

Summertime canopy albedo is sensitive to forest thinning

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Abstract

Despite an emerging body of literature linking canopy albedo to forest management, understanding of the process is still fragmented. We combined a stand-level forest gap model with a canopy radiation transfer model and satellite-derived model parameters to quantify the effects of forest thinning, that is removing trees at a certain time during the forest rotation, on summertime canopy albedo. The effects of different forest species (pine, beech, oak) and four thinning strategies (light to intense thinning regimes) were examined.

During stand establishment, summertime canopy albedo is driven by tree species. In the later stages of stand development, the effect of tree species on summertime canopy albedo decreases in favour of an increasing influence of forest thinning on summertime canopy albedo. These trends continue until the end of the rotation where thinning explains up to 50 % of the variance in near-infrared canopy albedo and up to 70 % of the variance in visible canopy albedo.

More intense thinning lowers the summertime shortwave albedo in the canopy by as much as 0.02 compared to unthinned forest. The structural changes associated with forest thinning can be described by the change in LAI in combination with crown volume. However, forests with identical canopy structure can have different summertime albedo values due to their location: the further north a forest is situated, the more the solar zenith angle increases and thus the higher is the summertime canopy albedo, independent of the wavelength. Despite the increase of absolute summertime canopy albedo values with latitude, the difference in canopy albedo between managed and unmanaged forest decreases with increasing latitude. Forest management thus strongly altered summertime forest albedo.

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1 Introduction

Albedo is the fraction of solar energy reflected from a surface back to the atmosphere; it is a radiative parameter, which is controlled by the characteristics of the surface. The size of the land surface albedo is a major factor controlling the energy budget of the Earth and albedo is thus a key parameter in the Earth's climate system. Of the main land surface types, i.e. trees, grasses, crops, bare soils, and ice and snow cover, trees generally have the lowest albedo, trapping more solar radiation than the shorter vegetation types (Amiro et al., 2006; Betts and Ball, 1997; Pielke and Avissar, 1990; Robinson and Kukla, 1984). The differences in albedo between broad vegetation classes, i.e. evergreen and deciduous forest, and among other vegetation types are reasonably well established, as are the subsequent climate effects (Anderson et al., 2011; Bala et al., 2007; Bathiany et al., 2010; Betts, 2000; Pielke et al., 1998; Schwaiger and Bird, 2010). However, more fine-scale albedo effects, such as those of species diversity in the canopy, tree species and forest management, remain poorly documented. Forest management is one of the key instruments proposed to mitigate climate change (UN, 1998), through maximizing forests' sequestration of atmospheric carbon dioxide. It is thus imperative to quantify the full range of climate impacts including the fine-scale effects of forest management on albedo.

Thinning is a forest management strategy to increase growth of individual trees, control stand composition and structure forests by removing trees at a certain time during the forest rotation. The site-level effect of forest thinning on albedo has only been quantified for a handful of stands. For a temperate pine forest in New Zealand thinning resulted in small increase in albedo (Kirschbaum et al., 2011). The same was observed for a thinned pine forest in Arizona (Dore et al., 2012). In contrast, a mid-rotation stand of loblolly pine in Eastern North Carolina showed lower averaged albedo compared to a recently established stand on a clear-cut site (Sun et al., 2010). The first thinning of a managed Norway spruce stand in Finland was simulated to reduce the albedo by 10 %, whereas the following thinning events had a smaller influence on

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stand albedo (Rautiainen et al., 2011). This reduction in surface albedo was reported to be a function of canopy structure and thinning (Rautiainen et al., 2011).

Although a body of literature linking forest albedo to forest thinning is emerging, process understanding is still fragmented, as these studies are limited to individual stands and single species (Dore et al., 2012; Kirschbaum et al., 2011; Moreaux et al., 2011; Rautiainen et al., 2011; Sun et al., 2010). To contribute to a fuller understanding of the effects of forest thinning on summertime canopy albedo for: (1) different sites, (2) tree species and (3) thinning strategies (Table 1), we coupled a stand-level forest gap model to a canopy radiation transfer model and used satellite-derived model parameters to unravel the factors controlling albedo.

2 Materials and methods

2.1 Modelling approach

Effects of forest thinning on stand structure were quantified using a forest gap model called ForGEM (FORest Genetics, Ecology and Management (Kramer et al., 2008)). Subsequently, radiation absorption, scattering and transmission by the forest canopy were calculated from a radiation transfer model (Pinty et al., 2006) using satellite-derived, species-specific and effective vegetation radiative properties (Fig. 1 and Table 2).

The forest gap model ForGEM is a spatially explicit, individual tree model that quantifies ecological interactions and forest management. Previously, ForGEM has been applied to diverse research questions ranging from the effects of wind throw on carbon sequestration to the adaptive potential of tree species under changing climate (Kramer et al., 2008; Schelhaas, 2008; Schelhaas et al., 2007). Inter-model comparison (Fontes et al., 2010) demonstrated that ForGEM is one of the few processed-based models that are capable of simulating complex relationships and interactions between tree species and forest management strategies. Direct validation of the simulated canopy structure

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against observations in not available yet due to the absence of sufficiently large observational datasets. This is, however, likely to change in the near future owing to the rapid development of radar based technology (Raumonen et al., 2013). In the mean time, inter-model comparison (Fontes et al., 2010) and stand level validation (Kramer et al., 2008) increased our confidence that the model simulates a realistic canopy structure under different management strategies. In this study, ForGEM was set up to simulate forest stands composed of different species and subject to different thinning regimes over one rotation (Table 1). These simulations provided us with key variables to describe the forest canopy structure, i.e., tree height, crown volume as ellipsoids, leaf mass, leaf area index (LAI) and the spatial position of all trees within the stand.

Given the complexity of radiation transfer, it is difficult to accurately simulate radiation transfer through structurally and optically complex vegetation canopies without using explicit 3-D models. Nevertheless, the 1-D canopy radiation transfer model by Pinty et al., 2006 has been shown to accurately simulate both the amplitude and the angular variations of all radiant fluxes with respect to the solar zenith angle (Widlowski et al., 2011). However, this requires the use of adopted variables: we refer to these as “effective” variables, which replace true state variables (Pinty et al., 2004). For example, the value of LAI used in the 1-D model is calculated from the true LAI such that the 1-D model reproduces the radiative fluxes of the 3-D model. LAI in the 3-D model is the true state variable; LAI in the 1-D model is the effective LAI.

The effective LAI was calculated by means of a “ray tracing approach”. For an incident single ray, the approach tests if that ray encounters a tree and measures the distance it travels through the canopy before reaching the forest floor. This process was repeated 100 000 times for different locations over the stand to estimate the probability density function of the distance rays travel within the canopy. The probability density function was combined with the crown density (LAI per crown volume, (Bréda, 2003)) to calculate the fraction of direct light reaching the forest floor for a given solar angle. This fraction was then used as input in the inverted Beer-Lambert’s law (see Eq. (25) in Pinty et al., 2004) to derive the effective LAI. This approach requires the ex-

explicit position of trees and their crown dimensions. This information was retrieved from the ForGEM simulations mentioned above.

To calculate the albedo from the effective LAI the following vegetation radiative properties are required: the effective leaf single scattering albedo (for both visible (VIS) and near-infrared (NIR) wavelengths), the effective preferred scattering direction of vegetation scattering (VIS and NIR), and the so-called true background albedo which is the albedo of the surface below the dominant tree canopy (VIS and NIR). All parameters were taken from the Joint Research Centre Two-stream Inversion Package (JRC-TIP) (Pinty et al., 2011a, 2011b), software which inverts the two-stream model (Pinty et al., 2006) to best fit the MODIS broadband visible and near-infrared white-sky surface albedo from 2001 to 2010 at 0.01 degree resolution.

Parameter values were only selected from the JRC-TIP if the posterior standard deviation of the probability density function was significantly smaller than the prior standard deviation, because this condition ensures statistically significant values. The vast majority of the retrieved values remained close to their prior values. The radiative properties extracted from JRC-TIP were successfully compared with in situ measurements for deciduous and needleleaf forest sites (Pinty et al., 2008, 2011c). It should be noted, however, that without field observations to constrain the prior values of the canopy and background properties used in the inversion, the right fluxes may be obtained from a wrong combination of canopy and background properties, especially for sparse canopies.

Effective species-specific radiative properties were derived from JRC-TIP by masking the scattering parameters with a forest species map for Europe (Brus et al., 2011). This map gives a spatial distribution of the 20 dominant tree species over Europe at 1 × 1 km resolution. As this study considers only pure forest stands, to avoid signal pollution only pixels where a single species dominated (Brus et al., 2011) were selected. The effective scattering and true background values for pine (*Pinus sylvestris* L.), beech (*Fagus sylvatica* L.) and oak (*Quercus robur* L. or *Q. petraea* Liebl) are listed in (Table 2).

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The diversity of techniques to measure and model albedo has resulted in a range of (slightly) different albedo specifications. In this study, albedo is defined as the black-sky albedo, also referred to as directional-hemispherical reflectance (DHR). This means that the surface is illuminated with a parallel beam of light from a single direction and the scattering is the integral over all viewing directions (Martonchik et al., 2000). It is not normally measured in the field where most measurements will also include illumination from diffuse solar radiation. Thus, we use bi-hemispherical reflectance (BHR), assuming diffuse illumination, for the comparison with observed albedo values. We report the albedo for direct-beam light and for the visible (0.3–0.7 μm) and near-infrared (0.7–3.0 μm) bands of the spectrum separately. The term “canopy albedo” describes the albedo of a combined shortwave band (0.3–3.0 μm) at the top of the canopy of a forest stand. If we refer to another albedo quantity or spectrum, it is mentioned in the text.

2.2 Set-up of the species-thinning experiment

The above model chain was applied to pine, beech and oak single-species forest. For each species we simulated four different thinning strategies, going from unmanaged to intensively thinned forest (see Table 1). All simulations were based on the growing conditions that approximate the highest site class of Dutch yield tables (Jansen et al., 1996), using observed climate over the period 1975–2010 for central Netherlands from the MARS database (accessed online 30 April 2013: <http://www.marsop.info/marsop3/>). The simulations start with about 5000 trees per hectare aged between 10 and 15 years and forest regeneration was considered absent within a rotation. For each species and thinning type, canopy albedo was calculated across Europe for a transect along the 9° E line of longitude stretching from 40° to 60° N, in discrete steps of 5°. The selected spatial domain is an ecologically feasible growing area for the species under study. Canopy albedo was reported for the location-specific solar-noon zenith angle of the sun at summer solstice under clear sky.

2.3 Validation

The model chain, was validated against forest properties and top-of-the-canopy albedo data from five observational sites. To capture all possible spatial scales of observed albedo values, each site is presented as the mean albedo of June (2001–2010) by MODIS (two pine, two beech, one oak forest, see Table 3 and SI). In contrast to the model chain used in the remainder of the study, the validation did not make use of FORGEM simulations to describe the canopy structure in the radiation transfer model. Instead the radiation transfer model was forced by observed diameter and height distribution and single-sided LAI and, in the case of needles, hemispherical LAI (Table 3).

Foliage in the tree crowns often clumps and typically clumping is more important in needleleaf compared to broadleaf plants. The so-called needle-to-shoot level clumping is quantified using the needle-to-shoot area ratio, which is measured through shoot samples and varies from species to species (Chen, 1996). The needle-to-shoot clumping factor for pine forests, taken from observations by Chen (1996) is 1.55. The hemispherical leaf area index (LAI of conifers) divided by the needle-to-shoot area ratio (1.55) equals the corrected LAI.

2.4 Statistical analysis

An analysis of variance (ANOVA) quantifies the relative contributions of variables to the mean of a given vector, i.e., the percentage of the total variance explained by a given variable. Multi-way ANOVA was used to quantify the relative contributions of species, latitude and thinning and species-latitude, species-thinning and latitude-thinning interactions to summertime canopy albedo. In the analysis all factors were considered to be so-called random effects. The analysis was repeated for every model year for the visible, near-infrared and shortwave wavelength bands separately to derive the temporal variability during rotation in the driving factors (species, latitude and thinning). All

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factors were tested but for the sake of clarity only factors that explained more than 10 % of the variance are shown.

2.5 Radiative forcing

We applied the concept of radiative forcing to quantify the site-specific per-unit area climate impacts of forest thinning on summertime canopy albedo. The radiative forcing is the mean change in reflected shortwave radiation in June at the top of the atmosphere resulting from changes in surface albedo due to intense thinning. Following the calculations presented by Bright et al. (2012) and Cherubini et al. (2012) for each year we compared the summertime canopy albedo changes between the intensely managed and the unmanaged forest stands.

The radiative forcing (RF) was calculated as:

$$RF = -R_{TOA} f \Delta\alpha \quad (1)$$

where R_{TOA} is the incoming solar radiation flux at the top of the atmosphere, f is a two-way atmospheric transmittance parameter accounting for reflection and absorption of solar radiation through the atmosphere and $\Delta\alpha$ is the difference in surface albedo between unmanaged and managed forest.

The two-way atmospheric transmittance, f , is estimated as the product between the clearness index, K , which is the fraction of downwelling solar radiation at the top of the atmosphere reaching the Earth's surface, and the atmospheric transmittance factor, T , which is the fraction of radiation reflected at the surface arriving back at the top of the atmosphere. The clearness index, K , was derived for every site specifically from NASA's Solar Surface Energy project (accessed online 30 April 2013 at: <http://eosweb.larc.nasa.gov/cgi-bin/sse/sse.cgi>). For the atmospheric transmittance factor, T , we use a global annual average of 0.854 (Lenton and Vaughan, 2009), whose suitability was tested by Cherubini et al., 2012. The incoming solar radiation, R_{TOA} , on any given day of the year number from 1 to 365 can be calculated from latitude, the declination angle, and the sunset-hour angle, following equations reported by (Bright

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single scattering albedo and direction of scattering values, whereas in the absence of a canopy the albedo is determined by the true background values. In both cases, the JRC-TIP inversion used for the optimization of these surface properties is well-constrained. For a sparse canopy, in contrast, the inversion needs to optimize effective single scattering albedo, direction of scattering values and the true background albedo (Pinty et al., 2011a). In the absence of field observations, the inversion problem is over-parameterized and therefore the top-of-the-canopy albedo can be reproduced by several sets of different values of the surface properties. In the inversion, errors in true background albedo values may be compensated for by errors in the effective parameters.

We calculated the near-infrared effective single scattering albedo that would have been needed to reproduce the site-level observed albedo. This value of 0.54 (before 0.67) was well within the range of likely values (Kuusk et al., 2010). We derived this value for NL-Loo but when applied at EE-Jär the near-infrared albedo decreased from the initial 0.23 to 0.17, which differs by only 0.01 from the observed value. This result confirms our belief that the observed deviation is not due to a shortcoming in the model itself but reflects the difficulties the JRC-TIP has with optimizing parameter values in the absence of field observations in the specific case of sparse canopies.

In addition, scale issues cannot be ruled out as a possible cause of the mismatch between observations and simulations. The albedo of sparse needleleaf forests seems to be challenging, not only to model (Kuusk et al., 2010) but also to observe (Davidson and Wang, 2004). The forest reflectance model called FRT overestimated the reflectance spectra for EE-Jär in the near-infrared domain by up to 0.08. We simulate the albedo for a forest stand of a size of 1 hectare ($=10\,000\text{ m}^2$) whereas the footprint of the site observations range from a few square metres (UAV) to 1200 m^2 (albedometer). Local measurements of sparse needleleaf forests underestimated the shortwave albedo considerably, in the case of snow on the ground by up to 0.3 (Davidson and Wang, 2004). This is due to the spatial heterogeneity inherent in point-to-pixel inter-comparison (Cescatti et al., 2012; Román et al., 2009).

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Our model chain tends to overestimate the near-infrared summertime albedo of needleleaf forest, but we considered this bias insufficient to hamper the use of the model for the factorial simulations presented in the next section, especially because the remainder of the study compares different treatments and thus discusses changes in summertime albedo rather than absolute albedo values.

3.2 Attribution

A multi-way ANOVA was performed for three different species, four thinning strategies and five different latitudes (see Table 1). Different factors contribute to the variance of summertime canopy albedo in the visible, near-infrared and shortwave wavelength bands (Fig. 4). During stand establishment, summertime canopy albedo is driven by tree species. In the following stages of stand development, the effect of tree species on summertime canopy albedo decreases in favour of an increasing influence of forest thinning on summertime canopy albedo. These trends continue until the end of the rotation where thinning explains up to 50 % of the variance in near-infrared summertime albedo and up to 70 % of the variance in visible summertime canopy albedo. Surprisingly, the latitude only plays a role in the near-infrared band where it contributes about 20 % to the total variance.

The contributing factors differ depending on whether the visible and near-infrared wavelength bands are treated separately or whether they are combined in a single, so-called, shortwave canopy albedo. This change in explanatory factors is because absorption in the visible band reaches its maximum when the absorption for the near-infrared band reaches its minimum. Hence the sum of both spectra shows substantially less variation than the individual spectra. The variation in shortwave summertime albedo is driven by tree species. This effect decreases towards the end of the forest rotation to about 40 %, whereas the contribution of thinning and latitude increase and explain the rest of variation equally with about 25 % each.

Interaction terms (given as $A \times B$) between species, latitude and thinning denote that the effect of variable A on canopy albedo depends on the level of variable B . There

were no significant interactions between species and thinning observed that explain more than 10 % of the variation in canopy albedo.

3.3 How does species affect summertime canopy albedo?

As expected, the summertime near-infrared canopy albedo of all species exceeds the canopy albedo in the visible wavelength band (Fig. 5), which is due to the higher effective single leaf scattering in the near-infrared band (see Table 2). Across all four thinning strategies, the summertime visible canopy albedo of all species ranges from 0.03 to 0.06 (Fig. 5) over one forest rotation time. In the near-infrared, the summertime canopy albedo of pine ranges between 0.20 and 0.27. Beech and oak show a smaller temporal variability compared to pine which only ranges between 0.24 and 0.28. The opposite temporal variabilities in the visible and near-infrared wavelength bands largely offset one another when the temporal variability in shortwave canopy albedo is considered (Fig. 5).

Simulations were performed for 25 subplots of 20 m × 20 m, adding up to one hectare of forest. For dense forest, the albedo of a single 20 m × 20 m subplot is similar to the albedo of the entire 1 ha plot as shown by the small variability in Fig. 5. Contrary to this, moderately sparse (cover ca. 0.5) canopies showed a considerable spatial variability within the 1 ha plot. At the end of the rotation, however, the very sparse canopies were again well represented by single 20 m × 20 m subplots. This approach confirms that except for the very dense and very sparse canopies, canopy albedo needs to be measured and modelled over sufficiently large enough areas to be representative for the entire stand (Román et al., 2009).

3.4 How does thinning affect the summertime canopy albedo?

Thinning strategies lead to a non-monotonic variation in summertime albedo over the forest rotation period compared to unmanaged forest (Fig. 5). The analysis reveals a tendency for more intensive thinning strategies having a stronger effect on summertime

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canopy albedo. In the case of no thinning, the summertime canopy albedo decreases in the visible spectrum and increases in the near-infrared spectrum during stand establishment. After this period of about 15–20 years the canopy is closed and the albedo stays constant. The different thinning strategies alter this behaviour. After stand establishment, the summertime near-infrared albedo drops by up to 22 % in the case of pine forest and intense thinning compared to the simulation without thinning. The drop is only half this amount for the beech and oak. After every thinning event, canopy albedo increases in the visible band and decreases in the near-infrared wavelength band. Thinning lowered the summertime shortwave canopy albedo compared to unmanaged forest (Fig. 6). Interestingly, the thinning strategy “intense thinning” reduces the summertime albedo slightly more than the thinning strategy labelled “strong thinning”. In total, the absolute maximal change in shortwave canopy albedo between managed and unmanaged forest stands ranges from 0.020 for pine and 0.015 for beech to 0.010 for oak.

3.5 How does latitude affect summertime canopy albedo?

The diurnal pattern of solar zenith angle at a given location is determined by the site’s latitude. We compared the average summertime canopy albedo over one rotation period of each species and thinning type for a transect along the 9° E longitude from 40° to 60° N. Independent of the spectrum band, species and thinning type all simulations reveal a linear trend (Fig. 7a, shortwave albedo) with a strong positive correlation between latitude and albedo, i.e., the further north the forest stand is situated the higher the summertime canopy albedo. This implies that forest with identical canopy structures will have different canopy albedo values due to their location. However for pine, the difference between unmanaged and intensively managed forest remains constant at each latitude, whereas the deciduous forests exhibit a decreasing difference in albedo between managed and unmanaged stands from low to high latitudes (Fig. 7b). Thus the absolute summertime albedo values of the forest stands increase with increasing

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latitude, but the difference between unmanaged and managed forest decreases with increasing latitude.

3.6 What drives changes in summertime canopy albedo?

In its most basic form, forest thinning interacts with stand structure through two processes: changing tree species composition (long-term strategy, for more than several decades) and changing stand diameter distribution (short-term strategy, less than several decades). Both processes may affect the structure of the canopy and thus the organisation in space and time of the bulk plant components such as foliage, branches and stems (Parker, 1995). Crown volume and LAI are positively correlated (Fig. 8), with low crown volumes typically exhibiting low LAI. However, above a certain LAI threshold, the crown volume may further increase whereas LAI saturates. The exact value of the LAI threshold depends on the species and thinning strategy. Nevertheless, all forest types show that low LAIs correspond to low summertime canopy albedo values where the albedo reaches its minimum with increasing crown volume. Thus, both changes in LAI and crown volume seem to drive the canopy albedo.

3.7 How do summertime albedo changes affect the climate system?

The radiative forcing is calculated for the site-specific largest albedo changes in June that occur between the unmanaged and the intense forest strategy (Fig. 9). For all three species, the integration of the radiation over a rotation results in a positive radiation forcing, and thus in a warming of the atmosphere. The mean radiative forcing over rotation ranges from 1.09 Wm^{-2} (oak forest at 50° N) to 3.39 Wm^{-2} (pine forest at 40° N). However, the forcing is non-monotonic over the rotation, after each thinning event the radiative forcing increases up to 5.18 Wm^{-2} . For pine and oak, the radiative forcing is largest during the first half of a rotation, whereas beech reaches its maximal radiative forcing in the middle of a rotation. The radiative forcings of all species display

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a negative correlation with latitude: the radiative forcing decreases from low to high latitude (Fig. 9).

4 Discussion

4.1 Thinning intensity as a driver of summertime albedo

5 Forest summertime shortwave canopy albedo is determined by: (a) the single scattering albedo which is a physical property of the leaves and needles and (b) canopy structure (i.e. crown volume and LAI), which is mainly determined by the functional group, tree location within the stand and growing conditions. Our simulations confirm the dependency of canopy albedo on these natural drivers, but adds insight into how
10 these natural processes are altered by humans through forest thinning.

Effective single scattering albedo and its direction in both the visible and near-infrared wavelength bands were observed to be remarkably similar across tree species and even between broadleaved and needleleaved species (Table 2). Despite the similarities in these physical leaf properties, the canopy albedo has been repeatedly reported to differ between forest stands composed of different tree species, hinting at
15 the importance of the canopy structure and background albedo as determinants of the canopy albedo. The similarity in effective single scattering albedo and scattering direction for the main European forest tree species is in contrast to the substantial differences in these properties between, for example, forest and herbaceous plants (Asner, 1998). We found no references contributing to an explanation of the observed similarities of woody plants or the differences between woody and herbaceous plants
20 in single leaf scattering and scattering direction. Hence, we can only speculate that the differences and similarities in the aforementioned leaf properties are plant traits that correlate with other traits such as leaf size, leaf to shoot clumping and hairiness of the leaf, to jointly optimize leaf temperature and light harvesting. Field observations are
25 needed to test this hypothesis.

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Variation in LAI is often considered a natural process driven by phenology (Betts and Ball, 1997; Bonan et al., 2011), which in turn is the outcome of natural succession (Amiro et al., 2006; McMillan and Goulden, 2008). Hence, LAI is a widely used descriptor of canopy structure, and it is the sole driver of albedo in several land surface models (De Noblet-Ducoudré et al., 1993; Otto et al., 2011). Our analysis confirms that canopy albedo relates to LAI as previously reported by others (Kuusk, 2012; Rautiainen et al., 2011) but this is only a partial relationship. Canopy structure as a whole determines scattering and absorption by, for example, influencing the depth at which rays first encounter foliage and the probability that after this initial interaction the reflected rays will interact with leaves located deeper in the canopy or with the forest floor below the canopy. Thinning activities are likely to affect both LAI and crown volume (Fig. 8) through changes in tree spacing, stand density, and size distribution. Thinning aims at creating a more uniform tree spacing; consequently, after thinning there will be less overlap between tree crowns and individual trees will fill the crown layer more uniformly than before. Subsequently, the remaining amount of LAI per crown volume determines how much light arrives at the forest floor. A sparse canopy cover allows more light to penetrate to the forest floor than a more complete cover and the former is therefore more likely to support an abundant understorey vegetation (Ares et al., 2010; Foré et al., 1997). When the albedo of the understorey vegetation exceeds the albedo of the tree canopy above, a low canopy cover is likely to result in a higher albedo compared to a stand with high canopy cover. Hence, LAI, canopy volume and background (i.e. understorey) albedo are all needed to model thinning-induced changes in canopy albedo.

Beside the physical parameters determining canopy albedo of forests, the variation of canopy albedo is often explained as a function of forest age (e.g., (McMillan et al., 2008; Nilson and Peterson, 1994). However, the correlation with forest age is most likely spurious because there is no physical univariate relationship between age and albedo. This relationship should only be applied during stand establishment when the changes in foliage composition evolve with time, i.e., when a homogeneous grass layer

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is replaced by a heterogeneous tree layer where foliage is aggregated into tree crowns. Further, the relationship no longer holds if the forest is thinned: our simulations show that during stand establishment, summertime albedo is driven by tree species. After establishment, the effect of tree species on albedo decreases in favour of an increasing importance of forest thinning on canopy albedo. These trends continue until the end of the rotation where forest thinning finally explains up to 70 % of the variance in (visible) canopy albedo. Hence, thinning makes a considerable contribution to the variations in canopy albedo and decouples stand age and forest albedo.

4.2 The effects of forest thinning on summertime albedo

Thinning-driven variations in summertime canopy albedo amount in absolute terms to up to 0.02, with the largest changes being induced by intensive thinning strategies. In textbooks, the shortwave albedo of different deciduous forests ranges between 0.15–0.20 and for needleleaf forest from 0.05–0.15 (e.g. Oke 1987; Lucht et al., 2000; Gao 2005). The range is usually explained by different species (e.g. Davidson and Wang, 2004) and solar zenith angles (e.g. Dickinson et al. 1993). However, these values are reported without specifying the applied thinning strategy and time of rotation. Thus, as much as 20 to 50 % of this range may be the result of thinning-induced changes in forest structure.

Observations show opposing effects of thinning on albedo: measurements in a ponderosa pine stand (Dore et al., 2012) and a maritime pine plantation (Moreaux et al., 2011) have reported that thinning increases slightly the summertime canopy albedo, measurements of a loblolly pine plantation showed a decrease of summer canopy albedo due to thinning (Sun et al., 2010). The conflicting results may be due to different stand structures (see above), regrowth of understorey layer (Ares et al., 2010) or due to changes in the water balance (Sun et al., 2010). A modelling study indicates that regular thinning of boreal forests reduce stand summer albedo of coniferous forests (Rautiainen et al., 2011). Our study confirms this effect. In addition, we showed that this finding also applies for deciduous forests, independent of their location.

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Increase sequestration of atmospheric carbon dioxide (Anderson et al., 2011) through forest management is considered to be one of the instruments available to mitigate climate change (UN, 1998). Our analysis shows that thinning, which is one decision variable of forest management, will not only affect the greenhouse gas balance but will also impact the forest albedo. The concept of radiative forcing (Hansen et al., 1997) is one way to quantify the local per-unit area climate impacts of forest thinning. Despite the removal of individual trees, moving from a natural unthinned forest to a thinned forest results in a decreasing summertime albedo and atmospheric warming of at most 5 Wm^{-2} (June) due to more uniform filling of the crown volume (see above) with leaves or needles. The complete cutting of trees, however, would remove the entire canopy and thus presumably have the opposite effect. A negative radiative forcing of up to -18 Wm^{-2} in summer was measured from clear cutting in the temperate zone (Houspanossian et al., 2013). Our study is restricted to albedo changes and radiative forcing in June and therefore the results are thought to be more relevant for local than for global climate i.e., the effect of thinning on summer albedo may enhance the strength of local summer temperatures. For global climate, the results should be integrated over all four seasons because thinning-induced effects on albedo - and on the magnitude of radiative forcing- may differ with snow on the forest floor (Manninen and Stenberg, 2009). The effect of albedo and the magnitude of radiative forcing may differ on a seasonal and annual basis, possibly leading to the different effect along with the time period over which the effects are considered (Kirschbaum et al., 2011).

4.3 Climate effects of thinning

Observations showed that changes in albedo due to thinning did not consistently alter any energy balance component (e.g. soil temperature and net radiation) (Dore et al., 2012; Moreaux et al., 2011). This may be caused by a change in outgoing longwave radiation offsetting the albedo effect (Moreaux et al., 2011). Another reason could be a difference in canopy wetness after rainfall or lower sensitivity to soil water availability (Moreaux et al., 2011). However, indirect climatic effects linked to changes in canopy

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Acer pseudoplatanus are co-dominant. The second beech stand was located in France (FR-Hes, 48.67° N, 7.07° E). It was a rather young forest (48 years in 2013) and, with 2616 trees per hectare, densely populated. The dominant tree cover was 21 m tall with a high canopy closure. The oak stand is situated in France (FR-Fon, 48.48° N, 2.78° E) and consists mainly of *Quercus petraea* L. In 2006 the stand density was 1134 trees per hectare, of which 234 were *Quercus petraea* and 900 were *Carpinus betulus*. The average canopy height of *Quercus petraea* was about 27 m whereas the *Carpinus betulus* were about 10 to 20 m tall, stand age was about 150 years.

For all validation sites, stand-level albedo was observed from in situ incoming and outgoing shortwave radiometric measurements and recorded in the IMECC database with the exception EE-Jär. From this database years were only selected when outgoing and incoming shortwave radiation was recorded. Albedo was calculated as the ratio of downward and upward radiation as observed with two-way pyranometers. The overall expected instrumental accuracy is in the range 4–7 % in clear sky and 1–4 % in overcast conditions (Cescatti et al., 2012). The radiation measurements cover the wavelengths from 0.21 to 2.80 μm .

The albedo at EE-Jär is measured as top-of-canopy bidirectional reflectance factor (BRF) with a UAV spectrometer (Kuusk, 2011). The measured BRF was carried out at different dates in July and August in 2012 and transformed with the help of the 6S atmosphere radiation transfer model (Vermote et al., 1997) and the FRT forest reflectance model (Kuusk and Nilson, 2000) into visible and near-infrared albedo for the solar zenith angle 39.8 degree which corresponds to the maximum solar zenith angle at midday at Järvselja site at summer solstice.

Only EE-Jär and DE-Hai provided measured crown sizes (Table 3). For the remaining sites, species-specific allometric relationships were used to estimate the height of the crown base, the crown radius and length derived from three different data sets (Condés and Sterba, 2005; Pretzsch et al., 2002; Zeidel, 1991). For sites where the coordinates of the individual trees were absent, we assumed a uniform tree distribution. Only the simulation for EE-Jär was run exclusively with observed parameters (see Table 3) and

compared with simulated albedo. For all other sites, the observed albedo was, finally, compared to the calculated albedo. However, variation in the amount and timing of cloudiness causes considerable day-to-day variation which can be smoothed out when integrated over several weeks (Hollinger et al., 2010). Therefore, integrated daily values for the whole month June were calculated to compare to the simulated values.

Every simulation was performed for 1 hectare (10 000 m²) of forest. This one hectare was divided in 25 squares (20 m × 20 m) and the albedo was simulated for each square separately. The variation between the squares was considered to be a measure of the sensitivity of albedo to the footprint for a given canopy structure. The scan line of the UAV spectrometer is about 2.5–3.0 m (Kuusk, 2011). The footprint of surface albedo measured by the pyranometers depends on their height above the canopy (ranging from 5 to 10 m). However, for the experimental sites under study, typically 80 % of the signal originates from within 300–1200 m² (i.e. 10–20 m) around the tower (Cescatti et al., 2012). To capture all possible spatial scales of observed albedo values, each site is presented as the mean albedo of June (2001–2010) by MODIS (Pinty et al., 2011a; Schaaf et al., 2002) at ~ 1 km resolution. The range of MODIS observations are derived from 9 pixels surrounding the tower.

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Table 1. Overview of the simulation set up used in this study. P: *Pinus sylvestris* L., F: *Fagus sylvatica* L. and Q: *Quercus robur* L. or *Q. petraea* Liebl). Explanation of forest management strategies: (I) unmanaged forest: The forest stand is an even-aged forest and no management measures are applied. (II) light thinning: The forest stand is thinned from below according to yield tables. The trees with the smallest diameters are removed until the required density from the yield table is reached. This is repeated every five years. (III) strong thinning: This measure is similar to (II) but only half the density of the yield tables is applied, i.e. more trees are removed than in the simulations (II). (IV) intense thinning: This measure is similar to (III) but the thinning occurs only every ten years, to the same density as (III) for the same age.

location / species	unmanaged forest (I)	light thinning (II)	strong thinning (III)	intense thinning (IV)
60° N 9° E	P, F & Q	P, F & Q	P, F & Q	P, F & Q
55° N 9° E	P, F & Q	P, F & Q	P, F & Q	P, F & Q
50° N 9° E	P, F & Q	P, F & Q	P, F & Q	P, F & Q
45° N 9° E	P, F & Q	P, F & Q	P, F & Q	P, F & Q
40° N 9° E	P, F & Q	P, F & Q	P, F & Q	P, F & Q

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Table 2. Observed mean radiative properties for the tree species used in this study for June: effective single scattering albedo, effective preferred direction of scattering and true background albedo were extracted from the JRC-TIP product. One standard deviation is given in brackets. In addition, the same variables are given for each site used for the validation of the model chain.

	effective single scattering albedo (VIS)	effective direction of scattering (VIS)	effective single albedo scattering (NIR)	effective direction of scattering (NIR)	true background albedo (VIS)	true background albedo (NIR)
<i>Pinus sylvestris</i> at NL-Loo	0.15 (0.03)	0.99 (0.02)	0.73 (0.04)	2.01 (0.05)	0.09 (0.04)	0.17 (0.08)
at EE-Jär	0.12	0.97	0.67	1.95	0.06	0.10
	0.12	0.96	0.67	1.93	0.08	0.14
<i>Fagus spp</i> at DE-Hai	0.15 (0.03)	0.99 (0.03)	0.74 (0.04)	2.05 (0.07)	0.13 (0.04)	0.25 (0.09)
at FR-Hes	0.13	0.97	0.74	2.07	0.16	0.29
	0.17	1.01	0.76	2.10	0.15	0.30
<i>Quercus robur</i> & <i>Q. petraea</i> at FR-Fon	0.18 (0.02)	1.02 (0.02)	0.76 (0.03)	2.09 (0.04)	0.15 (0.02)	0.28 (0.05)
	0.17	1.01	0.75	2.08	0.15	0.29

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Table 3. Data availability for site level validation. The symbol (*) indicates that for FR-Hes tree height was calculated from provided site-specific allometric relationship.

Site	2-way pyranometers	CHRIS/UAV spectrometer	Gap fraction	Tree position	DBH	Tree height	Crown radius	Crown length	LAI
DE-Hai	y	n	n	y	y	y	y	y	y
FR-Hes	y	n	n	n	y	y*	n	n	y
EE-Jar	n	y	y	y	y	y	y	y	y
FR-Fon	y	n	n	y	y	y	n	n	y
NL-Loo	y	n	n	y	y	y	n	n	y

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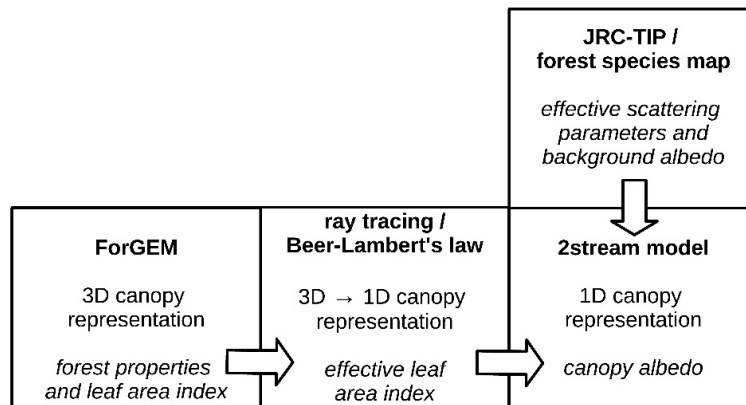


Fig. 1. Sketch of the model chain linking the forest gap-model, ray tracing, two-stream radiation transfer model and remote sensing based model parameters. Model output is given at the bottom of each box and the dimensions of the canopy representation are indicated by 3-D and 1-D for respectively a three-dimensional and one-dimensional representation of the forest canopy. The variables calculated by the single models are in italic. ForGEM = “Forest Genetics, Ecology and Management”, JRC-TIP = “Joint Research Centre Two-stream Inversion Package”.

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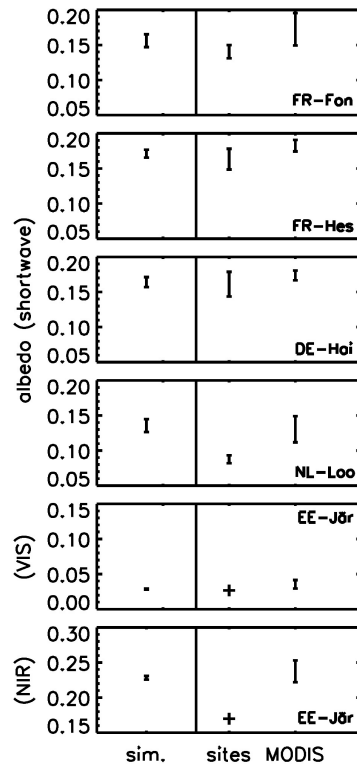


Fig. 2. Comparison of simulated June albedo for five different sites (left column) with in situ and satellite observations. The range of simulated albedo is shown for different crown allometries used to estimate crown volume from observed tree diameters. The range of in situ observations is taken from 2-hour window centred on local solar noon in June at each site during the years 1999 and 2010. EE-Jär is a single measurement (6 March 2013) but separated into visible and near-infrared albedo. The range of MODIS (2001-2010) observations are derived from nine pixels surrounding the tower. DE-Hai: beech, FR-Hes: beech, FR-Fon: oak, EE-Jär: pine, NL-Loo: pine.

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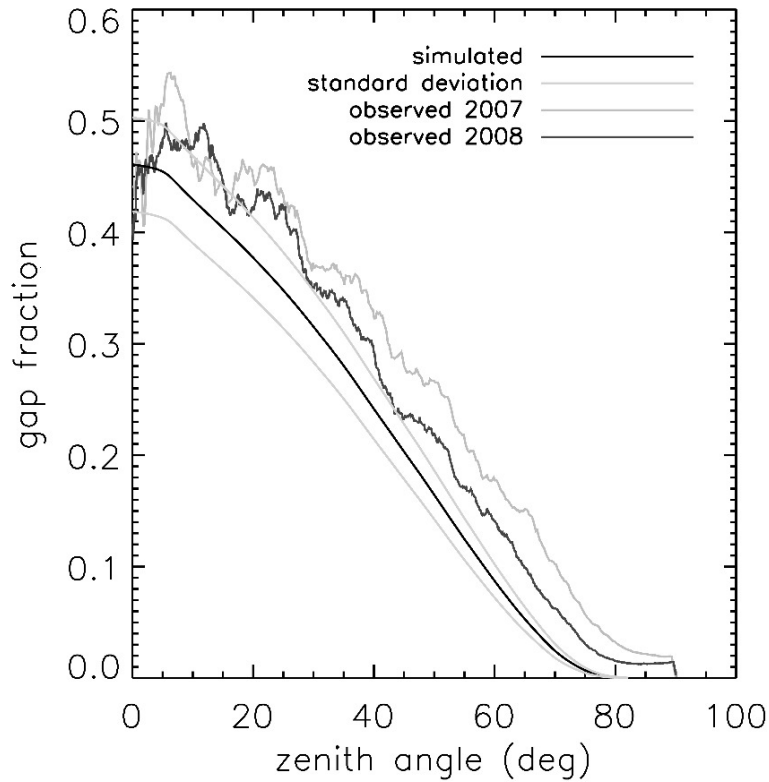


Fig. 3. Gap fraction measured in 2007 and 2008 at the EE-Jär pine forest compared to the modelled gap fraction.

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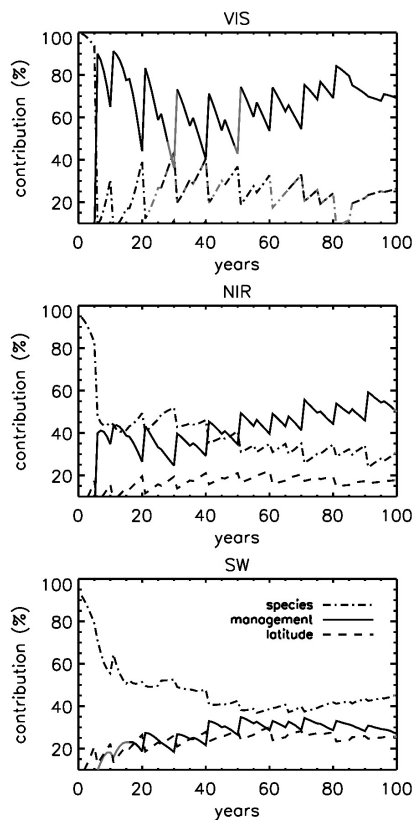


Fig. 4. Contribution (%) of the factors species, management, and latitude to the total variance of albedo (June) in visible (VIS), near-infrared (NIR) and the shortwave (SW) wavelength bands. Only contributions larger than 10% are shown. The black line segments indicate significant contributions ($p < 0.01$). Contributions of the interaction terms do not exceed 10%.

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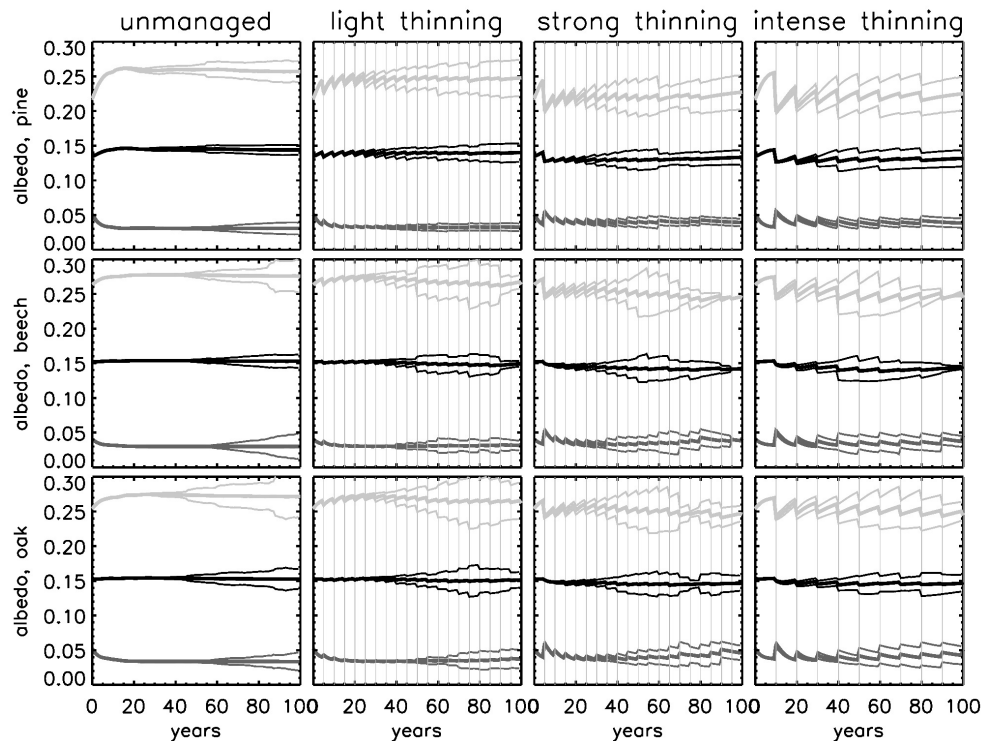


Fig. 5. Albedo (June) of three tree species and four management strategies at 50° N and with the maximum solar angle of 27.41° at summer solstice. The black line indicates shortwave, dark grey visible albedo, light grey near-infrared albedo. The thin lines represent one standard deviation of 25 simulations of 20 × 20 m forest samples.

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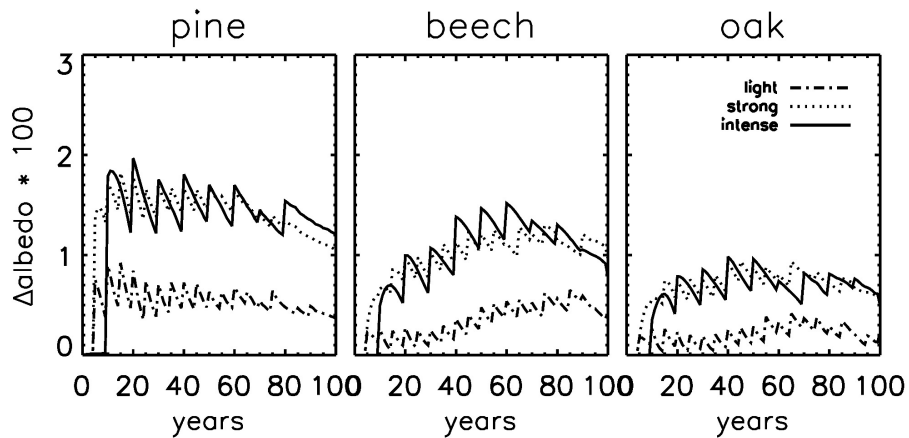


Fig. 6. Difference between shortwave albedo (June) of unmanaged forest and managed forest for 50° N. Note the albedo values are multiplied by 100 for better visibility.

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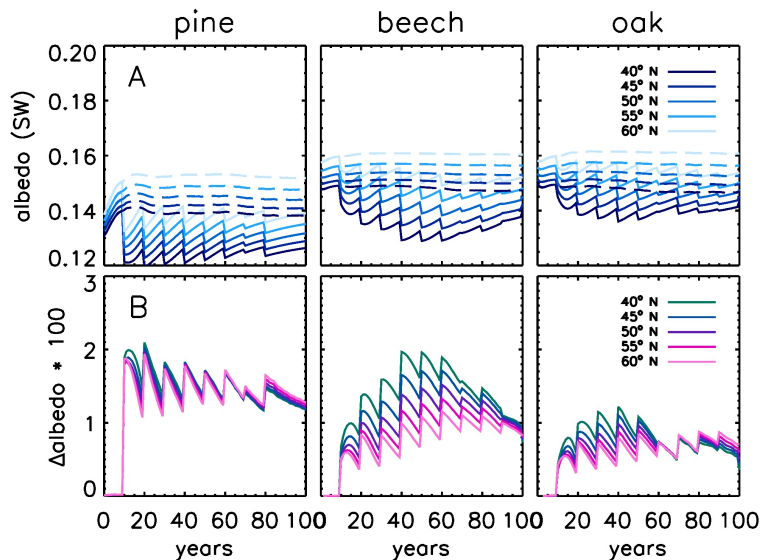


Fig. 7. Maximal difference between shortwave albedo (June) of unmanaged forest and managed forest occurs for the case of intensely managed forest. This difference is shown for each species and for the transect along 9° E stretching from 40° to 60° N in discrete 5° steps. The brighter the colour, the further north the albedo is calculated. Upper panel **(A)** shows shortwave albedo of unmanaged forests (staggered line) and intensely managed forest (smooth line). Lower panel **(B)** shows the difference between the two management strategies (unmanaged - intense). Note the albedo values are multiplied by 100 for better visibility.

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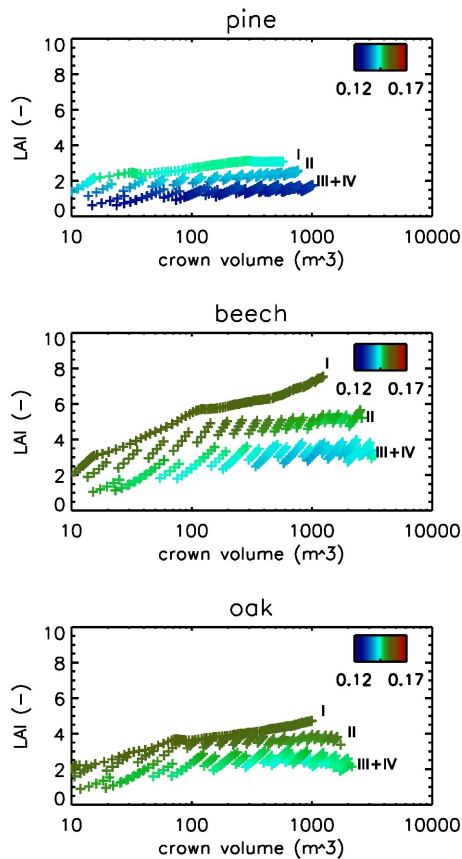


Fig. 8. Canopy albedo (June) as a function of stand crown volume (m^3) and stand LAI (-). The colour scale indicates the respective shortwave albedo value. For this analysis the results for all management strategies were pooled per tree species, the Roman numerals indicate the management strategy (see caption Table 1). Please note the logarithmic x-axis.

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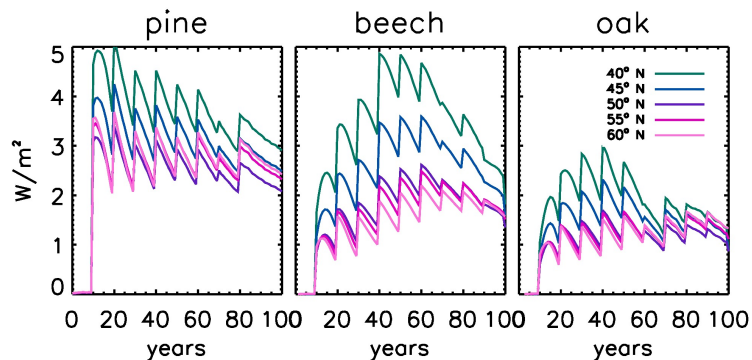


Fig. 9. Local radiative forcing for June calculated over a rotation for all three species resulting from the difference between unmanaged and intensely thinned forest for the transect at 9° E stretching from 40° to 60° N in discrete 5° steps.

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