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 climate effects that follow a change in albedo (Anderson et al., 2011; Bala et al., 2007; Bathiany et al., 2010; Betts, 2000; Pielke et al., 1998; Schwaiger and Bird, 2010).

Finer-scale albedo effects, such as those of species diversity in the canopy, tree species and forest management, remain poorly documented. Although a body of literature linking forest albedo to forest thinning is emerging, process understanding is still fragmented, because these studies are limited to individual stands or single species and the observed stand-level relationships have not been explored on a regional or global scale. The site-level effect of forest thinning on albedo has been quantified for a handful of stands. For a pine forest in Arizona thinning resulted in a small increase in albedo (Dore et al., 2012). In contrast, a mid-rotation stand of loblolly pine in North Carolina showed lower average albedo compared to a recently established stand on a clear-cut site (Sun et al., 2010). The same effect was observed for a thinned pine forest in New Zealand (Kirschbaum et al., 2011). The first thinning of a managed Norway spruce stand in Finland was simulated to reduce the albedo by 10 %, whereas the subsequent thinning events had a smaller influence on 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).

Maximising forests' sequestration of atmospheric carbon dioxide through forest management, including species selection and stand thinning, is one of the key instruments proposed to mitigate climate change (UN, 1998). However, managing forests for carbon sequestration will at the same time affect the biophysical interaction with the atmosphere through changes in albedo, canopy roughness and evapotranspiration. Thus, before we can hope to mitigate climate change through forest management we must quantify and understand the full range of climate impacts through both biogeochemical and biophysical land–atmosphere interactions that forest management can control. Land surface models, including forest growth and management (Bellassen et al., 2010), are an ideal tool for analysing this effect on a larger scale. The radiation transfer schemes in today's models, however, are not suitable for simulating the effect of changes in canopy structure on albedo (Loew et al., 2013). Here, we present an approach that could be implemented in Earth system models to fill this gap in our knowledge.

We couple a tree-based forest gap model to a canopy radiation transfer model and use satellite-derived model parameters to determine which factor has the strongest effect on summertime canopy albedo: (1) site location and thereby different solar zenith angles, (2) tree species or (3) thinning strategies.

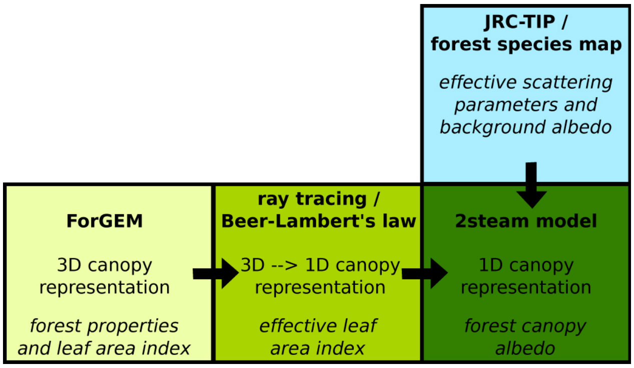

Fig. 1. Sketch of the model chain linking the forest gap-model, ray tracing, two-stream radiation transfer model and remote-sensing-based model parameters. Model output is given at the bottom of each box and the dimensions of the canopy representation are indicated by 3-D and 1-D for a three-dimensional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

2 Materials and methods

2.1 The modelling chain

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

2.2 Forest gap model (ForGEM)

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). Intermodel 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 strategy. Direct validation of the simulated canopy structure against observations has not yet been achieved due to the absence of sufficiently large observational data sets. 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