedo decreases as the stands become older and as their standing stock increases, and that regular thinning procedures reduce stand summer albedo of coniferous forests.

Introduction

Vegetation cover and land-use changes induced by human activities have changed the surface albedo, or the extent to which incoming solar radiation is reflected back to the atmosphere, around the globe. It is assumed that a decreasing albedo exerts a positive radiative forcing on climate (e.g. Betts 2000), and vice versa, but quantification of these effects is very difficult. Recent studies have investigated the role of afforestation on climate change through its impact on the forest albedo and carbon sequestration (e.g. Bala *et al.* 2007). Results indicated that new forests in tropical areas tend to mitigate global warming whereas new forests would be

counterproductive if implemented at high latitudes, and would offer only marginal benefits in temperate regions. The study also suggested that the removal of boreal forests at high latitudes, in the tundra-taiga transition zone, would result in the strongest cooling of the global climate (Bala *et al.* 2007). On the other hand, other global climate modeling studies indicate that significant temperature changes in the northern hemisphere are not directly related to any land cover change events (e.g. Feddema *et al.* 2005).

Forest surface broadband albedo is a critical variable affecting the Earth's climate, yet it is still among the main uncertainties of the radiation budget in current climate modeling (Liang 2007). Further, land surface albedo and reflect-

ance anisotropy belong to the set of essential climate variables (ECVs, Schaaf 2009) defined by the Global Climate Observing System (GCOS). Land surface albedo is a key forcing parameter controlling the planetary radiative energy budget and partitioning of radiative energy between the atmosphere and the surface. A synthesis of current research results clearly indicates a need for more reliable quantitative predictions of the effect of forest structure and abundance on the global albedo. Physically-based vegetation reflectance models combined with new satellite remote sensing technology is the only possible method for linking vegetation structure and albedo at a global level. Global land surface albedo is regularly estimated by Earth observation satellite sensors (e.g. MODIS Terra and Aqua, NOAA/AVHRR, MSG/SEVIRI). The total amount of hemispherically reflected radiation cannot be directly measured by a satellite instrument. Furthermore, satellite images provide only a sparse angular sampling, while hemispherical data are necessary to estimate surface albedo (Pokrovskya *et al.* 2003). Therefore, bidirectional reflectance distribution function (BRDF) models are used to convert satellite reflectance measurements into estimates of directional-hemispherical reflectance (i.e. black-sky albedo) and bi-hemispherical reflectance (i.e. white-sky albedo). Characterizing radiative transfer in vegetation with BRDF models and matching the output of the models with satellite reflectance data provide a rigorous and reliable method for quantitatively assessing the complex interaction between forest 3D structure and the albedo. BRDF models can also be used to simulate forest albedo assuming different forest structures and illumination schemes.

A region where current model predictions of the effect of forest structure and abundance on the global albedo seem to be particularly unreliable is the northern hemisphere forest zone. To be realistic enough, the BRDF models need to properly account for the highly heterogeneous structure of boreal forest canopy and understory, and the presence or absence of snow on the ground and canopies (e.g. Ni and Woodcock 2000). In addition, the BRDF models need to be sensitive to forest management practices that alter stand development.

The large overall question that motivated this study was: how do forest structure and management procedures influence forest albedo and hence also affect our surrounding climate? From the perspective of climate predictions, information on the influence of forest cover and density (characterized by forest inventory parameters) on forest albedo is crucially needed. Currently, radiative transfer modeling is the most efficient way to study the sensitivity of albedo to a large number of forest variables and different forest structures at stand-level. Linking radiative transfer simulations to satellite images and variable atmospheric conditions enables producing landscape and global-level albedo predictions and potentially also assessing the reliability of the results (Soja *et al.* 2010).

In this case study, we apply a forest BRDF model to simulate the shortwave albedo of typical, managed Norway spruce forests of different age and investigate the extent to which variation in stand structure influences the albedo of a forest stand.

Material and methods

Stand data

We used a system of growth and yield simulation models, called MELA (Hynynen *et al.* 2002), to follow the development of a Norway spruce (*Picea abies*) stand from the age of 20 years to 100 years. The MELA system has been developed for national forest management purposes in Finland and includes several simulation models predicting regeneration, growth and mortality. The models are based on standard stand and tree variables. For simulating the future development of a stand, information on the geographical location, site properties and initial stand structure are required. A site index is determined from the site properties (i.e. soil characteristics, relative sea and lake cover indices, altitude and temperature sum).

We used the MELA system to generate nine different managed stand scenarios (Fig. 1 and Table 1). The stands were managed according to typical, current management practices: thinning was applied at 45 years (thinning intensity, TI:

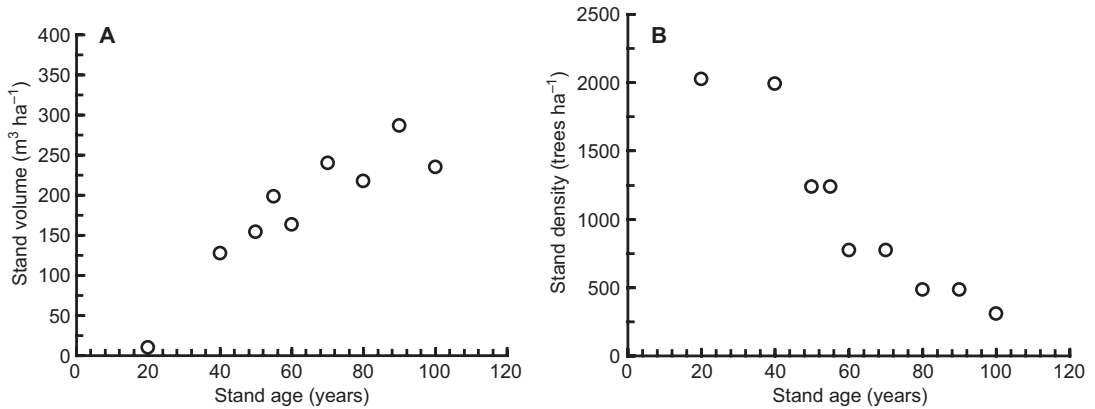


Fig. 1. Structure of the Norway spruce stands used in the albedo simulations: (A) stand volume as a function of stand age, (B) stand density as a function of stand age.

33%), 60 years (TI: 34%), 75 years (TI: 34%) and 95 years (TI: 35%). The growth models for the simulated stands used in this study corresponded to the conditions of central Finland (Suonenjoki: 62°39'N, 27°05'E, 130 meters above sea level, temperature sum 1120 dd). The selected area has also been an intensively studied VALERI (Validation of Land European Remote Sensing Instruments, URL: <http://www.avignon.inra.fr/valeri/>) test site since 2003. The stands were located on relatively fertile soil (*Myrtillus* site type); understory vegetation on a *Myrtillus* site consists mainly of dwarf shrubs (*Vaccinium myrtillus*, *V. vitis-idaea*) and a few grasses. Development of foliage biomass for trees is not included in MELA simulations. In this study, we estimated it with Marklund's (1988) allometric equations which use different combinations of basic forest inventory variables.

Atmospheric data

This paper focuses on blue-sky albedo which also corresponds to the 'actual albedo' of a vegetated surface. The blue-sky albedo (bihemispherical reflectance factor, BHR) corresponds to ambient illumination conditions. It is a function of aerosol optical depth i.e. is influenced by the combined direct and diffuse irradiance, and is, therefore, also referred to as the actual albedo.

In this study, blue-sky albedo was calculated using a modeled spectrum of incident radiation (sum of direct and diffuse fluxes), simulated with the 6S radiative transfer model (Vermote *et al.* 1997) for an average summer day in central Finland (Fig. 2). The 6S model was chosen for its reliability, sufficient accuracy and the possibility to find realistic estimates of input parameters. For atmospheric gases and aerosols, we used

Table 1. Stand variables used as input in the albedo simulations with FRT.

Stand age (years)	Mean tree height (m)	Mean diameter at breast height (cm)	Leaf area index (m² m⁻²)	Canopy cover
20	5.4	5.6	2.2	0.61
40	10.8	11.6	6.9	0.62
50	13.2	15.7	7.5	0.36
55	14.3	17.0	9.0	0.37
60	15.4	18.3	10.5	0.26
70	17.2	21.3	7.9	0.27
80	19.0	23.7	9.9	0.18
90	20.6	26.1	11.5	0.19
100	22.2	29.0	7.9	0.13

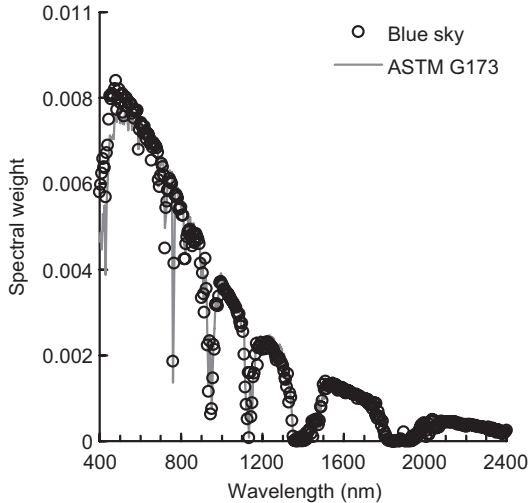


Fig. 2. The spectral weights of incoming radiation used in this study for forest blue-sky (BHR) albedo calculations (Table 2). The standard ASTM G173 spectrum (direct + circumsolar) at ground level is shown for comparison.

the simulation results of the GOCART (Goddard Chemistry Aerosol Radiation and Transport, Chin *et al.* 2002) model. Data for Central Finland were retrieved using the Giovanni Web-based tool (<http://disc.sci.gsfc.nasa.gov/giovanni>) (Acker and Leptoukh 2007) for the summer months (June to August) of 2000–2006. The set of input parameters for 6S is given in Table 2. Finally, a broadband blue-sky albedo was obtained by integrating over the wavelength range 400–2400 nm. Typical field pyranometers measure in the range from 305 to 2800 nm — the albedos simulated in this study correspond to a

Table 2. Input parameters for the 6S model (Vermote *et al.* 1997): average composition of the atmosphere in Central Finland in summer.

Parameter	Value
H ₂ O (g cm ⁻²)	1.8
Ozone (Dobson unit)	340
AOT at 550 nm	0.18
Fractions of aerosol types (%)	
dust-like	29
water-soluble	66
oceanic	2
soot	3
Solar zenith angle (°)	50

slightly smaller wavelength range. Nevertheless, the range used contains 98.1% of the total solar radiation (Gueymard 1995, 2001).

As a theoretical comparison, we also provide results for black-sky and black-soil conditions. Black-sky albedo (directional-hemispherical reflectance factor, DHR) is the ratio of the radiant flux reflected by a unit surface area into the view hemisphere to the illumination radiant flux, when the surface is illuminated with a parallel beam from a single direction (uncollided irradiance, i.e. assuming no scattering). It corresponds to pure direct illumination (no atmospheric influences) and depends on the actual illumination angle of the direct component. For computing black-sky albedo we used the CEOS (Committee on Earth Observation Satellites) standard for exo-atmospheric solar spectral irradiance (Thuillier *et al.* 2003). We removed both the effect of varying atmospheric conditions and forest understory layer which are present in the blue-sky and green-understory albedo (described previously), and were able to investigate purely the role of the tree-layer structure on forest albedo.

Forest albedo simulations

Forest albedo for the study stands was simulated with the Forest Reflectance and Transmittance model (FRT) (Kuusk and Nilson 2000) which has recently been modified to conserve energy (Möttus *et al.* 2007). FRT is a directional, multispectral hybrid type forest reflectance model which includes properties of both geometric-optical and radiative transfer equation based models.

FRT has performed well in the most recent Radiative transfer Model Intercomparison (RAMI) exercise: it was numerically the most efficient and required the least computer power of the compared models for performing the required calculations (Widlowski *et al.* 2007). In this study, we used the version of FRT which also participated in RAMI Phase-3, since its performance has been compared with that of other similar vegetation radiative transfer models in detail and also published by Widlowski *et al.* (2007). Previously, the FRT model has been applied as an interface between satellite images

and forestry databases (Nilson *et al.* 2000), to simulate satellite images of hemiboreal forests using varying input variables (Lang *et al.* 2007), to estimate forest leaf area index from satellite images through model inversion (Rautiainen 2005, Rautiainen *et al.* 2003) and to track the seasonal reflectance dynamics of hemiboreal forests (Rautiainen *et al.* 2009).

The FRT model performs in the visible and shortwave infrared domain (i.e. wavelength range from 400 nm to 2400 nm) at 1 nm spectral resolution. The reflectance quantities of a stand are calculated as the sum of three components: (1) single scattering of direct radiation from the crowns, (2) single scattering of direct radiation from the ground, and (3) single scattering of diffuse sky radiation and multiple scattered radiation (including both direct and diffuse) from crowns and ground. Stand structure in FRT is characterized by basic forest inventory parameters, e.g. tree species, stand density, tree height and breast height diameter. Canopies are modeled to consist of separate tree crowns, modeled as combinations of, for example, ellipsoids or cones. In this study, we used an elliptical crown shape to describe Norway spruces: Rautiainen *et al.* (2008) reported that a conical a crown shape model underestimates crown volume most severely whereas elliptical crown shape renders a crown volume closer to the measured crown. Finally, canopy structure is described with foliage biomass, needle or leaf clumping index and branch area index. Background (i.e. forest floor, understory vegetation) spectra are simulated by MCRM, an analytical multispectral canopy reflectance model (Kuusk 2001).

In this study, the input needed to describe stand structure in the albedo simulations was obtained directly from the MELA simulations (described in the section on stand data). All trees within a stand were modeled identical i.e., we did not assume between-tree structural variation. This is justified since we are examining the relationship of albedo and area-based forest variables (e.g. leaf area index, stand volume) and not single tree variables. The canopy structure of the spruce stands was described by several other parameters needed as input to FRT, which were set equal for all stand ages: branch area index (BAI/LAI) was 0.12, shoot shading coefficient

(i.e. needle clumping index) 0.57, shoot length 5 cm and specific needle area $50 \text{ cm}^2 \text{ g}^{-1}$. Bark spectra were based on previous measurements (Lang *et al.* 2002) and are directly tabulated into the FRT model. The simulated understory nadir spectra used in this study, on the other hand, corresponded to a mix of dense grasses, blueberry shrubs and mosses (obtained from the nadir spectra database by Lang *et al.* 2002). Reflectance anisotropy of the understory layer was obtained with simulations made with the MCRM model integrated in the FRT model.

All albedo simulations were run at 5 nm spectral resolution from 400 nm to 2400 nm for the study stands. A 12×12 quadrature was used to integrate over all the viewing and illumination zenith and azimuth angles in the hemisphere. Four illumination configurations were used in blue-sky albedo computations (solar zenith angle, SZA = 40° , 50° , 60° , 70°); these angles cover the lion's share of incoming radiation during the growing season in central Finland ($\sim 62^\circ\text{N}$; minimum solar zenith angle 38.5°).

Results

For the stands, blue-sky albedo (BHR) (assuming a green forest understory) ranged from 0.15 to 0.23 and black-sky albedo (DHR) (assuming a black soil) from 0.07 to 0.24 (Fig. 3). Common to all different 'scenarios' was that the highest BRF and DHR values were observed for the highest Sun zenith angles and vice versa. Sun angle had a significant effect on forest albedo: BRF at SZA 70° (i.e. spring midday situation) was approximately 20% larger for all stands than BRF at SZA 40° (i.e. summer midday situation). As expected, the variation of albedo with solar zenith angle was higher for DHR. Overall, variations in both BHR and DHR with solar angle did not depend on forest age: the spread for a 20-year-old forest was (in absolute albedo units) similar to that for a 100-year-old forest.

Stand volume increased and stand density decreased as the stands aged (Fig. 1) and leaf area index grew steadily between thinning procedures (Table 1). Albedo values initially increased with stand age and were at their highest for 40-year-old stands, after which both blue-sky (BHR) and

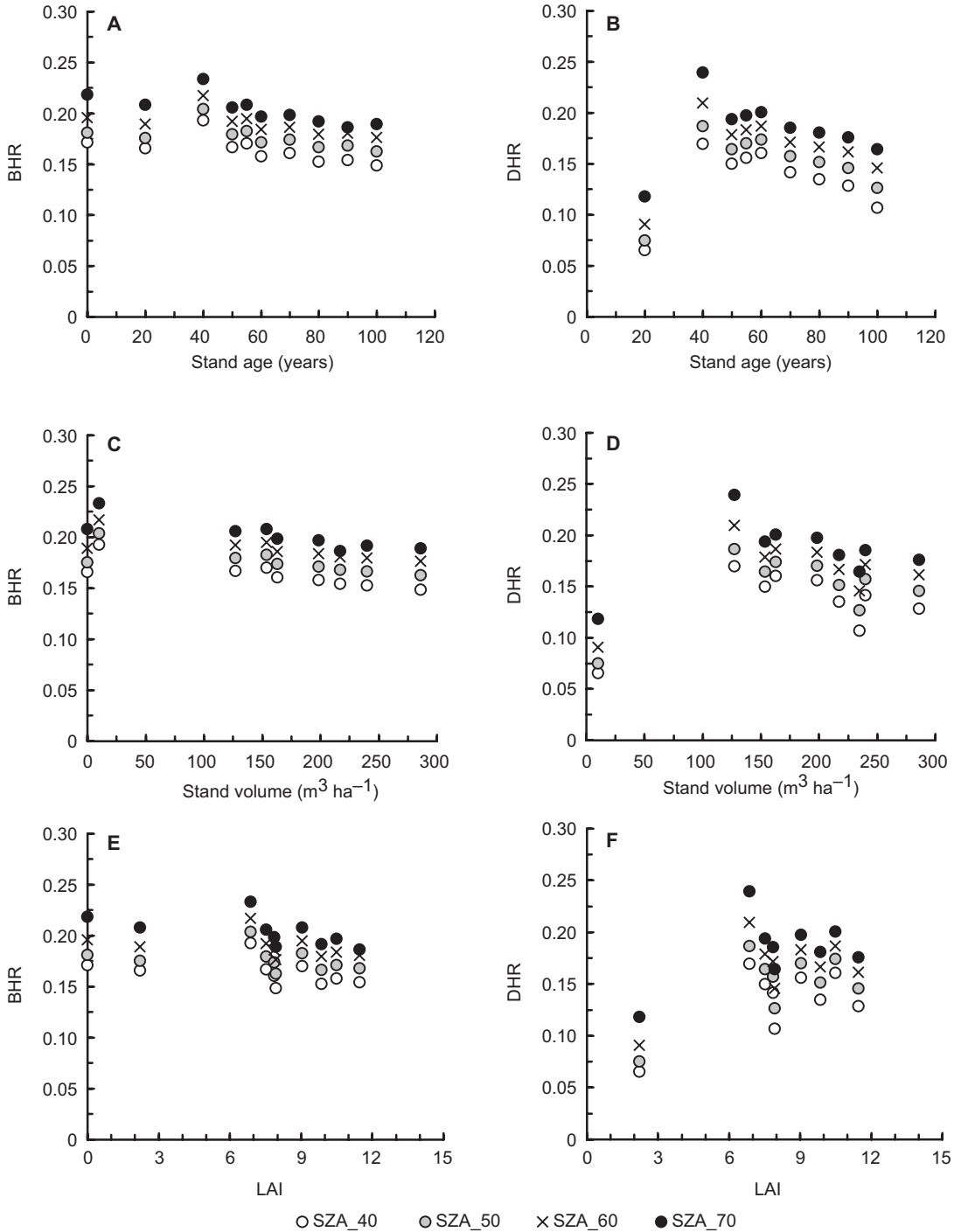


Fig. 3. Blue-sky albedo (BHR, green understory) and black-sky albedo (DHR, black soil) for Norway spruce stands at four solar zenith angles (SA = 40°, 50°, 60°, 70°). **(A)** Blue-sky albedo as a function of stand age. **(B)** Black-sky albedo as a function of stand age. **(C)** Blue-sky albedo as a function of stand volume (standing stock). **(D)** Black-sky albedo as a function of stand volume (standing stock). **(E)** Blue-sky albedo as a function of tree-layer leaf area index (LAI). **(F)** Black-sky albedo as a function of tree-layer leaf area index (LAI). Please note in **A**, **C** and **E**: when x = 0, BRF corresponds to the understory BRF.

black-sky (DHR) albedo generally decreased as the stands became older (Fig. 3A–B). Two age classes stand out in different figures: the 20-year-old and 40-year-old forests which have not yet been thinned but are following a natural development trajectory. The out-of-the-line behaviour of the 20-year-old forest can be witnessed in Fig. 3A, B and D; the forty-year old forest stands out in Figs. 3E and F. The small value of the DHR of the 20-year-old forest (Fig. 3B) is mostly due to a low leaf area index not completely covering the underlying black soil as well as the high amount of woody material. However, small LAI (or canopy cover) is not the main reason for the low BHR albedo (Fig. 3A), as a layer of green understory was placed between the soil and tree layer. The BHR value of the 20-year-old stand was actually lower than that of the understory (corresponding to stand age zero in Fig. 3A), but also lower than that of the 40-year-old stand. The result indicates the important role of woody elements and canopy structure.

Starting from the 40-year-old stand, both blue-sky (BHR) and black-sky (DHR) albedos decreased as the stands became older and as their standing stock increased (Fig. 3A–D). A comparison of our blue-sky albedo (assuming a green forest understory) and black-sky albedo (assuming a black soil) results reveals that the combined influence of the atmosphere and a forest understory layer on stand albedo is approximately 20% when the Sun is high (SZA 40°, 50°) and approximately 10% when the Sun is relatively low (SZA 60°, 70°) (Figs. 3 and 4).

The dependency of BHR and DHR on tree-layer leaf area index (LAI) was relatively poor (Fig. 3E–F): the relationship between canopy cover and LAI was scattered, and thus, the influence of the green understory was variable at different LAI values. In addition, the albedo values of the canopy and the forest floor are relatively close to each other.

We observed the effect of thinning procedures on stand albedo: after the first thinning (i.e. at stand age 45 years) BHR dropped by approximately 10% and then stayed rather constant, i.e. the next thinning procedures (at stand ages 60, 75, 95 years) had smaller influences on stand albedo due to a joint effect of changes in stand leaf area index and canopy cover. The

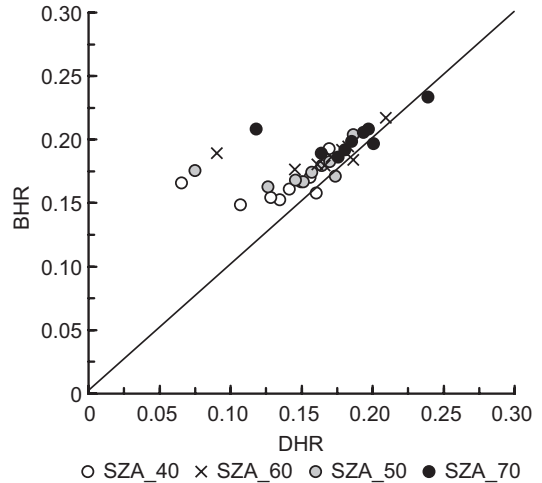


Fig. 4. Comparison of black-sky albedo (DHR, black soil) and blue-sky (BHR, green understory) albedo for four solar zenith angles (SZA = 40°, 50°, 60°, 70°). Note that the four outlier points all belong to the 20-year-old stand.

effect of the final thinning (at stand age 95 years) in decreasing forest albedo, while evident in the DHR plot (Fig. 3D), is almost non-existent in BHR or even shows up as an increase for some solar zenith angles (Fig. 3A), most likely due to a larger influence of the understory vegetation.

Discussion

A specific feature in albedo estimation in the boreal zone is the small range of solar elevation angles but a large range of forest structures. As the solar elevation angles are typically low even during the summer months, the influence of canopy structure (e.g. crown internal arrangement and grouping of foliage) has a larger role than in temperate and tropical forests. Our simulation results for typical spruce forests in Finland indicated that the blue-sky albedo (BHR) and black-soil black-sky albedo (DHR) decrease as the stand becomes older (Fig. 3A and B) after the age of 20 years. While, according to our simulations, the changes in both BRF and DHR are considerable with both sun angle and stand age, the effect of sun zenith angle is virtually independent of stand age. Thus, natural and anthropogenic changes in forest age and structure are

expected to have little effect on canopy albedo anisotropy.

In the series of simulated forests, the 20-year-old and 40-year-old stands stand out in many figures (Fig. 3). At the age of 20, the LAI of the forest is about 2. By the age of 40, LAI reaches a value of almost 7 and canopy has reached its highest closure. The first 40 years represent a fast growing period for the boreal forest stands and are accompanied by changes in canopy reflectance values. At 45 years, the first thinning is performed in the MELA system, and the reflectance values become more stable. Such stabilization is achieved by active forest management. It is evident, however, that the quick changes visible during the first 40 years of forest development cannot continue forever, and some stabilization of reflectance can be expected also for the natural development trajectory.

Naturally, it is not stand age *per se* that influences stand reflectance but the associated changes in stand structure: canopy cover, LAI, basal area, stand volume, etc. (Fig. 1 and Table 1). Our results showed that thinning procedures reduce stand albedo of boreal coniferous forests during the summer months. After thinning, stands have smaller stand density, stand volume and canopy cover but larger individual tree size and an increased leaf area density within tree crowns (since fewer stems result in an increase in crown foliage). However, stands regain lost volume in a decade after the thinning (Fig. 1A) and the general trend of stand volume (and thus above-ground standing biomass) is strongly positive. Therefore, the general trend of albedo with canopy volume corresponds to a trend with canopy age. Excluding the point corresponding to the youngest (20-year-old) forest, the trend is negative for both BHR and DHR (Figs. 3C and D).

On the other hand, the dependence of albedo on LAI is quite dissimilar. The effect of dark background is eliminated in the BHR simulations (Fig. 3E), resulting in a lack of clear trend of the blue-sky albedo with LAI. Such behavior points towards an interesting conclusion: forests may become darker with age due to changes in structure (i.e. an increased level of grouping) and an increase in their above-ground standing biomass, not necessarily only due to increasing LAI. However, this preliminary hypothesis is

only based on our limited modeling results for boreal forests and needs to be further explored.

In optical remote sensing, the amount of leaf area (LAI) is generally considered a descriptor of the amount of vegetation. Woody biomass, while affecting the signal, is considered to be of secondary importance in constructing the reflectance signal and is often retrieved via its relation to LAI. We agree with this view and propose that the effect of biomass on albedo is not directly causal. Instead, the occurrence of the albedo to stand volume dependence can be contributed to influence of canopy structure. This emphasizes the need to better understand the role of canopy structure on its reflective properties (Widlowski *et al.* 2007). Besides the direct effect of forest structure on albedo, a quantitative description of the structure on reflectance is required to estimate the relevant parameters from remote sensing data.

Further, the fact that the amount of above-ground standing biomass cannot be considered the primary direct contributor to reflectance, parametric models valid on local scales may still be constructed to relate canopy biomass to albedo. Especially in managed forests, the goals of the practices adopted in forestry have a dual effect on canopy radiation regime. In the short term, removing timber leads to a decrease in LAI and an increase in reflectance values. In the long run, however, one typical goal of forest management is to maximize timber (standing volume) production by altering canopy structure to optimize the utilization of available resources. It is plausible that such alterations in structure lead not only to an increased absorption in the photosynthetically active radiation (PAR) waveband, but the whole shortwave spectrum. The positive albedo–canopy-volume relationship may thus be speculated to be a consequence of forest management practices.

It must also be recognized that assumptions concerning the background (understory) reflectance have large impact on the results. Generally speaking, if the foliage has higher albedo than the background (e.g. ‘black soil’) stand reflectance increases with canopy cover (and LAI). For a highly reflecting background (e.g. snow covered forest floor) on the other hand, an increase in stand density (or canopy cover) decreases the albedo (Manninen and Stenberg 2009). In addition, our simulation results agreed with previ-

ously well-known facts related to solar angle: BHR values at SZA 70° (i.e. spring midday situation) were 20% larger than BHR values at SZA 40° (i.e. summer midday situation) (Fig. 3). This is due to volume scattering effects (i.e. longer path lengths through the canopy and increased multiple scattering) and has been noted also previously (e.g. Ni and Woodcock 2000). In other words, when solar zenith angle increases, the contribution of the understory layer to stand albedo decreases. However, the path lengths within the crowns also increase and this results in a higher level of multiple scattering.

Radiative transfer modeling offers an efficient tool for predicting the influence of various environmental management practices on vegetation cover albedo. It also enables producing predictions for situations where empirical studies are not feasible, e.g. due to the length of the experiment. However, the approach also has its limitations. In the case of boreal forests, the main problems are currently related to the lack of reliable input data and its seasonal variation. For example, the role of forest understory (i.e. its spectral and structural seasonal changes) should be investigated in more detail. All radiative transfer models also have limitations arising from the need to relate model inputs to measurable forest parameters: it is not possible to exactly describe the almost infinite natural complexity of a natural forest canopy. Actual models may have additional limitations depending on their mathematical implementation of the simulation of within-canopy radiative processes. The specific limitations of the FRT model used in this study are the lack of in-depth understanding of the effects of the simplifications made when modeling multiple scattering, and a lack of shoot-level reflectance model. While the first shortcoming can be solved by an extensive study of the influence of the actual stand parameters on multiply scattered signal, the second limitation could be overcome only by representative measurements of a conifer shoot BRDF. To our knowledge, no such measurement data exist today. Finally, atmospheric conditions and the role of aerosols (Table 1) will change in the future and the incoming radiation spectra may thus vary. In this study, the atmospheric conditions used were an example of a typical case. Large variation of

the aerosol optical depth would affect also the broadband albedo values due to the difference in the irradiation spectrum at the surface.

The type of modeling presented in this case study can have an important role in the validation of empirical albedo products. In the future, similar radiative transfer simulations could also be linked to national forest statistics; growing stock volume, expected annual increment and age class distribution of tree species (e.g. from national forest inventory statistics) could be used as an alternative input in albedo simulations.

Conclusions

This paper reported a case study on the application of a forest radiative transfer model in shortwave albedo simulations. We simulated the blue-sky and black-sky albedos of typical Norway spruce stands in Finland, and linked forest albedo to stand structure and management practices. Our results indicated that boreal forest albedo decreases as the stands become older and as their standing stock increases. This albedo decrease is better related to increase in stand volume (or above-ground standing biomass) than to changes in LAI, thus indicating the crucial role of canopy structure on the albedo value. Canopy reflectance anisotropy, on the other hand, was found to be rather insensitive to stand age. The effect of understory reflectance on forest albedo decreased rapidly with LAI and was the largest for forests less than 40 years old. Our results also suggested that regular thinning procedures reduce stand albedo of coniferous forests during the summer months.

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