

Abstract

Since 70 % of global forests are managed and forests impact the global carbon cycle and the energy exchange with the overlying atmosphere, forest management has the potential to mitigate climate change. Yet, none of the land surface models used in Earth system models, and therefore none of today's predictions of future climate, account for the interactions between climate and forest management. We addressed this gap in modelling capability by developing and parametrizing a version of the land surface model ORCHIDEE to simulate the biogeochemical and biophysical effects of forest management. The most significant changes between the new branch called ORCHIDEE-CAN (SVN r2290) and the trunk version of ORCHIDEE (SVN r2243) are the allometric-based allocation of carbon to leaf, root, wood, fruit and reserve pools; the transmittance, absorbance and reflectance of radiation within the canopy; and the vertical discretisation of the energy budget calculations. In addition, conceptual changes towards a better process representation occurred for the interaction of radiation with snow, the hydraulic architecture of plants, the representation of forest management and a numerical solution for the photosynthesis formalism of Farquhar, von Caemmerer and Berry. For consistency reasons, these changes were extensively linked throughout the code. Parametrization was revisited after introducing twelve new parameter sets that represent specific tree species or genera rather than a group of unrelated species, as is the case in widely used plant functional types. Performance of the new model was compared against the trunk and validated against independent spatially explicit data for basal area, tree height, canopy structure, GPP, albedo and evapotranspiration over Europe. For all tested variables ORCHIDEE-CAN outperformed the trunk regarding its ability to reproduce large-scale spatial patterns as well as their inter-annual variability over Europe. Depending on the data stream, ORCHIDEE-CAN had a 67 to 92 % chance to reproduce the spatial and temporal variability of the validation data.

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1 Introduction

Forests play a particularly important role in the global carbon cycle. Forests store almost 50 % of the terrestrial organic carbon and 90 % of vegetation biomass (Dixon et al., 1994). Globally, 70 % of the forest is managed and the importance of management is still increasing both in relative and absolute terms. In densely populated regions, such as Europe, almost all forest is intensively managed by humans. Recently, forest management has become a top priority on the agenda of political negotiations to mitigate climate change. Because forest plantations may remove CO₂ from the atmosphere, harvested timber is a substitute for fossil fuel if used for energy production. Forest management thus has great potential for mitigating climate change, which was recognized in the United Nations Framework Convention on Climate Change and the Kyoto Protocol.

Forests not only influence the global carbon cycle, they also dramatically affect the water vapour and energy fluxes exchanged with the overlying atmosphere. It has been shown, for example, that the evapotranspiration of young plantations can be so great that the streamflow of neighbouring creeks is reduced by 50 % (Jackson et al., 2005). Modelling studies on the impact of forest plantations in regions that are snow-covered in winter suggest that because of their darkness (the so-called albedo), forest could increase regional temperature by up to four degrees (Betts, 2000; Bala et al., 2007; Davin et al., 2007; Zhao and Jackson, 2014). Management-related changes in the albedo, energy balance and water cycle of forests (Amiro et al., 2006a, b) are of the same magnitude as the differences between forests, grasslands and croplands (Luysaert et al., 2014). Moreover, changes in the water vapour and the energy exchange may offset the cooling effect obtained by managing forests as stronger sinks for atmospheric CO₂ (Pielke et al., 2002). Despite the key implications of forest management on the carbon-energy-water exchange there have been no integrated studies on the effects of forest management on the Earth's climate.

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Earth system models are the most advanced tools to predict future climate (Bonan, 2008). These models represent the interactions between the atmosphere and the surface beneath, with the surface formalized as a combination of open oceans, sea ice and land. For land, five classes are distinguished: glacier, lake, wetland, urban and vegetated. Vegetated surfaces are sub-divided in patches of different plant functional types. ORCHIDEE is the land surface component of the IPSL (Institut Pierre Simon Laplace) Earth System Model. Hence, by design, the ORCHIDEE model can be run coupled to the global circulation model LMDz. In this coupled set-up, the atmospheric conditions affect the land surface and the land surface, in turn, affects the atmospheric conditions. Coupled land-atmosphere models thus offer the possibility to quantify both the climatic effects of changes in the land surface and the effects of climate change on the land surface. The most advanced land-surface models used, for instance, in Earth System Models to predict climate changes (see the recent CMIP5 exercise), account for changes in vegetation cover but consider forests to be mature and ageless, e.g., JSBACH (Reick et al., 2013), CLM (Stöckli et al., 2008), MOSES (Cox et al., 1999), ORCHIDEE (Krinner et al., 2005) and LPJ-DVGM (Bonan et al., 2003). At present, none of the predictions of future climate thus account for the essential interactions between forest management and climate. This gap in modelling capability provides the motivation for further development of the land-surface model ORCHIDEE to realistically simulate both the biophysical and biogeochemical effects of forest management on the climate. The ORCHIDEE-CAN (short for ORCHIDEE-CANOPY) branch of the land surface model was specifically developed to quantify the climatic effects of forest management.

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2 Model overview

2.1 The Starting point: ORCHIDEE SVN r1170

The land surface model used for this study, ORCHIDEE, is based on two different modules (Krinner et al., 2005, their Fig. 2). The first module describes the fast processes such as the soil water budget and the exchanges of energy, water and CO₂ through photosynthesis between the atmosphere and the biosphere (Ducoudré et al., 1993; de Rosnay and Polcher, 1998). The second module simulates the carbon dynamics of the terrestrial biosphere and essentially represents processes as maintenance and growth respiration, carbon allocation, litter decomposition, soil carbon dynamics and phenology (Viovy and de Noblet-Ducoudré, 1997). The trunk version of ORCHIDEE describes global vegetation by 13 metaclasses (MTC) with a specific parameter set (one for bare soil, eight for forests, two for grasslands and two for croplands). Each MTC can be divided into a user-defined number of PFTs which can be characterised by at least one parameter value that differs from the parameter settings of the MTC. Parameters that are not given at the PFT-level are assigned the default value for the MTC to which the PFT belongs. By default none of the parameters are specified at the PFT-level, hence, MTCs and PFTs are the same for the standard ORCHIDEE trunk version. A concise description of the main processes in the ORCHIDEE-trunk version and a short motivation to change these modules in ORCHIDEE-CAN is given in Table 1.

Before running simulations, it is necessary to bring the soil carbon pools into equilibrium due to their slow fill rates, an approach known as model spin-up (Thornton and Rosenbloom, 2005; Xia et al., 2012). For a long time, spin-ups have been performed by brute force, i.e., running the model iteratively over a sufficiently long period which allows even the slowest carbon pool to reach equilibrium. This native approach is reliable but slow (in the case of ORCHIDEE it takes 3000 years) and thus comes with a large computational demand, often exceeding the computational cost of the simulation itself. Alternative spin-up methods calling only parts of the model, e.g., subsequent cycles of 10 years of only photosynthesis followed by 100 year cycles of only soil pro-

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cesses, have been used for ORCHIDEE to reduce the computational cost in the past. These approaches, however, tend to lead to instabilities in litter and carbon pools. In recent years, semi-analytical methods have been proposed as a cost-effective solution to the spin-up issue (Martin et al., 2007; Lardy et al., 2011; Xia et al., 2012). A matrix-sequence method has been implemented in ORCHIDEE following the approach used by the PaSim model (Lardy et al., 2011). The semi-analytical spin-up implemented in ORCHIDEE relies on algebraic methods to solve a linear system of equations describing the seven carbon pools separately for each PFT. Convergence of the method and thus equilibrium of the carbon pools is assumed to be reached when the variation of the passive carbon pool (which is the slowest) drops below a predefined threshold. The net biome production (NBP) is used as a second diagnostic criterion to confirm convergence. In order to optimize computing resources, the semi-analytical spin-up will stop before the end of the run once the convergence criteria are met. ORCHIDEE's implementation of the semi-analytical spin-up has been validated at regional and global scales against a native spin-up, and has been found to converge 12 to 20 times faster. The largest gains were realised in the tropics and the smallest gains in boreal climate.

2.2 Modifications between ORCHIDEE SVN r2243 and ORCHIDEE-CAN SVN r2290

One major overarching change in the ORCHIDEE-CAN branch is the increase of internal consistency within the model by adding connections between the different processes (see Fig. 1, red arrows). A more specific novelty is the introduction of circumference classes within forest PFTs, based on the work of Bellassen et al. (2010). For the temperate and boreal zone, tree height and crown diameter are calculated from allometric relationships of tree diameter that were parametrized based on the French, Spanish, Swedish and German forest inventory data and the observational data from Pretzsch, 2009). The circumference classes thus allow calculation of the social position of trees within the canopy which justifies applying an intra-tree competition rule (Deleuze et al., 2004) to account for the fact that trees with a dominant position in

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the canopy are more likely to intercept light than suppressed trees, and, therefore, contribute more to the stand level photosynthesis and biomass growth. To respect the competition rule of Deleuze et al. (2004), a new allocation scheme was developed based on the pipe model theory (Shinozaki et al., 1964) and its implementation by Sitch et al. (2003). The scheme allocates carbon to different biomass pools (leaves, fine roots, and sapwood) while respecting the differences in longevity and hydraulic conductivity between the pools. In addition to the biomass of the different pools, LAI, crown volume, crown density, stem diameter, stem height and stand density are calculated and now depend on accumulated growth. The new scheme allows for the removal of the parameter that caps the maximum LAI (see Table 1).

The calculation of tree dimensions (e.g., sapwood area and tree height) that respect the pipe theory supports making use of the hydraulic architecture of plants to calculate the plant water supply (Fig. 1, arrow 1), which is the amount of water a plant can transport from the soil to its stomata. The representation of the plant hydraulic architecture is based on the scheme of Hickler et al. (2006). The water supply is calculated as the ratio of the pressure difference between soil and leaves, and the total hydraulic resistance of the roots, leaves and sapwood, where the latter is increased when cavitation occurs. Species-specific parameter values were compiled from the literature. As the scheme makes use of the soil water potential, it requires the use of the 11 layer hydrology scheme of de Rosnay (2002) (see Table 1). When transpiration based on energy supply exceeds transpiration based on the water supply, the latter restricts stomatal conductance directly, which is a physiologically more realistic representation of drought stress than the reduction of $k_{V_{\text{cmax}}}$ done in the trunk (Flexas et al., 2006). In line with this approach, the drought stress factor used to trigger phenology and senescence is now calculated as the ratio between the transpiration based on water supply and transpiration based on atmospheric demand (Fig. 1, arrow 2).

The new allocation scheme also drastically changed the way forests are represented in the ORCHIDEE-CAN branch. Although the exact location of the canopies in the stand is not known, individual tree canopies are now spherical elements with their

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horizontal location following a Poisson distribution across the stand. Each PFT contains a user-defined number of model trees, each one corresponding to a circumference class. Model trees are replicated to give realistic stand densities. Following tree growth, canopy dimensions and stand density are updated (Fig. 1, arrow 3). This formulation results in a dynamic canopy structure that is exploited in other parts of the model, i.e., precipitation interception, transpiration, energy budget calculations, albedo (Fig. 1, arrow 4) and absorbed light for photosynthesis (Fig. 1, arrow 5). In the trunk version these processes are driven by the big-leaf canopy assumption. The introduction of an explicit canopy structure is thought to be a key development with respect to the objectives of the ORCHIDEE-CAN branch, i.e., quantifying the biogeochemical and biophysical effects of forest management on atmospheric climate.

The radiation transfer scheme at the land surface benefits from the introduction of canopy structure. The trunk version of ORCHIDEE prescribes the vegetation albedo solely as a function of LAI. In the ORCHIDEE-CAN branch each tree canopy is assumed to be composed of uniformly distributed single scatterers. Following the assumption of a Poisson distribution of the trees on the land surface, the model of Haverd et al. (2012) calculates the transmission probability of light to any given vertical point in the forest. This transmission probability is then used to calculate an effective LAI, which is a statistical description of the vertical distribution of leaf mass that accounts for stand density and horizontal tree distribution. The complexity and computational costs are largely reduced by using the effective LAI in combination with the 1-D two stream radiation transfer model of Pinty et al. (2006) rather than resolving a full 3-D canopy model. By using the effective LAI, the 1-D model reproduces the radiative fluxes of the 3-D model. The approach of the two stream radiation transfer model was extended for a multi-layer canopy (McGrath et al., 2014). The scattering parameters and the background albedo (i.e. the albedo of the surface below the dominant tree canopy) for the two stream radiation transfer model were extracted from the Joint Research Centre Two-stream Inversion Package (JRC-TIP) remote sensing product (see Sect. 4.7). This approach produces fluxes of the light absorbed, transmitted, and re-

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flected by the canopy at vertically discretized levels, which are then used for the energy budget (Fig. 1, arrow 6) and photosynthesis calculations (Fig. 1, arrow 5).

The canopy radiative transfer scheme of (Pinty et al., 2006) separates the calculation of the fluxes resulting from downwelling direct and diffuse light, with different scattering parameters available for near-infrared (NIR) and visible (VIS) light sources. The snow albedo scheme in the trunk does not distinguish between these two shortwave bands. Therefore, the snow albedo scheme of the Biosphere-Atmosphere Transfer Scheme (BATS) for the Community Climate Model (Dickinson et al., 1986) was incorporated into the ORCHIDEE-CAN branch, since it distinguishes between the NIR and VIS radiation. The radiation scheme of Pinty et al. (2006) requires snow to be put on the soil below the tree canopy instead of on the canopy itself. The calculation of the snow coverage of a PFT therefore had to be revised according to the scheme of Yang et al. (1997), which allows for snow to completely cover the ground at depths greater than 0.2 m. The parameter values of Yang et al. (1997) were used in the ORCHIDEE-CAN branch.

The ORCHIDEE-CAN branch differs from any other land surface model by the inclusion of a newly developed multi-layer energy budget. There are now subcanopy wind, temperature, humidity, longwave radiation and aerodynamic resistance profiles, in addition to a check of energy closure at all levels. The energy budget represents an implementation of some of the characteristics of detailed single site, iterative canopy models (e.g., Baldocchi, 1988; Ogee et al., 2003) within a system that is coupled implicitly to the atmosphere. Contrary to the trunk version of ORCHIDEE (see Table 1), the new approach generates a leaf temperature, using the same vegetation and radiation profile generated in the radiation scheme above, which will be fully available when parametrisation of the scheme has been completed across test sites corresponding to the species within the model. As with the trunk version, the new energy budget is calculated implicitly (Polcher et al., 1998; Best et al., 2004), so as to allow for, given the 15 min time-step, a computationally efficient and stable coupling to the atmospheric model LMDz. Parameters were derived by optimizing the model against observations from short-term field campaigns. The new scheme may also be reduced to the existing

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single layer case so as to provide a means of comparison and compatibility with the trunk version of ORCHIDEE.

The combined use of the new energy budget and the hydraulic architecture of plants required changes to the calculation of the stomatal conductance and photosynthesis (Fig. 1, arrow 7). When water supply limits transpiration, stomatal conductance is reduced and photosynthesis needs to be recalculated. Given that photosynthesis is among the computational bottlenecks of the model, the semi-analytical procedure as available in previous trunk versions is replaced by an adjusted implementation of the analytical photosynthesis scheme of Yin and Struik (2009), which is also implemented in the latest ORCHIDEE-trunk version. In addition to an analytical solution for photosynthesis the scheme includes a modified Arrhenius function for the temperature dependence that accounts for a decrease of $k_{V_{cmax}}$ and $k_{J_{max}}$ at high temperatures and a temperature dependent $k_{J_{max}/V_{cmax}}$ ratio (Kattge and Knorr, 2007). The temperature response of $k_{V_{cmax}}$ and $k_{J_{max}}$ was parametrized with values from reanalysed data in literature (Kattge and Knorr, 2007), whereas $k_{V_{cmax}}$ and $k_{J_{max}}$ at a reference temperature of 25 °C were derived from observed species-specific values in the TRY database (Kattge et al., 2011). As the amount of absorbed light varies with height (or canopy depth), the absorbed light computed from the albedo routines is now directly used in the photosynthesis scheme resulting in full consistency between the top of the canopy albedo and absorption. This new approach replaces the old scheme which used multiple levels based on the leaf area index, not the physical height.

ORCHIDEE-CAN incorporates a systematic mass balance closure for carbon cycling to assure that carbon is not getting created or destroyed during the simulation. Hence, budget closure is now consistently checked for water, carbon and energy throughout the model.

The trunk uses 13 plant functional types (PFT) to represent vegetation globally: one PFT for bare soil, eight for forests, two for grasslands, and two for croplands. The ORCHIDEE-CAN branch makes use of the externalization of the PFT-dependent parameters by adding 12 parameter sets that represent the main European tree species.

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Species parameters were extracted from a wide range of sources including original observations, large databases, primary research and remote sensing products (see Sect. 4). The use of age classes is introduced through externalization of the PFT parameters as well. Age classes are used during land cover change and forest management to simulate the regrowth of a forest. Following a land cover change, biomass and soil carbon pools (but not soil water columns) are mixed. The number of age classes is user defined. Contrary to typical age classes, the boundaries are determined by the tree diameter rather than the age of the trees.

Finally, the forest management strategies in the ORCHIDEE-CAN branch were refined from the original forest management branch (Bellassen et al., 2010). Self-thinning was activated for all forests regardless of human management, contrary to the original FM branch. The new default management strategy thus has no human intervention but includes self-thinning, which replaces the fixed 40 year turnover time for woody biomass. Three management strategies with human intervention have been implemented: (1) “High stands”, in which human intervention is restricted to thinning operations based on stand density and diameter, with occasional clearcuts. Aboveground stems are harvested during operations, while branches and belowground biomass are left to litter. (2) “Coppices” involve two kinds of cuts. The first coppice cut is based on stem diameter and the aboveground woody biomass is harvested whereas the belowground biomass is left living. From this belowground biomass new shoots sprout, which increases the number of aboveground stems. In subsequent cuts the amount of shoots is not increased, although all aboveground wood biomass is still harvested. (3) “Short rotation coppices”, where rotation periods are based on age and are generally very short (3–6 years). The different management strategies can occur with or without litter raking, which reduces the litter pools and has a longterm effect on soil carbon (Gimmi et al., 2012). All management types are parametrized based on forest inventory data, yield tables and guidelines for forest management. The inclusion of forest management resulted in two additional carbon pools, branches and coarse roots (i.e., aboveground and belowground woody biomass) and therefore required an extension to the semi-

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analytical spin-up method (see Sect. 2.1). The semi-analytical spin-up is now run for nine C pools.

3 Description of the developments

3.1 Allocation

5 Following bud burst, photosynthesis produces carbon that is added to the labile carbon pool. Labile carbon is used to sustain the maintenance respiration flux (F_{rm}), which is the carbon cost to keep existing tissue alive (Amthor, 1984). Maintenance respiration for the whole plant is calculated by summing maintenance respiration of the different plant compartments, which is a function of the nitrogen concentration of the tissue
10 (Zaehle and Friend, 2010, their Eqs. 6 and 7) and subtracted from the whole-plant labile pool (up to a maximum of 80 % of the labile pool).

The remaining labile carbon pool is split into an active and none-active pool. The size of the active pool is calculated as a function of plant phenology and temperature and was formalized following Ryan (1991); Sitch et al. (2003); Zaehle and Friend (2010).
15 The remaining non-active pool is used to restore the labile and carbohydrate reserves pools according to the rules proposed in Zaehle and Friend (2010). The labile pool is limited to 1 % of the plant biomass or 10 times the actual daily photosynthesis. Any excess carbon is transferred to the non-respiring carbohydrate reserve pool. The carbohydrate reserve pool is capped to reflect limited starch accumulation in plants, but
20 carbon can move freely between the two reserve pools. After accounting for growth respiration (F_{rg}), i.e., the cost for producing new tissue excluding the carbon required to build the tissue itself (Amthor, 1984), the total allocatable C used for plant growth is obtained (M_{totinc}).

25 New biomass is allocated to leaves, roots, sapwood, heartwood, and fruits. Allocation to leaves, roots and wood respects the pipe model theory (Shinozaki et al., 1964) and thus assumes that producing one unit of leaf mass requires a proportional amount

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of sapwood to transport water from the roots to the leaves as well as a proportional fraction of roots to take up the water from the soil. The scaling parameter between leaf and sapwood mass is derived from:

$$d_l = k_{ls} \times m_w \times d_s \quad (1)$$

5 where d_l is the one-sided leaf area of an individual plant, d_s is the sapwood area of an individual plant, k_{ls} a parameter linking leaf area to sapwood area and, m_w is the water stress as defined in Sect. 3.2. Alternatively, leaf area can be written as a function of leaf mass (M_l) and the specific leaf area (k_{sla}):

$$d_l = M_l \times k_{sla} \quad (2)$$

10 Sapwood mass M_s can be calculated from the sapwood area d_s as follows:

$$M_s = d_s \times d_h \times k_{\rho s} \quad (3)$$

where d_h is the tree height and $k_{\rho s}$ is the sapwood density. Following substitution of Eqs. (2) and (3) into Eq. (1), leaf mass can be written as a function of sapwood mass:

$$M_l = (M_s \times f_{KF}) / d_h \quad (4)$$

15 where,

$$f_{KF} = (k_{ls} \times m_w) / (k_{sla} \times k_{\rho s}) \quad (5)$$

where, k_{ls} is calculated as a function of the gap fraction as supported by site-level observations (Simonin et al., 2006):

$$k_{ls} = k_{lsmin} + f_{Pgap,trees} \times (k_{lsmax} - k_{lsmin}) \quad (6)$$

20 k_{lsmin} is the minimum observed leaf area to sapwood area ratio, k_{lsmax} is the maximum observed leaf area to sapwood area ratio and $f_{Pgap,trees}$ is the actual gap fraction. By

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boreal, temperate and Mediterranean climate zones and validation focused on Europe. Parametrization of the tropical zone is subject of a follow-up study.

4.1 Introducing twelve new PFTs

5 Similar to the ORCHIDEE trunk, the ORCHIDEE-CAN branch distinguishes 13 meta-classes (MTC) for vegetation. Outside Europe the original MTC classification of ORCHIDEE was kept, while inside Europe 12 new parameter sets representing the main European tree species were added. The default vegetation distribution map in ORCHIDEE, i.e., Olson et al. (1983), was replaced by an up-to-date global MTC map which has been produced using the ESA CCI ECV Land Cover map (<http://www.esa-landcover-cci.org/>) (Poulter et al., 2014). The mapping from land cover to MTC basically followed Poulter et al. (2011), although Table 5 (the “cross-walking” table) has been updated following discussions with the LC_CCI team at Universite Catholique de Louvain. For the European domain, the global MTC distribution was overlaid by a tree species distribution map (Brus et al., 2012).

15 This study focusses on tree species with a coverage of more than 2% in Europe, yielding seven species groups covering in total 78.8% of the European forest area: *Betula sp.*, *Fagus sylvatica*, *Pinus sylvestris*, *Picea sp.*, *Pinus pinaster*, *Quercus ilex* and a group combining *Quercus robur* and *Quercus petraea*. For *Pinus sylvestris*, *Picea sp.* and *Betula sp.* An additional distinction between boreal and temperate forest was made for the species map and parametrization: trees located in Norway, Sweden and Finland were considered boreal, while trees growing at lower latitudes were categorized as temperate. Given the potential role of tree species of the Salicaceae genus in short rotation coppice management, a separate PFT was parametrized for *Populus sp.* Furthermore, to improve the parametrization of the MTC of boreal needleleaved deciduous forest, observations from *Larix sp.* were included when possible.

20 For these 12 forest species, 12 new PFTs were created with each PFT belonging to a single MTC (see Tables 4, 5, 6) Almost 79% of the European forest was parametrized at the species level. The remaining 21% was reclassified in four residual groups, i.e.,

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a temperate and boreal needleleaf evergreen and a temperate and boreal broadleaved residual group. For use outside Europe, the original MTC classification of ORCHIDEE was kept. The parameters of the residual groups and MTCs are the mean of the parameters of the species-level PFTs that are in the MTC, with the exception of albedo parameters that could be extracted from remote sensing products.

5 Finally, separate PFTs were introduced for boreal grasses and croplands, which allowed for a boreal parametrization of phenology, senescence and growth. This approach, which distinguishes a total of 28 PFTs, allows a higher taxonomic resolution over Europe, better defines forest types compared to the more general MTC approach and facilitates the use of observations to derive parameters.

4.2 Sources of parameter values

Species parameters were extracted from a wide range of sources including original observations (i.e. POPFULL), large databases (national forest inventories, TRY), primary research reports and remote sensing products (JRC-TIP Pinty et al., 2011a, b). 15 The mean values and standard deviations were calculated without weighting. For most parameters, the mean values were used as the parameter value in ORCHIDEE without further processing. Using the mean parameter estimates at the species level avoids hidden model-tuning and largely reduces the likelihood that simulation results are biased by hidden calibration owing to a poor taxonomic definition of PFTs (Scheiter et al., 2013). The phenology-related parameters of the deciduous MTCs were optimised by MacBean et al. (2014), using MODIS-derived NDVI data normalised to model fAPAR over the 2000–2008 time period.

4.3 Selection of parameters for optimization

25 The vegetation structure simulated by the ORCHIDEE-CAN branch is sensitive to the value of k_{ls} which describes the ratio between the leaf and sapwood area of an individual tree. The available observations show a wide range within and across species.

observations were used to fit the species-specific parameter values (Table 4). Parameter values for MTCs were derived by grouping the species into MTCs and fitting the parameters. No observations were available for the boreal zone and temperate evergreen deciduous species. For the boreal species a subset of the temperate observations (*Pinus sylvestris*, *Picea abies* and *Betula pendula*) was used, i.e., the relationship between d_{csa} and d_{dbh} was fitted to all available data for *Pinus sylvestris*. Next, all observations with a d_{csa} that falls below the predicted d_{csa} were selected as considered to represent a boreal subset. Given the importance of snow pressure on crown structure, selecting observations with sub average d_{csa} is justifiable as a first approximation. Subsequently, the parameters were fitted to this subset of data. For *Quercus ilex* no data were available and parameters were tuned such that the crown diameter was 0.85 m less than the tree height.

4.7 Multi-layer two-way albedo for tall canopies

The radiation transfer scheme makes use of parameters describing leaf and background properties, i.e., leaf single scattering and preferred scattering direction (for both visible (VIS) and near-infrared (NIR) wavelengths) and the so-called background albedo or 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, b). This is a software package (Pinty et al., 2007) which inverts a 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 1 km resolution (Pinty et al., 2011a). The inverse procedure implemented in the JRC-TIP is shown to be robust, reliable, and compliant with large-scale processing requirements (Pinty et al., 2011a). Furthermore, this package ensures the physical consistency between sets of observations, the two-stream model parameters, and radiation fluxes.

Only parameter values for which the posterior standard deviation of the probability density functions were significantly smaller than the prior standard deviation were selected from the JRC-TIP since this condition ensures statistically significant values.

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Species and MTC specific values were derived from JRC-TIP by performing a multiple regression (Table 6). This method determines, in an objective way, how the fractions of each MTC or species explain the JRC-TIP parameter. The multiple regression was performed separately for the six parameters: the single scattering of leaves (for both VIS and NIR), the scattering direction of leaves (VIS and NIR) and the background albedo (VIS and NIR). Each JRC-TIP parameter was used as the dependent variable and the independent variables consisted of the fractions of each MTC (Poulter et al., 2014) or species (Brus et al., 2012). These fractions were used to find a linear function that best predicted each JRC-TIP parameter. The corresponding slope of a regression of each MTC or species fraction gives the MTC or species dependent JRC-TIP value. The multiple regression was performed without an intercept. To avoid pollution by the seasonal cycle, the multiple regression was applied only for the pixels of the Northern Hemisphere. Only pixels that were less than 10 % covered by non-vegetative fractions were selected for the analysis and only significant results following an F-test and positive r^2 values were selected.

4.8 Analytical solution for photosynthesis

Three originally MTC-specific photosynthetic parameters (k_{Vcmax} , k_{Jmax} and k_{sla}) were derived at the species level by obtaining weighted site means for each species from the global leaf trait database TRY (Kattge et al., 2011) and additionally from Medlyn et al. (2002). Only k_{Vcmax} and k_{Jmax} standardized to a common formulation and parametrization of the photosynthesis model by (Farquhar et al., 1980) were used. Most k_{Vcmax} and k_{Jmax} values in the TRY database had already been standardized to a reference temperature of 25 °C (Kattge and Knorr, 2007). Subsequently, a species-specific $k_{\text{Jmax,opt}}/k_{\text{Vcmax,opt}}$ ratio was calculated from the records which included both $k_{\text{Vcmax,opt}}$ and $k_{\text{Jmax,opt}}$ measurements. From this ratio, which was within a range of 1.91–2.47 for each species, $k_{\text{Jmax,opt}}$ was calculated for records which originally only included k_{Vcmax} . Only geo-referenced observations within Europe were used and the distinction between boreal and temperate forest was made similar to the species map.

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5 Validation

ORCHIDEE-CAN is designed as the land surface model to be coupled to the atmospheric model LMDz. As such future applications of ORCHIDEE-CAN are expected to be regional to global in the spatial domain and to span several years in the temporal domain. Given its anticipated uses, the ability of the model to reproduce large-scale spatial patterns as well as their inter-annual variability is essential. The first applications of the model, both offline and coupled to the atmosphere, will focus on Europe. The validation, therefore, reports performance indices both over Europe as over eight separate regions within Europe (Bellprat et al., 2012). These eight regions, which partially overlap, are defined after Bellprat et al. (2012). Furthermore, the performance indices are calculated for winter, spring, summer and autumn and thus allow to evaluate the capacity of the model to reproduce observed annual cycles.

In addition to the root mean square error, a land performance index (LPI) based on the principles laid out for the Climate Performance Index (Murphy et al., 2004, their SI) was also calculated. LPI normalizes the root of the squared differences between the simulations and observations by the observed spatial and temporal variance. The LPI was used to estimate the likelihood that the simulated variable belongs to the same population as the observed variable, defined as $\exp(-0.5LPI^2)$. An LPI equal to 1 indicates that the model correctly reproduces the mean observed value and implies a likelihood of 61 % (Murphy et al., 2004) that the simulations and observations come from the same population. Similarly, an LPI of 2 reduces this likelihood to 13 %. An LPI of less than 0.32 has a likelihood of more than 95 % and therefore indicates a statistically significant result.

While developing ORCHIDEE-CAN, the numerical approaches that added functionality to the code were selected on the basis of their performance at the site-level (see below). Rather than running the same site-level tests for our implementation, we performed a complementary large-scale validation. The strength of our approach lies not in the details, as is the case for site-level validation, but in its width by simultaneously

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testing model performance for structural variables such as basal area (de Rigo et al., 2014), canopy structure (Pinty et al., 2011a) and canopy height (Simard et al., 2011), biogeochemical fluxes such as GPP (Jung et al., 2011), biophysical fluxes such as albedo (Schaaf et al., 2002) and fluxes at the interface of biogeochemistry and biophysics such as evapotranspiration (Jung et al., 2011). The selection of variables was limited by the availability of spatially explicit data-derived products for Europe.

For the validation, both the trunk and ORCHIDEE-CAN branch were run from 1850 to 1900 using CRU-NCEP climate forcing from 1901–1950 at 0.5° resolution. From 1901 until 2012, the corresponding CRU-NCEP forcing data for each year were used. Both versions used the 11-layer soil hydrology, the single-layer energy budget and the same land cover map (Poulter et al., 2014). Given that no European-wide, spatially explicit and data-derived products were found for the validation of the net carbon flux, there was no need for a carbon spin-up. For the ORCHIDEE-CAN branch, the observed tree height and basal area were compared against the simulation values at the end of 2010 (the trunk does not simulate these variables). For both the trunk and the ORCHIDEE-CAN branch, the observed GPP, evapotranspiration, effective LAI and VIS and NIR albedos were compared against monthly means between 2001 and 2010.

5.1 Allocation

In ORCHIDEE-CAN, functional relationships which vary by species and light stress are used to allocate carbon among the fine roots, foliage and sapwood. The allocation scheme largely follows Zaehle and Friend (2010), who in turn was inspired by Sitch et al. (2003). Approaches simulating allocation based on functional relationships were found to outcompete allocation schemes based on constant fractions or resource limitation (De Kauwe et al., 2014). The ability of these schemes to reproduce foliage, fine root and sapwood reported in large observational data sets (for example, Luysaert et al., 2007) demonstrates that these schemes capture the main observed features (Zaehle and Friend, 2010). In addition, allocation schemes making use of functional relationships were also capable of simulating the observed effect of elevated CO₂ on

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two mature forest ecosystems (De Kauwe et al., 2014). Despite these successes, the schemes were reported to be sensitive to their parametrization. Differences in parameters were reported to result in substantial differences in the simulated allocation. The parameters for the functional relationships used in ORCHIDEE-CAN are given in Table 4. The main conceptual difference between the allocation scheme by Zaehle and Friend (2010) and ORCHIDEE-CAN is that the latter was designed to simulate one or more diameter classes.

Given that photosynthesis is still calculated at the stand level (and thus not at the tree level) the allocation rule of Deleuze et al. (2004) was integrated in the functional allocation scheme to account for light and resource competition within a stand (see Sect. 5.6). Where the functional relationships are used to simulate carbon allocation within an individual tree of a given diameter, the rule of Deleuze and Dhote allocates carbon across the different diameter classes. The allocation rule which models the radial increment for individual trees in pure even-aged stands was successfully tested for Norway spruce and Douglas fir stands in France (Deleuze et al., 2004). A similar approach for modelling radial increment has already been implemented in a version close to the trunk of ORCHIDEE (Bellassen et al., 2010) and was able to successfully simulate stand characteristics such as height, basal area and stand diameter (Bellassen et al., 2011). This previous implementation differs from the current implementation in its time resolution (which is now daily instead of yearly), its analytical solution and the underlying allocation scheme (which is now based on functional relationships instead of resource limitation).

The aforementioned studies performed a detailed validation of the two approaches dealing with carbon allocation, which were combined in ORCHIDEE-CAN. Complementary to these studies we performed a European-wide validation of our implementation and parametrization of these well-tested schemes against a remote-sensing based map of tree height (Simard et al., 2011), upscaled eddy-covariance observations for GPP (Jung et al., 2011) and a map of basal area based on national forest inventory data (de Rigo et al., 2014). The model's ability to reproduce GPP is thought to reflect

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its capacity to simulate the foliage biomass, a correct simulation of height reflects the model's capacity to simulate aboveground woody biomass and its capacity to reproduce observed basal areas suggest that the interaction of stand density and individual tree diameter are well-captured.

The new implementation and parametrization of the within-tree and within-stand allocation schemes were found to have an 91, 68 and 72 % chance that the simulations reproduced the observations for GPP, tree height and basal area for Europe, respectively (Table 7). Given that basal area and height are not available from the trunk version of ORCHIDEE, we could not compare the performance of model versions in this respect. With respect to GPP, the ORCHIDEE-CAN branch was found to outperform the trunk by 12 % and thus increased the likelihood that ORCHIDEE-CAN is an unbiased simulator of the spatial and temporal variability of GPP from 79 to 91 %. Improved performance of the ORCHIDEE-CAN branch compared to the trunk is observed for all regions in summer where the RMSE of GPP was halved from 2.5–5 to 1–2 gCm⁻² day⁻¹ (Figs. 2 and 3).

Although part of the high likelihood could be due to the fact that the observed GPP was upscaled making use of similar climatologies being used as the forcings of the models, this circularity could neither have contributed to the improved performance between the trunk and the ORCHIDEE-CAN branch nor to the decrease in RMSE. The improvements are thought to be due to structural changes to the model such as allocation, hydraulic architecture and canopy structure as well as to the use of more consistent parametrization as the ORCHIDEE-CAN branch makes use of tree species rather than plant functional types.

5.2 Plant water supply

Our implementation of plant hydraulic architecture was largely based on the scheme of Hickler et al. (2006), which was tested globally and at site level. Global simulation results for actual evapotranspiration were found to reproduce available data (Baumgartner and Reichel, 1975; Henning, 1989). At the site level, the model agreed well

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tion in addition to the low RMSE (Fig. 2) are expected to be propagated in the performance of the energy budget.

5.6 Forest management strategies

Model comparison has previously demonstrated that explicitly treating thinning processes is essential to reproduce local and large scale biomass observations (Wolf et al., 2011). This finding justifies the implementation of generic approaches to forest management despite the difficulties associated with defining and quantifying forest management and its intensity (Schall and Ammer, 2013). Although the use of so-called naturalness indices, in which the current state of the forest is referenced against the potential state of the forest, has been criticised because of difficulties in defining the potential state of the forest (Schall and Ammer, 2013), such approaches were demonstrated to correctly rank different management strategies according to their intensity (Luyssaert et al., 2011).

Naturalness indices making use of only diameter and stand density or the so-called Relative Density Index (RDI) have been previously implemented at the stand-level (Fortin et al., 2012) and as well as in large scale models (Bellassen et al., 2010). This approach was shown to successfully reproduce the biomass changes during the life cycle of a forest (Bellassen et al., 2011; Fortin et al., 2012). The implementation of a forestry model based on the relative density index was reported to perform better than simple statistical models for stand-level variables such as stand density, basal area, standing volume and height (Bellassen et al., 2011). Although the performance of the model was reported as less satisfying for tree-level variables, the approach is nevertheless considered reliable to model the effects of forest management on biomass stocks of forests across a range of scales from plot to country (Bellassen et al., 2011).

The forestry model implemented in ORCHIDEE-CAN is based on the RDI approach by Bellassen et al. (2010). We complemented earlier validation of such an approach over France (Bellassen et al., 2011) by a new European-wide validation for basal area. At the European scale we verified the simulated basal area and height against ob-

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served basal area from national forest inventories (de Rigo et al., 2014) and height from remote-sensing (Simard et al., 2011). With an RMSE of 3–7 for height and 7–15 for BA, and a chance of, respectively, 68 and 72 % to reproduce the data at the European scale (Table 7), our model is capable of correctly simulating the mean height and basal area but fails to capture much of the spatial variability (temporal variability was not considered because the data products were only available for one time period). This finding could be due to the simulation protocol that started in 1850 with 2 to 3 m tall trees all over Europe. A longer simulation accounting for the major historical changes in forest management such as the reforestation in the 1700 s following an all time low in the European forest cover, the start of high stand management at the expense of coppicing in the early 1800s, and the reforestation programs following World War II (Farrell et al., 2000) is expected to improve the spatial variability in tree height and basal area. Regional deviations such as those observed in the Iberian Peninsula or over the entire Mediterranean (thus including part of the Iberian Peninsula) may be due to the lack of shrubs in the land cover map and parametrization of the ORCHIDEE-CAN branch. Therefore the models simulates a higher stand density and higher basal area for regions where in reality shrubs occur.

The parametrization of the forestry module strongly depends on the national forest inventories from Spain, France, Germany and Sweden. Therefore verification against the same data contains little information about the model quality. Nevertheless, no time-dependent relationships were used in the ORCHIDEE-CAN branch thus the model's capacity to reproduce the relationship between basal area and stand age, diameter and stand age or wood volume and stand age could be considered as largely independent test of the model quality. These tests were performed over 8 bioclimatic regions of France and the ORCHIDEE-CAN branch was found to largely capture the time dependencies of basal area, diameter and wood volume (not shown).

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Table 2. Continued.

Symbol in text	Unit	Symbol in ORCHIDEE-CAN	Description
d_s	m^{-2}	–	Sapwood area of an individual plant
d_{hinc}	m	delta_height	Height increment
d_{dbh}	m	dia	Plant diameter
d_{ba}	$m^2 plant^{-1}$	ba	Basal area
d_{bainc}	$m^2 plant^{-1}$	delta_ba	Basal area increment
d_{circ}	m	circ	Circumference of an individual plant
d_{ind}	trees	n_circ_class	Number of trees in diameter class /
d_c	m^2	crown_shadow_h	Projected area of an opaque tree crown
d_{csa}	m^2	csa_sap	Projected crown surface area
d_{LAI}	$m^2 m_{ground}^{-2}$	–	Leaf area index
d_{LAIeff}	–	laieff	Effective leaf area index
$d_{LAIabove}$	–	lai_sum	Sum of the LAI of all levels above the current level
$d_{A,i}$	m^2	–	Cross-sectional area of vegetation level "i"
$d_{h,i}$	m	delta_h	Vegetation height of level "i"
$d_{V,i}$	m^3	–	Volume of vegetation level "i"
d_{rd}	–	root_dens	Root density
d_j	$ind m^2$	–	Inverse of the individual plant density
p_{delta}	MPa	delta_P	Pressure difference between leaves and soil
p_{usr}	MPa	psi_soilroot	Bulk soil water potential in the rooting zone
p_{us}	MPa	psi_soil	Soil water potential for each soil layer
R_r	$MPa s m^{-3}$	R_root	Hydraulic resistance of roots
R_{sap}	$MPa s m^{-3}$	R_sap	Hydraulic resistance of sapwood
R_l	$MPa s m^{-3}$	R_leaf	Hydraulic resistance of leaves
R_{temp}	$MPa s m^{-3}$	–	Hydraulic resistance of roots, sapwood or leaves adjusted for temperature
$R_{a,i}$	$s m^{-1}$	big_r	Aerodynamic resistance of vegetation at level "i" in the canopy
$R_{s,i}$	$s m^{-1}$	big_r_prime	Stomatal resistance of vegetation at level "i" in the canopy

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Table 2. Continued.

Symbol in text	Unit	Symbol in ORCHIDEE-CAN	Description
f_{Pwc}	–	Pwc_h	Porosity of a tree crown
f_{Pgap}^{trees}	–	PgapL	Gap probability for trees
f_{Pgap}^{gr}	–	PgapL	Gap probability for grasses and crops
f_{Pgap}^{bs}	–	PgapL	Gap probability for bare soil
f_{mort}	–	mortality	Mortality fraction per circumference class
f_{KF}	–	KF	Leaf allocation factor
f_{LF}	–	LF	Root allocation factor
f_{γ}	–	gamma	Slope of the intra-specific competition
f_s	m	s	Slope of linearised relationship between height and basal area
f_{rl}	–	leaf_reflectance	Reflectance of a single leaf
f_{tl}	–	leaf_transmittance	Transmittance of a single leaf
f_{bgd}	–	bdg_reflectance	Reflectance of the ground beneath the canopy
$f_{Coll,veg}^n$	–	Collim_alb_BB	Reflected fraction of light to the atmosphere which has collided with canopy elements, separated for direct and diffuse sources, respectively
$f_{UnColl,bgd}^n$	–	Collim_alb_BC	Reflected fraction of light to the atmosphere which has not collided with any canopy elements, separated for direct and diffuse sources, respectively
$f_{UnColl,veg}^T$	–	Collim_Tran_Uncoll	Transmitted fraction of light to the ground which has not collided with any canopy elements
$f_{Coll,bgd,1}^n$	–	–	Reflected fraction of light which has struck the background a single time and has collided with vegetation
$f_{Coll,bgd,n}^n$	–	–	Reflected fraction of light which has struck the background multiple times and has collided with vegetation
z	m	z_array	Height above the soil
θ_z	radians	solar_angle	Solar zenith angle
θ_u	radians	–	Cosine of the solar zenith angle
g_G	–	–	Leaf orientation function
g_c	–	sigmas	Cut-off circumference of the intra-specific competition, calculated as a function of K_{ncirc}

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Table 3. Description of the parameters in ORCHIDEE-CAN.

Symbol in text	Unit	Value	Symbol in ORCHIDEE-CAN	Description	References
k_{cmaint}	–	Table 3	coeff_maint_init	Fraction of allocatable photosynthates that is consumed for maintenance and growth respiration	Ryan (1991)
$k_{\text{lsa}}, k_{\text{lsamin}}, k_{\text{lsamax}}$	m	Table 3	k_latosa, k_latosa_min, k_latosa_max	Leaf area to sapwood area of an individual tree	Pothier and Margolis (1991); Bartelink (1997); Berthier et al. (2001); Mencuccini and Bonosi (2001); Wullschlegler et al. (1998); Novick et al. (2009); Schäfer et al. (2000); Samuelson et al. (2007); Gould and Harrington (2008); McDowell et al. (2002); Meadows and Hodges (2002); David et al. (2004); Limousin et al. (2012); Bréda and Granier (1996); Martin et al. (1998); Vincke et al. (2005); Margolis et al. (1995)
k_{sar}	–	Eq. (7)	c0_alloc	Sapwood mass to root mass for an individual tree	Calculated from other parameters
k_{Vcmax}	$\mu\text{mol m}^{-2} \text{s}^{-1}$	Table 4	Vcmax25	Carboxylation capacity	TRY
$k_{\text{Jmax}/\text{Vcmax}}$	$\mu\text{mol e}^{-}(\mu\text{mol CO}_2)^{-1}$	Table 4	arjv	Ratio of electron transport capacity to carboxylation capacity	TRY
k_{sla}	$\text{m}^2 \text{gC}^{-1}$	Table 4	sla	Specific leaf mass	TRY
k_{ps}	gC m^{-3}	Table 3	pipe_density	Carbon density of sapwood	TRY; Gaspar et al. (2008); Repola (2006); Knapic et al. (2008); Jenkins et al. (2003)
k_{tl}	days	Table 3	tau_leaf	Leaf longevity	ICP forest, TRY
k_{ts}	days	Table 3	tau_sap	Sapwood longevity	Björklund (1999); Longuetaud et al. (2006); Gebauer et al. (2008); Schulze et al. (1995)

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Table 3. Continued.

Symbol in text	Unit	Value	Symbol in ORCHIDEE-CAN	Description	References
k_{tr}	days	Table 3	tau_root	Root longevity	Brunner et al. (2013)
k_{ap}	m	Table 3	pipe_tune1	Parameter in the relationship between diameter and projected crown surface area	Pretzsch and Dieler (2012)
k_{bp}	–	Table 3	pipe_tune_exp_coeff	Parameter in the relationship between diameter and projected crown surface area	Pretzsch and Dieler (2012)
k_{ncirc}	–	3	ncirc	Number of circumference classes	Assumed
$k_{\alpha}, k_{\alpha'}$	n.a.	n.a.	n.a.	Generic parameter to develop Eq. (40)	n.a.
k_{β}	n.a.	n.a.	n.a.	Generic parameter to develop Eq. (40)	n.a.
$k_{\alpha 1}$	m^{-1}	Table 3	pipe_tune2	Allometric constant relating tree diameter and height	Swedish, German, French and Spanish NFI
$k_{\beta 1}$	–	Table 3	pipe_tune3	Allometric constant relating tree diameter and height	Swedish, German, French and Spanish NFI
$k_{\alpha 2}$	–	Table 3	alpha_self_thinning	Allometric constant of the self-thinning relationship	Swedish, German, French and Spanish NFI
$k_{\beta 2}$	–	Table 3	beta_self_thinning	Allometric constant of the self-thinning relationship	Swedish, German, French and Spanish NFI
k_{m}	–	1	m	Relaxation constant of intraspecific competition relationship	Assumed
k_{diff}	–	1	death_df	Factor by which the smallest and largest circumference classes differ	Assumed
k_{resid}	years	Table 3	residence_time	Residence time of tree, accounting for mortality due to pest, diseases and windfall	Assumed

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Table 3. Continued.

Symbol in text	Unit	Value	Symbol in ORCHIDEE-CAN	Description	References
k_{icon}	$\text{m s}^{-1} \text{MPa}^{-1}$	Table 4	k_leaf	Hydraulic conductivity of leaves	Hickler et al. (2006); Sellin et al. (2013); Aranda et al. (2005);
k_{scon}	$\text{m}^2 \text{s}^{-1} \text{MPa}^{-1}$	Table 4	k_sap	Hydraulic conductivity of sapwood	Manzoni et al. (2013); Cochard (1992); Magnani et al. (2000); Quero et al. (2011); Sellin et al. (2013)
k_{rcon}	$\text{m}^3 \text{kg}^{-1} \text{s}^{-1} \text{MPa}^{-1}$	Table 4	k_root	Hydraulic conductivity of roots	Magnani et al. (2000); Steudle (2000); Arneft et al. (1996)
$k_{\psi 50}$	MPa	Table 4	psi_50	Soil water potential that causes 50% loss of xlem conductivit through cavitation	Choat et al. (2012); Manzoni et al. (2013); Corcuera et al. (2004); Fichot et al. (2010, 2011); Hickler et al. (2006); Cochard (1992)
$k_{\psi \text{imin}}$	MPa	Table 4	psi_leaf	Minimal leaf water potencial	Choat et al. (2012); Martinez-Vilalta et al. (2004); Magnani et al. (2000); Limousin et al. (2012); Hacke and Sauter (1995); Sellin et al. (2013); Schulze et al. (1985)
k_c	–	3	c_cavitation	Shape parameter for vulnerability curve for cavitation	Hickler et al. (2006)
$k_{\alpha 1v}$	–	0.556	a_viscosity(1)	Empirical parameter for the temperature dependence of hydraulic resistance	Cochard et al. (2000)
$k_{\alpha 2v}$	–	0.022	a_viscosity(2)	Empirical parameter for the temperature dependence of hydraulic resistance	Cochard et al. (2000)
$k_{\lambda, \text{LE}}$	J kg^{-1}		chalev0	Latent heat of evaporation	
$k_{\rho a, i}$	kg m^{-3}		rau	Air density, calculated from air temperature and pressure	
$k_{\rho w, i}$	kg m^{-3}	1000	rho_veg	Leaf density, assumed to be equal to the heat capacity of water	

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Table 3. Continuation of Table 3. Soil parameters are given for each soil tile: BS, bare soil, GC: grasses and crops, T: trees.

Symbol in text	Unit	Value	Symbol in ORCHIDEE-CAN	Description	References
$k_{\text{inc}, i}$	J kg K^{-1}	4.1810^{-3}	jtheta	Leaf layer heat capacity	
$k_{\rho w}$	g cm^{-3}		rho_h2o	Density of water at 15 °C	
k_g	m s^{-2}		cte_grav	Gravitational constant	
$k_{k, i}$	$\text{m}^2 \text{s}^{-1}$		k_eddy	Diffusivity coefficient	
$k_{\alpha v}$	m^{-1}	0.0075 (BS),			
0.0036 (GC), 0.0019 (T)	avan_fao	Van Genuchten (1980) coefficient α	Carsel and Parrish (1988)		
k_{SWCS}	$\text{m}^3 \text{m}^{-3}$	0.41 (BS),			
0.43 (GC), 0.41 (T)	mcs_fao	Saturated soil water content	Carsel and Parrish (1988)		
k_{SWCR}	$\text{m}^3 \text{m}^{-3}$	0.065 (BS),			
0.078 (GC), 0.095 (T)	mcr_fao	Residual soil water content	Carsel and Parrish (1988)		
k_{mv}	–	Calculated from n	–	Van Genuchten (1980) coefficient m	Carsel and Parrish (1988)
k_{nv}	–	1.89 (BS),			
1.56 (GC), 1.31 (T)	nvan_fao	Van Genuchten (1980) coefficient n	Carsel and Parrish (1988)		
Leaf ^{vis} _{ssa}	–	Table 6	leaf_ssa_vis	Leaf single scattering albedo, visible light	Derived from Pinty et al. (2007)
Leaf ^{nir} _{ssa}	–	Table 6	leaf_ssa_nir	leaf single scattering albedo, near infrared	Derived from Pinty et al. (2007)
Leaf ^{vis} _{psd}	–	Table 6	leaf_psd_vis	Leaf preferred scattering direction, visible light	Derived from Pinty et al. (2007)
Leaf ^{nir} _{psd}	–	Table 6	leaf_psd_nir	Leaf preferred scattering direction, near infrared	Derived from Pinty et al. (2007)
Bgrd ^{vis} _{ef}	–	Table 6	bgd_reflectance_vis	Background reflectance, visible light	Derived from Pinty et al. (2007)
Bgrd ^{nir} _{ef}	–	Table 6	bgd_reflectance_nir	Background reflectance, near infrared	Derived from Pinty et al. (2007)

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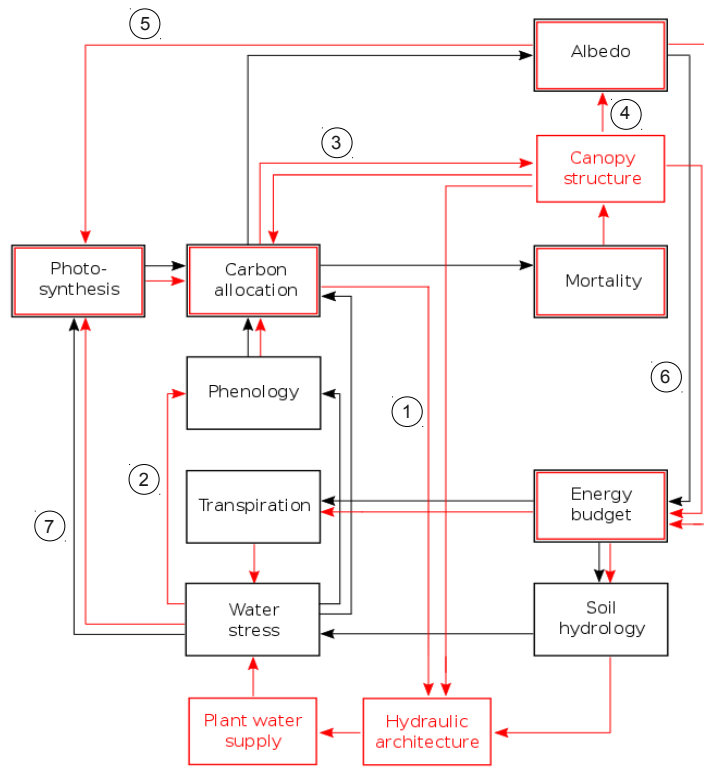


Figure 1. Schematic overview of the changes in ORCHIDEE-CAN. For the trunk the most important processes and connections are indicated in black, while the processes and connections that were added or changed in ORCHIDEE-CAN are indicated in red. Numbered arrows are discussed in Sect. 2.2.

8645

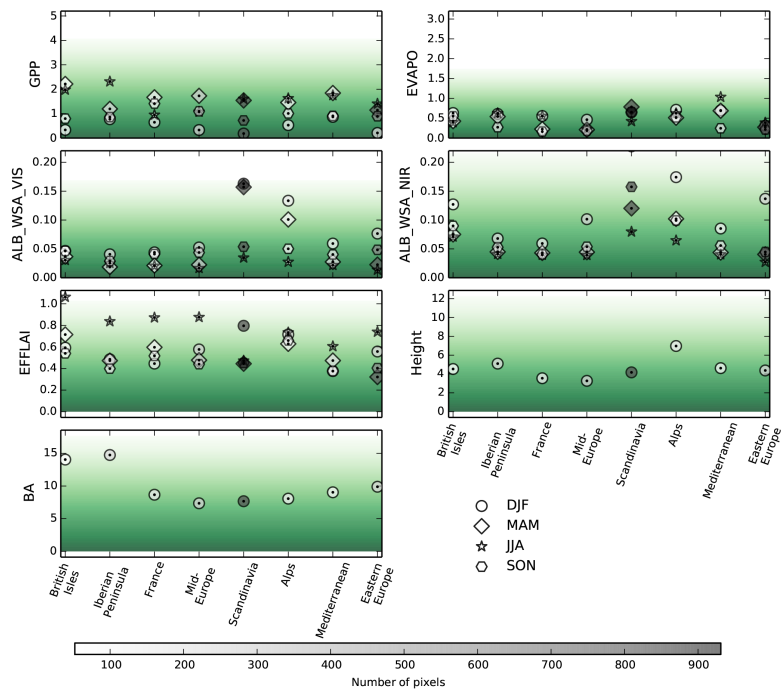


Figure 2. Root mean square error of ORCHIDEE-CAN for gross primary production, evapotranspiration, visible and near-infra-red albedo, effective leaf area index, basal area and height for different regions and periods (DJF: December–February, MAM: March–May, JJA: June–August, SON: September–November). The number of pixels included in the calculation is indicated in a gray-scale. The transition from green to white indicates an RMSE of 100 %.

8646

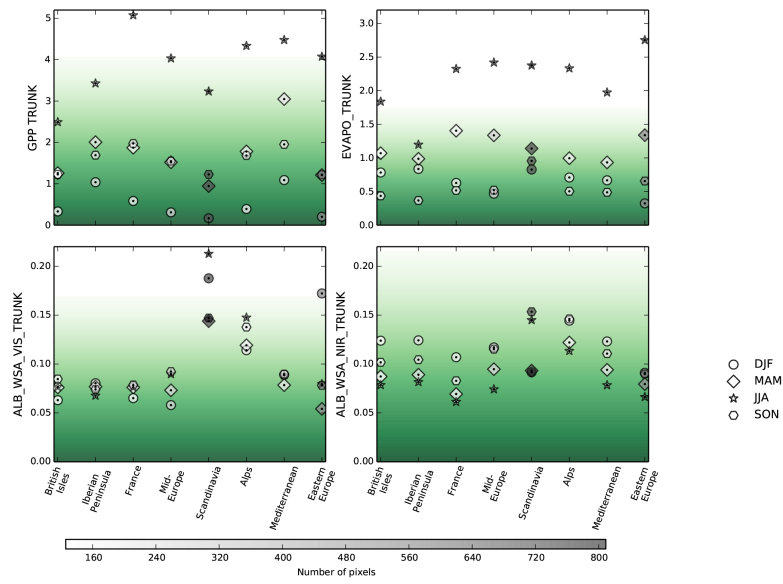


Figure 3. Root mean square error of ORCHIDEE-trunk for gross primary production, evapotranspiration and visible and near-infrared albedo for different regions and periods (DJF: December–February, MAM: March–May, JJA: June–August, SON: September–November). The number of pixels included in the calculation is indicated in a gray-scale. The transition from green to white indicates an RMSE of 100%.