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 cylinders, leaf mass, leaf area index (LAI) and the spatial position of all trees within the stand.

2.3 Canopy radiation transfer scheme

The complexity of radiation transfer makes it 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 adapted 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 (see Table 1) 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 thus expresses the amount of vegetation that a 1-D model requires to match the solar radiation attenuated by a 3-D model. Any change in the true LAI is reflected in the representation of effective LAI including information on changes in canopy structure.

The effective LAI was calculated by means of a "ray-tracing approach". For an incident single ray, the approach tests whether that ray encounters a tree and measures the distance it travels from the first contact with a canopy element 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 travelling within the canopy. For a given solar angle, the probability density function was combined with the crown density (LAI per crown volume; Bréda, 2003) to calculate the fraction of light reaching the forest floor without meeting a canopy element (Pinty et al., 2011a, 2011b). This fraction was then used as input for the inverted Beer–Lambert's law (see Eq. (25) in Pinty et al., 2004) to derive the effective LAI. This approach requires the explicit position of trees and their crown dimensions; these were retrieved from the ForGEM simulations mentioned above.

2.4 Parameters for the radiation transfer scheme

The following vegetation radiative properties are required to calculate the albedo from the effective LAI: 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 Moderate Resolution Imaging Spectroradiometer (MODIS, Schaaf et al., 2002) broadband visible and near-infrared white-sky surface albedo from 2001 to 2010 at 0.01 degree resolution. The parameters derived are equally suitable for calculating white-sky albedo and black-sky albedo.

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 combination of the wrong 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 or species groups over Europe at 1×1 km resolution. As this study considers only pure forest stands, to avoid signal contamination only pixels where a single species dominates (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.

The diversity of techniques to measure and model albedo has resulted in two 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 collimated 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. This so-called white-sky albedo is used for validation, assuming that isotropic incoming radiation prevails during European summer. 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 spectral band, it is mentioned in the text.