HoliSoils

Working together for forest soils

D6.1 Updated open source versions of the models used in WP6 of HoliSoils

Holistic management practices, modelling and monitoring for European forest soils, HoliSoils

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Coordinator: Natural Resources Institute Finland (Luke)

Deliverable D6.1: Updated open source model code		
Updated open-source versions of ORCHIDEE, EFISCEN-Space & ECOSSE: New open-source releases of each model, including novel functionality to simulate five selected CSF management strategies		
Due date: 31/10/2022	M18	
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CO	Confidential, only for members of the consortium (including the Commission Services)	
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Nature of the Deliverable		
R	Document, report	
DEM	Demonstration, pilot, prototype, plan design	
DEC	Websites, patents filing, market studies, press & media actions, videos etc.	
OTHER	Software, technical diagram etc.	X
Ethics	Ethics deliverables	

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Contents

1. Introduction

The HoliSoils project tackles gaps in knowledge on forest soil processes and aims to harmonise available soil monitoring information to support decision making towards climate and sustainability goals. HoliSoils identifies and tests novel climate-smart forest management practices, with a focus on forest soils, aiming to mitigate climate change and sustain provision of various ecosystem services essential for human livelihoods and wellbeing.

Climate-Smart Forestry (CSF) has been introduced as a holistic approach to guide forest management in Europe (Bowditch et al., 2020; Jandl et al., 2018; Nabuurs et al., 2017; Verkerk et al., 2020; Yousefpour et al., 2018), with the aim of connecting mitigation with adaptation measures, enhancing the resilience of forest resources and ecosystem services, and meeting the needs of a growing population. Climate-Smart Forestry builds on the concepts of sustainable forest management, with a strong focus on climate and ecosystem services. It builds on three mutually reinforcing components (Verkerk et al., 2020):

- Increasing carbon storage in forests and wood products, in conjunction with the provisioning of other ecosystem services
- Enhancing forest health and resilience through climate change adaptive forest management, and
- Using wood resources sustainably to substitute non-renewable, carbon-intensive materials.

Climate-Smart Forestry aims at a mix of these by developing spatially diverse forest management strategies that acknowledge all carbon pools, emissions and removals simultaneously to provide longer-term and larger mitigation benefits, while supporting biodiversity and other ecosystem services.

Within this context, the overall aim of Holisoils WP6 is to develop mathematical models to quantify impacts, trade-offs, and synergies of sustainable, Climate-Smart Forestry management scenarios for **forest soils** on Europe's greenhouse gases balance, soil quality, and water budget under future climate conditions and disturbance regimes. More specifically, this deliverable describes the updated open-source versions of ORCHIDEE, EFISCEN-Space and ECOSSE, including the novel functionality that has been added to simulate at least five Climate-Smart Forestry management strategies.

This deliverable (D6.1) describes the updated open-source versions of ORCHIDEE, EFISCEN-Space and ECOSSE, including the novel functionality that has been added to simulate Climate-Smart Forestry management strategies. In a next step, the models will be parameterized and applied to develop an atlas (deliverable report D6.2) containing maps that will contain a model evaluation and document the initial conditions of the selected models, as well as responses of the models to CSF management

2. Model overview and availability

The complementary models selected in HoliSoils, i.e., EFISCEN-Space, ORCHIDEE, ECOSSE will be ran in sequence, rather than as an ensemble (Fig 1). The sequence of using ORCHIDEE for long-term (80+ years) coarse-resolution (50 × 50 km) simulations that account for major anticipated biological and climatic changes, followed by EFISCEN-Space simulations, to better account for local conditions (tree species, stand age, stand structure), but for a shorter timeframe, and ECOSSE simulations, to better account for organic soils, has been labelled as a “nested approach”.

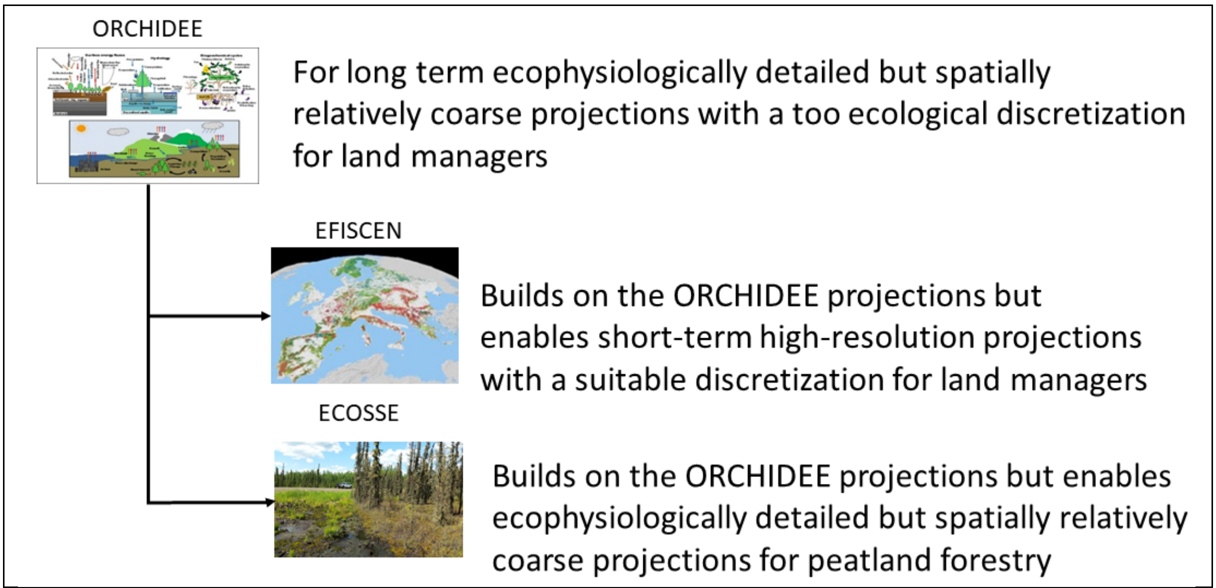

Fig. 2.1. Relationships between ORCHIDEE, EFISCEN-Space and ECOSSE within the nested-approach of the HoliSoils project.

This nested approach has additional requirements for model initialisation and model evaluation. The initial conditions of all three models must be similar. Model initialisation will, therefore, be harmonised across models by assimilating observational data in the description of the initial state of soils and forests (see D6.2). Although the selected models have already been extensively evaluated against data and have participated in numerous model intercomparisons the model response to the newly implemented CSF management will be (re)evaluated in D6.2. Within Holisoils D6.1, EFISCEN-Space, ORCHIDEE and ECOSSE have been extended to include a number of options that can be used for assessing climate-smart forestry practices. The different management options are shown in Table 1 and detailed in section 6.

Within the nested-approach, the EFISCEN-Space and ORCHIDEE models simulate forest ecosystem development and consider soil dynamics via linked soil carbon models (based on CENTURY and Yasso15, resp.), focusing on mineral soils. Section 3 of this report describes EFISCEN-Space and section 4 describes ORCHIDEE.

To cover all forest soils, including organic soils, the ECOSSE model is applied. The ECOSSE model simulates soil carbon and nitrogen dynamics in both mineral and organic soils using meteorological, land use, land management and soil data. ECOSSE is a soil model which does not simulate aboveground biomass growth. However, because forest management affects the quantity and quality of the litter, ECOSSE can simulate the impact of forest management on soil processes through the litter inputs. ECOSSE thus depends on the litter quantity and quality simulated by another model, i.e., EFISCEN-Space or ORCHIDEE in the context of HoliSoils. The ECOSSE team developed the functionality to import litter quality and quantity as simulated by external models. A more detailed description of ECOSSE is given in section 5.

Table 2.1. Major decisions involved in forest management (modified from Duncker et al. 2012) and implementation in ORCHIDEE, EFISCEN-Space & ECOSSE.

Management decision	Silvicultural operations	Examples of silvicultural operations	Section	ORCHIDEE	EFISCEN-Space	ECOSSE
Naturalness of tree species composition	Selection of tree species	Species composition in relation to the potential natural vegetation, share of site-adapted tree species, and share of introduced tree species	6.1	X*	X	X
Type of regeneration	Stand establishment	Natural regeneration, planting, seeding and coppice	6.2, 6.7	X	X	X
Forest reproductive materials	Selection of populations and tree genotypes	Selection of site adapted forest genetic material, use of improved breeding material	6.3		X	
Machine operation	Fertilizing, liming, soil preparation, thinning, final harvest	Use of forest machinery for soil preparation, thinning and final harvest	-			
Soil preparation	Soil preparation, drainage, prescribed burning	Physical site preparation (mechanical and use of prescribed burning) and drainage	6.4	X		X
Fertilization / Liming	Fertilization, Liming	Fertilization to increase yield (amelioration), compensation for nutrient extraction, and re-establishment of natural biogeochemical cycles	6.5	X		X
Application of chemical agents	Pest control	Application of pesticides and herbicides and their effect on soil biological activity	-			
Integration of nature protection	Tree retention, special habitats	Retention of biotope/habitat trees, tolerance of deadwood, and biotope protection within stands	6.6	X	X	
Harvesting regimes	Harvesting regime of final harvest	Continuous cover, shelterwood, clearcutting, coppice, coppice with standards	6.7, 6.8, 6.9	X	X	X
Rotation length	Timing of final harvest or interval of selection harvesting in continuous cover forestry	Felling age in relation to the potential life span of a given tree species	6.7, 6.10	X	X	X
Wood removal	Thinning, final felling	Tree components (stem, stem tops, branches and stumps) extracted in thinning and harvesting operations	6.6, 6.7, 6.8	X	X	X

*ORCHIDEE considers changes in Plant Function Types, not species.

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Deliverable D6.1 describes the updated open-source versions of ORCHIDEE, EFISCEN-space & ECOSSE, with a focus on the novel functionality that has been included in these models, which can be used to simulate selected Climate-smart management strategies. The updated model codes are shared in repositories and distributed under different licenses (Table 2).

Table 2.2. Code repositories and licenses for the models used in WP6. The criteria listed were inspired on the FAIR principles for software (https://fair-software.eu/).

	ECOSSE	EFISCEN-Space	ORCHIDEE
Url to source code	ECOSSE	EFISCEN-Space	ORCHIDEE tag 4.1
Publicly available	Yes	No	Yes
License	Affero General Public License	To be decided	Cecill
Quality checks	The model has been tested and evaluated to simulate short-rotation forestry in Britain (Dondini et al., 2015). The application of the model to simulate the climate smart forest management strategies still need to be evaluated.	A number of code test, implementation tests and sensitivity tests have been performed. An evaluation of the model performance can be found in Chapter 6 of Schelhaas et al. (2022). The newly developed routines in EFISCEN-Space 1.1 still need to be tested and evaluated.	Release 4.1 successfully passed internal coding guidelines, technical trusting, benchmarking against ORCHIDEE 2.2 and ORCHIDEE 3.0, and benchmarking against global data. The newly developed climate smart forest management strategies in Tag 4.1 still need to be evaluated.
Cite as	While preparing a manuscript dedicated to the evaluation of the forest management strategies, cite as: Smith et al. (2010a) and Dondini et al. (2015).	For the moment, cite as Schelhaas et al. (2022).	While preparing a manuscript dedicated to the evaluation of the forest management strategies in Tag 4.1 cite as: Naudts et al. (2015) and Vuichard et al. (2019).

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3. EFISCEN-Space

3.1 Model Description

EFISCEN-Space is an empirical forest scenario simulator. It keeps track of the evolution of the diameter distribution of 20 tree species (groups) for individual plot locations (Nabuurs et al. 2006). The diameter distribution changes over time due to the growth of trees (simulated by the movement of trees to a larger diameter class), the removal of trees due to natural (background) mortality or harvest, and the occurrence of new trees (ingrowth) in lowest diameter classes. For HoliSoils we currently obtained initialisation data for ~200,000 plots from the national forest inventory data from 16 European countries (Fig. 3.1) (Nabuurs et al. 2010). These data are used to initialize forest structure and are the basis for the model's detailed and dynamic (i.e. sensitive to forest structure) simulation of growth (Fig. 3.2) (Schelhaas et al. 2018b). Growth is entirely related to the current forest structure (plus the abiotic predictors), there is no specific thinning effect included. At the start of the work in HoliSoils, natural mortality and harvesting are included as fixed regimes (I.e. insensitive to forest structure) based on repeated forest inventories, depending on the region (Schelhaas et al. 2018a). Within HoliSoils, a dynamic natural mortality module is developed, a dynamic ingrowth module, as well as a more flexible way to simulate harvesting.

The model estimates volume and above- and belowground biomass, while growth in terms of timber volume as well as net ecosystem productivity can be derived. For a full carbon balance, the soil model YASSO15 (Järvenpää et al., 2015; Repo et al., 2016) has been linked. Parameterization and evaluation for the application of YASSO15 within EFISCEN-Space is ongoing.

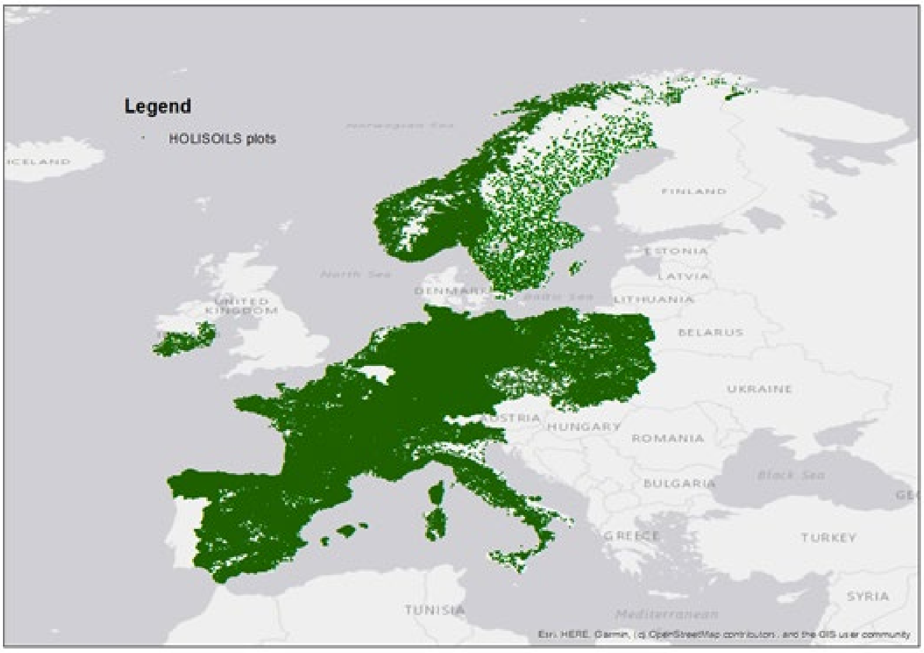

Figure 3.1. Location of plots with initialization data for EFISCEN-Space that are currently (11/2022) included in the model's database

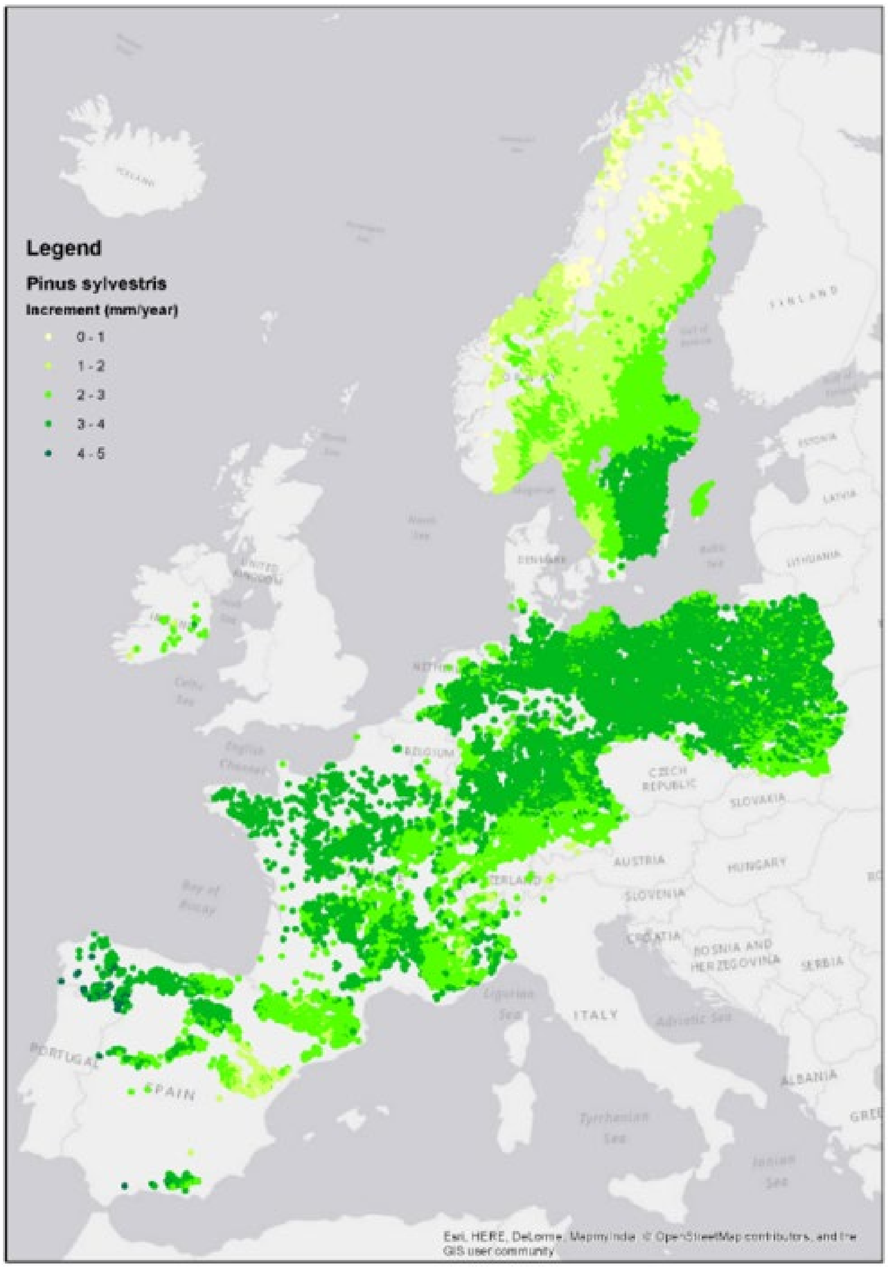

Figure 3.2. Increment of a median tree (mm/yr) in each plot where *Pinus sylvestris* occurs (Schelhaas et al. 2018b).

3.2 Forest management in EFISCEN-Space

Forest management consists of a coherent set of activities carried out in the forest to achieve certain objectives (Duncker et al. 2012). Such activities can include harvesting, planting, soil preparation, fertilization, fencing, etc. Various studies attempted to classify forest management systems at the European scale. Duncker et al. (2012) introduced a methodology to classify forest management at a specific location or case study into five forest management alternatives of different intensity (passive-unmanaged forest nature reserve, low-Close-to-nature, medium-combined objective forestry, high-intensive even-aged and intensive-short rotation), based on a suite of main forest management decisions (see also Table 2.1), ranging from passive management (nature reserves) via multi-purpose forestry to short rotation coppice. Similarly, Nabuurs et al. (2019) distinguished six intensity classes (strict nature reserve, close-to-nature, low-intensity, multifunctional, intensive and very intensive management). Both approaches have the difficulty that they cannot be mapped reliably at European scale due to missing information on both the intention of the forest owner and the data needed by Duncker et al. (2012), such as application of fertilizer. Furthermore, for practical application in modelling, each of these approaches need to be translated into actual management actions in the forest. Given the broad description of some of the classes, still many options remain. Moreover, over time new concepts were put forward such as nature-oriented forest management (Nabuurs et al. 2001), continuous cover forestry (Mason et al. 2021), closer to nature forest management (Larsen et al. 2022) and climate smart forestry (Nabuurs et al. 2017, 2018; Verkerk et al. 2020) which may or may not fit easily to one of the classes defined by Duncker et al. (2012) and Nabuurs et al (2019). Many of these new concepts put greater emphasis at maintaining forest microclimate and protecting soil, consider multiple forest functions, aim at a greater diversity of species, a more natural species composition and/or the inclusion of natural processes. All of these concepts will likely result in a greater diversity of species and stand structures.

Another approach is to focus less on the intention of the forest owner but to classify the silvicultural system in use. This approach was for example adopted in the FORMIT modelling system (Härkönen et al. 2019). A wide range of silvicultural systems exists (Matthews 1991), including the conventional rotation based forestry with clearcuttings, shelterwood systems, individual-tree selection systems (selection harvesting of continuous cover forestry), coppice, and many intermediate forms with smaller or larger canopy openings, leading to stand structures of varying (ir)regularity. In practice, it is impossible to make a solid classification system of silvicultural systems and to clearly define, distinguish and label the different systems in the field. As a consequence, the FORMIT system was lacking a map of what silvicultural systems is currently applied where, and had to rely on broad-scale averages or expert interpretations. Another problem for usage of any of these concepts in EFISCEN-Space is the fact that most of them are based on the broad distinction between even-aged and non-even-aged systems, while age does not exist in EFISCEN-Space. Moreover, some of the silvicultural systems have a strong spatial aspect (distribution of trees and harvesting within the stand) that cannot be covered by EFISCEN-Space.

We therefore developed a new approach where we classify both the state of the forest as well as the goal of the management in terms of its diameter distribution and its species composition. In this approach, the diameter distribution can be characterized as being either narrow or wide. A narrow distribution is likely to correlate with systems managed in an even-aged way, while a wide distribution would correlate with a range of systems such as shelterwood, selective felling, group-felling and uneven-aged (plenterwald) systems. The species composition can be characterized as a single-species system or a multiple-species system. For the development of model scenarios, any scenario input element (for example FMAs or intensity classes) should be translated into an objective for that element in terms of a wide or narrow diameter distribution, and single or multiple species, in a spatial explicit way. These objectives can then be confronted with the actual state of a model stand, and a set of management actions that can be defined to progress towards the required objective. Such actions may for example include planting of additional species if a multiple-species stand is required, or selective thinning in certain diameter classes to make the diameter distribution narrower.

In EFISCEN-Space V1.1 a harvesting action is defined by its overall intensity (in terms of share of number of trees, basal area or volume removed), and by the distribution of the harvest over the diameter range. A harvesting event may preferably target the smaller trees or the larger trees, simulating respectively a thinning from below or above, or be uniformly distributed over the diameter classes.

4. ORCHIDEE

4.1 Model Description

ORCHIDEE is the land surface model of the IPSL (Institut Pierre Simon Laplace) Earth System Model. Hence, by conception, the ORCHIDEE model can be run coupled to a global circulation model (Fig. 4.1). In a 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 climate effects of changes in the land surface and the effects of climate change on the land surface. However, when a study focuses on changes in the land surface rather than on the interaction with climate, ORCHIDEE can be run offline as a stand-alone land surface model (Fig. 4.1b). The stand-alone configuration receives the atmospheric conditions such as temperature, humidity and wind, to mention a few, from the so-called “forcing files”. Unlike the coupled set-up, which needs to run at the global scale (but with the possibility of a regional zoom), the stand-alone configuration can cover any area ranging from the global domain to a single grid point. The stand-alone configuration is used for HoliSoils.

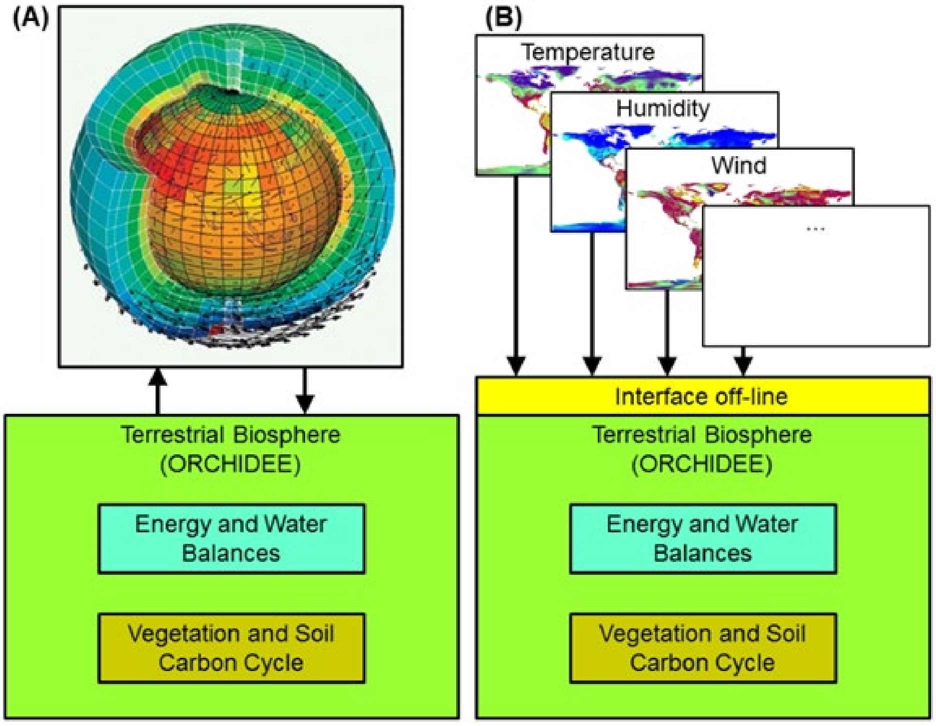

Figure 4.1. Overview of the configurations of the ORCHIDEE model. (A) Shows the coupled configuration in which the two-way interaction between the land and the atmosphere is accounted for. The land surface conditions affect the climate simulations which in turn affect the land surface conditions. (B) the offline configuration in which the climate forcing affects the land surface but the simulated land surface conditions does not affect the climate forcing.

In the stand-alone mode, the user provides files describing the boundary conditions, namely the (initial) vegetation distribution, a soil map, the atmospheric CO_2 concentration, and a river network map as well as the climate forcing. ORCHIDEE then uses these inputs to calculate its prognostic variables focussing on the terrestrial water cycle (Fig. 4.2a), the surface energy balance (Fig. 4.2b), biogeochemical processes (Fig.4.2c), and anthropogenic activities (Fig. 4.2d). The simulated biogeochemical processes, which are the focus of HoliSoils, include the carbon and nitrogen cycle (Vuichard et al 2019) providing detailed insights in photosynthesis, within plant carbon allocation, litter decomposition, soil carbon decomposition, maintenance and growth respiration, vegetation dynamics, and mortality. Mortality is caused by individual or gap-forming “background mortality” and stand replacing disturbances, i.e., drought, wind, bark beetles, land cover changes, and forest management.

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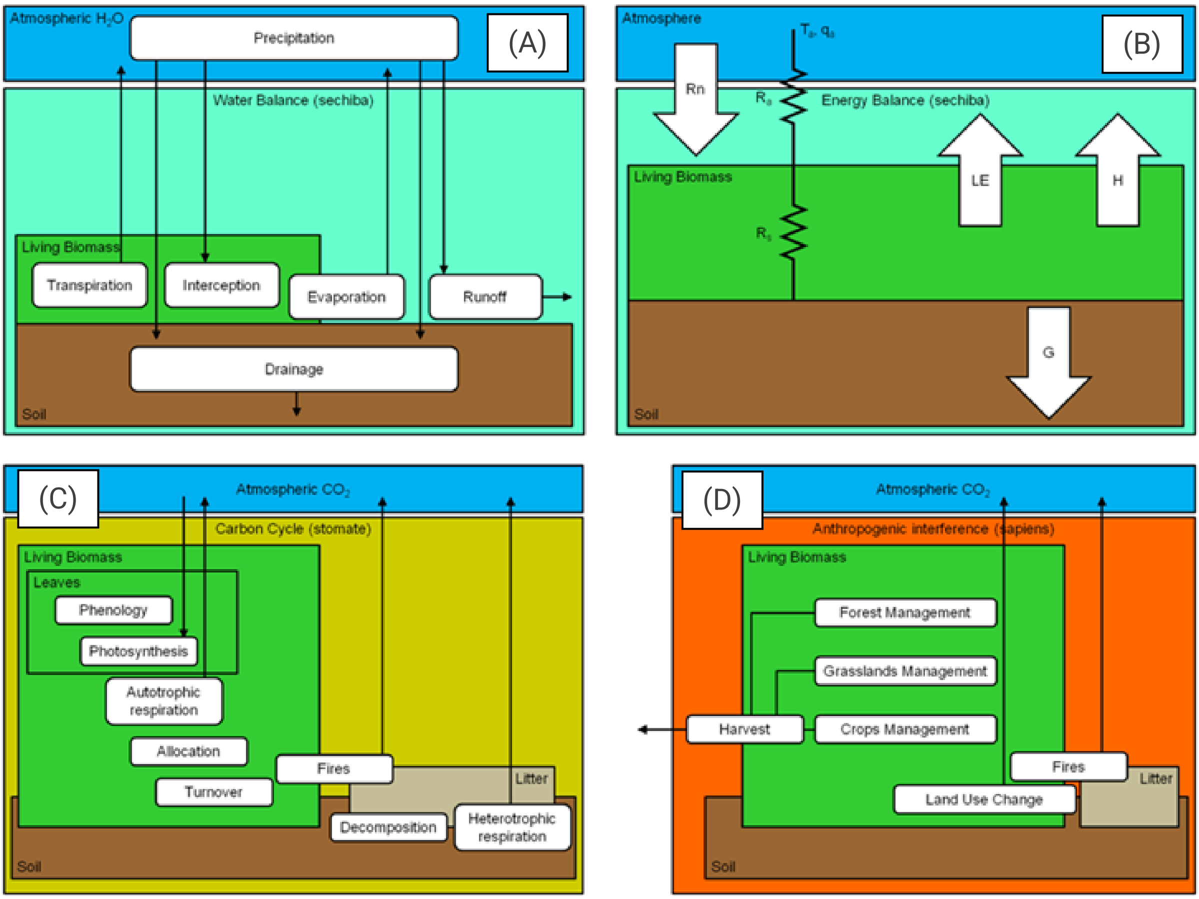

Figure 4.2. Processes represented in the ORCHIDEE model. (A) Main hydraulic processes simulated in ORCHIDEE. (B) Main energy fluxes and pools simulated in ORCHIDEE. (C) Main biogeochemical processes simulated in ORCHIDEE. (D) Main anthropogenic processes simulated in ORCHIDEE.

4.2 Forest management in ORCHIDEE

Although forest management has developed a wide range of locally appropriate and species-specific strategies, the nature of large-scale land-surface models such as ORCHIDEE requires a limited number of contrasting strategies that are expected to be relevant on the spatial scale (e.g., 50 x 50 km) of global and regional modelling studies. ORCHIDEE allocates part of the carbon from photosynthesis to a user-defined number of diameter classes (the default is 3). When an even-aged stand is simulated all three diameter classes belong to the same cohort. If recruitment occurs, the diameter classes will evolve in cohorts. The use of diameter classes introduces a stand structure into ORCHIDEE.

Stand structure is the basis of the forest management strategies implemented in ORCHIDEE. When the trees are growing, the stand approaches overstocking (prescribed through self-thinning relationships). The degree of over- or understocking is calculated as the relative density index. When the target for relative density is used, the stand will be thinned. If thinning would result in a too low stand density or too large diameters of the remaining trees, the stand is harvested. If the stand is not managed, overstocking results in self-thinning. Different management strategies have different targets for relative density and cut different diameter classes. This approach allows simulating a wide variety of management strategies resulting in different stand structures. Subsequently, stand structure is used in the calculation of the carbon and nitrogen budgets, the water and energy budget as well as in the vulnerability to natural disturbances. As such the biogeochemical and biogeophysical effects of forest management are simulated by the ORCHIDEE model.

ORCHIDEE simulates typical forestry variables such as basal area, stand density, quadratic mean diameter, quadratic mean height and diameter distribution. Wood harvest from coppicing, thinning and clear-cutting is also simulated by ORCHIDEE. Wood products affect the carbon balance of the forest sector through three different pathways which are accounted for: (i) the forest carbon and nitrogen sinks account for changes in in-situ carbon pools in forest biomass, forest litter, and forest soil. The model simulates the net ecosystem carbon balance referring to a change in carbon pools in the forest ecosystems; (ii) the carbon stored in the short, medium and long-lived wood products act as ex-situ carbon sinks, and (iii) when wood is used it may substitute for products or energy that require or emit more fossil fuels than the wood-based alternatives. Carbon storage in the forest and wood products is simulated by ORCHIDEE whereas product and energy substitution should be accounted for through postprocessing.

5. ECOSSE

5.1 Model Description

The ECOSSE model was developed to simulate highly organic soils from concepts originally derived for mineral soils in the RothC (Jenkinson and Rayner, 1977; Jenkinson et al. 1987; Coleman and Jenkinson, 1996) and SUNDIAL (Bradbury et al. 1993; Smith et al. 1996) models. Following these established models, ECOSSE uses a pool-type approach, describing soil organic matter (SOM) as pools of inert organic matter, humus, biomass, resistant plant material and decomposable plant material (Fig. 5.1). All processes of both carbon and nitrogen dynamics are considered (Smith et al., 2010a,b). ECOSSE can run in different modes and time steps. The two main modes are site-specific and limited data. In the latter version, basis assumptions/estimates for parameters can be provided by the model itself instead of relying on user input. This increases the uncertainty but makes ECOSSE a universal tool that can be applied for large scale simulations even if the data availability is limited. To increase the accuracy in the site-specific version of the model, detailed information about soil properties, plant input, nutrient application and management can be added as available.

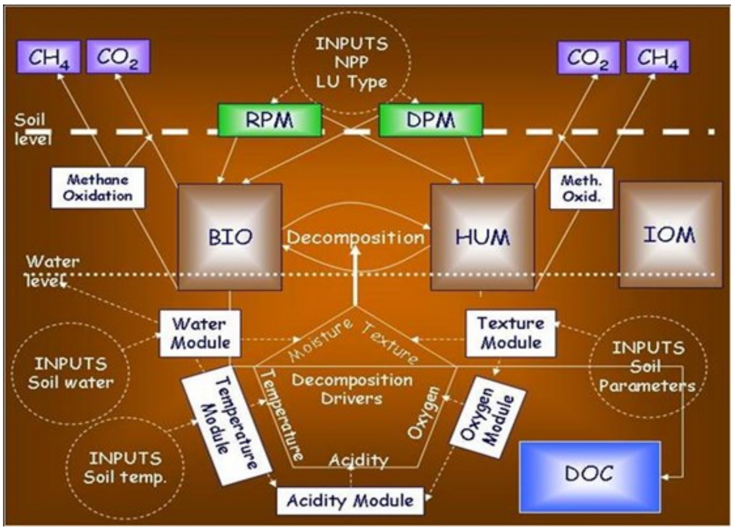

Figure 5.1. Structure of the carbon components of ECOSSE

The different processes are summarized in the ECOSSE user manual (Smith et al., 2011). During the decomposition process, material is exchanged between the SOM pools according to first order rate equations, characterised by a specific rate constant for each pool, and modified according to rate modifiers dependent on the temperature, moisture, crop cover and pH of the soil. Under aerobic conditions, the decomposition process results in gaseous losses of carbon dioxide (CO2); under anaerobic conditions losses as methane (CH_4) dominate. The N content of the soil follows the decomposition of the SOM (Figure 2), with a stable C:N ratio defined for each pool at a given pH, and N being either mineralised or immobilised to maintain that ratio. Nitrogen released from decomposing SOM as ammonium (NH_4^+) or added to the soil may be nitrified to nitrate (NO_3^-). Carbon and nitrogen may be lost from the soil by the processes of leaching (NO_3^-, dissolved organic C (DOC), and dissolved organic N (DON)), denitrification, volatilisation or crop uptake; C and N may be returned to the soil by plant inputs, inorganic fertilizers, atmospheric deposition or organic amendments. The soil is divided into 5 cm layers, so as to facilitate the accurate simulation of these processes down the soil profile.

For spatial simulations the model is implemented in a spatial model platform. This allows to aggregate the input parameters for the desired resolution. ECOSSE is a one-dimensional model and the model platform provides the input data in a spatial distribution and aggregates the model outputs for further analysis. While climate data are interpolated, soil data are represented by the dominant soil type or by the proportional representation of the different soil types in the spatial simulation unit (a grid cell in the context of the HoliSoils project).

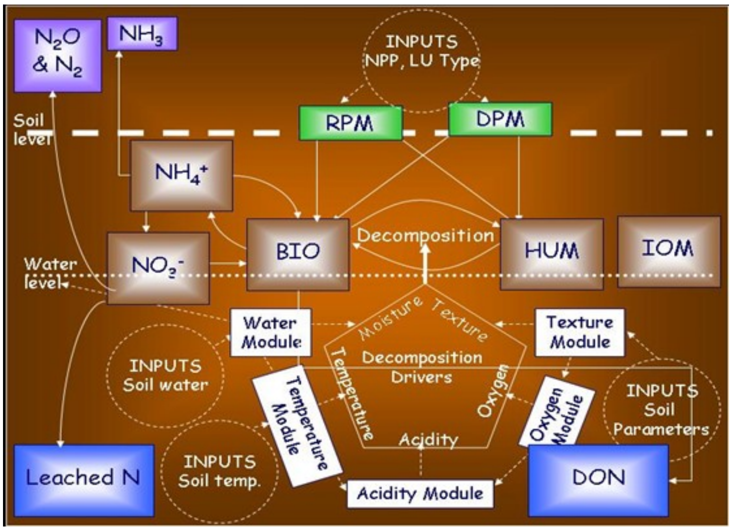

Figure 2. Structure of the nitrogen components of ECOSSE

5.2 Forest management in ECOSSE

The ECOSSE model does not simulate vegetation dynamics; instead, management events are set using standard values for the different land use types. As a model default, forests are assumed to stay have no management. ECOSSE requires plant inputs (litter, debris and root exudates) to the soil in order to determine the C returned to the soil from the growing plant. Consequently, plant C input is used as a proxy to mimic the impact of different management options, or species characteristics. In ECOSSE, yield estimates are obtained using NPP estimates from the MIAMI model (Leith, 1972), and the plant input is estimated as a fix fraction of the NPP. Alternatively, direct measurements or estimates from vegetation models can be used as ECOSSE inputs to mimic the impacts of different management practices on soil dynamics. The latter approach is used within this project, taking full advantages of the ability of ORCHIDEE and EFISCEN-Space to simulate vegetation dynamics under different CSF practices. The ECOSSE model uses a selection of the ORCHIDEE model outputs, such as total litter outputs and debris, to drive soil dynamics under different management practices. For practices not directly affecting plant residues, ECOSSE model parameters are adjusted based on literature review and measurements taken within Holisoils (WP2 and WP3 data).

Carbon sequestration, heterotrophic respiration, nitrous oxide and methane emissions from the forest soil is simulated by ECOSSE.

6. Novel functionality for simulating climate-smart forest management strategies

6.1 Selection of tree species

6.1.1 EFISCEN-Space

The modelled forest stands in EFISCEN-Space are initialized with the current species as observed in the NFI plots. The species composition can actively be influenced by harvesting (removing) specific species and by planting trees of a certain species, either in the existing stand (underplanting) or after harvesting the current stand. Such actions are steered by the overall goal as defined for that model stand in terms of aiming at a single- or multiple-species stand. Guidance on the actual choice of tree species is influenced by further specification of the goals, mainly if the aim is production or nature-oriented, and the location of the stand (which species are eligible).

6.1.2 ORCHIDEE

ORCHIDEE prescribes the plant functional types which can be change to another prescribed plant functional type following a stand replacing disturbance.

6.1.3 ECOSSE

The ECOSSE model uses litter inputs to determine the C returned to the soil from the growing plant. Quality and quantity of this model input can be changed by the user to simulate the species changes.

6.2 Stand establishment

6.2.1 EFISCEN-Space

EFISCEN-Space distinguishes natural ingrowth and planting. Natural ingrowth occurs when the stand conditions are favourable for establishment, while planting is prescribed by the user. (Partial) regeneration of a stand can thus be achieved by harvesting actions that increase the probability of natural ingrowth, or by actively planting trees, possibly in combination with full or partial removal of the existing stand. The choice of the actual method to be used depends on the goal set for the model stand, in terms of aiming at a wide or narrow diameter structure and in how far the management is aimed at using natural processes.

6.2.2 ORCHIDEE

ORCHIDEE can (re)establish a forest stand either by replanting the stand or through natural regeneration. In ORCHIDEE, natural regeneration is limited to regeneration in canopy gaps whereas replanting is used in stand replacing disturbances.

6.2.3 ECOSSE

The ECOSSE model uses litter inputs to determine the C returned to the soil from the growing plant. Quantity of this model input can be changed by the user to simulate stand establishment.

6.3 Provenance selection

6.3.1 EFISCEN-Space

A provenance can be regarded as a new tree species, with characteristics similar to the old species, but with a different growth rate and/or biomass allocation compared to the original species. The introduction of a new provenance can then be implemented in the same way as the introduction of any other species, e.g. planting in an existing stand or a full regeneration after clearfelling.

6.3.2 ORCHIDEE

In HoliSoils, ORCHIDEE simulations will use of plant functional types. Provenance will not be accounted for.

6.3.3 ECOSSE

ECOSSE doesn't account for provenance to simulate soil dynamics. Therefore, provenance will not be considered.

6.4 Post-harvest litter removal

6.4.1 EFISCEN-Space

Following a thinning or harvest, logging residues such as stem tops and branches can be extracted. The fraction of stem tops and branches that is extracted from the site is determined by a user-defined parameter. This parameter can be changed to simulate forest management strategies that leave more or less logging residues on site

6.4.2 ORCHIDEE

Following a thinning or harvest, aboveground wood and part of the branches are left on site. The fraction of branches that is left on site is determined by a user-defined parameter. This parameter can be changed to simulate strategies that leave more or less litter on site.

6.4.3 ECOSSE

The ECOSSE model uses litter inputs to determine the C returned to the soil from the growing plant. This model input can be changed by the user to simulate forestry strategies that leave more or less litter on site.

6.5 Fertilization

6.5.1 EFISCEN-Space

Fertilization is currently not implemented in EFISCEN-Space.

6.5.2 ORCHIDEE

ORCHIDEE simulates a fully dynamic nitrogen cycle. The model accounts for the following sources nitrogen sources: (i) soil nitrogen from model spin-up, (ii) atmospheric deposition, (iii) organic fertilizers increasing both the soil nitrogen and soil carbon, and (iv) synthetic fertilizers only increasing the soil nitrogen. As a climate smart forestry strategy, ORCHIDEE can simulate the effects of forest fertilization with organic or synthetic fertilizers.

6.5.3 ECOSSE

All major processes of N turnover in the soil are included in the ECOSSE model. The N content of the soil follows the decomposition of the soil organic matter, with a stable C:N ratio defined for each pool at a given pH, and N being either mineralised or immobilised to maintain that ratio. Nitrogen released from decomposing SOM as ammonium or added to the soil may be nitrified to nitrate. Nitrogen may be lost from the soil by the processes of leaching, denitrification, volatilisation, or it may be returned to the soil by plant inputs, inorganic fertilizers, atmospheric deposition or organic amendments. Fertilization can be prescribed by modifying model parameters (amount of fertiliser N applied, amount of organic manure applied). As a model default, forest soils are assumed to have no fertiliser applications.

6.6 Conservation management

6.6.1 EFISCEN-Space

When no management is applied, the stands will get very dense, which slows down growth and increases natural mortality. Large trees will eventually die (with a probability depending on the species and the density of the forest), causing the forest to be opener and giving natural recruitment the opportunity to appear and grow. Natural disturbances are not included in the model.

6.6.2 ORCHIDEE

When recruitment is accounted for, self-thinning will result in gaps which enable light to reach the forest floor. This light will result in recruitment. Under constant environmental conditions, an equilibrium biomass is reached within a few decades. In the absence of recruitment, self-thinning drives stand dynamics and continues until too few trees are left on site. Subsequently, an undefined stand replacing disturbance moves over the course of 10 years the remaining standing biomass into the appropriate litter pools and a new stand is established. Following a stand replacing disturbance, the user can choose from the four options to define the new stand: (i) a stand of a different species with the same silvicultural system; (ii) the same species with a different silvicultural system; (iii) a different species with a different silvicultural system; or replanted with (iv) the same species and tended with the same silvicultural system as before.

6.6.3 ECOSSE

The ECOSSE model is a soil process-based model, and it does not simulate the impacts of managements on vegetation, but the effects on soil C and N dynamics of such management can be estimated by using different inputs of organic carbon to the soil (litter, debris and roots exudates) arising from specific management strategies. Conservation management of current plant functional types can be therefore simulated by altering the organic material returned to the soil. The balance and size of litter inputs are constrained by the simulations carried out by the ORCHIDEE model.

6.7 Thin and fell

6.7.1 EFISCEN-Space

Thinnings can be initiated when a certain threshold is exceeded, which is typically defined in terms of basal area. If the threshold is exceeded, a thinning with a user-defined intensity will be executed. This should be a thinning from below to keep a narrow diameter structure. A final felling is executed when the user-defined target diameter is exceeded. After felling, the stand can be regenerated naturally or it can be planted. Natural regeneration can be facilitated by removal of the canopy trees in several steps (for example via a shelterwood system where seed trees are removed later). All thresholds can vary by species and region within Europe and can be defined by the user.

6.7.2 ORCHIDEE

Thin and fell management is characterised by regular thinning and a final harvesting and runs without recruitment. Thinning is decided on the basis of the deviation between the actual and potential stand density for any given diameter. This approach relates to the so-called relative density index (Fortin et al., 2012), the land use disturbance index (Luyssaert et al., 2011) or hemeroby and naturalness approaches (Schall and Ammer, 2013). Exceeding a threshold diameter results in a clear cut and the stand is replanted in the next year (mast years or extensive mortality of seedlings is not yet accounted for). For both thinning and harvest, leaves, roots and belowground wood are transferred to the appropriate litter pools, whereas the aboveground woody biomass is removed from the site and stored in a product pool. Trees with a diameter below a species-specific threshold are stored in a short-lived product pool which accounts for wood uses for fuel, paper and cardboard. Trees with larger dimensions are moved to medium- and long-lived product pools which account for, for example, particle boards and timber usages, respectively. When the stand has reached maturity and needs to be harvested the stand can be replaced by one out of four options – (i) a stand of a different species with the same silvicultural system; (ii) the same species with a different silvicultural system; (iii) a different species with a different silvicultural system; or replanted with (iv) the same species and tended with the same silvicultural system as before.

6.7.3 ECOSSE

Thin and fell management involves cutting the standing trees; litterfall quantity and quality is directly affected by such practices. Changes in litter alter forest floor accumulation an contributes to changes in soil C stocks. The ECOSSE model uses litter inputs to determine the C returned to the soil from the growing plant. This model input can be changed by the user to simulate thinning and/or harvest events that will decrease or increase the quantity of carbon going into the soil from the vegetation.

6.8 Coppice

6.8.1 EFISCEN-Space

Coppice is not implemented as a specific management option in EFISCEN-Space but coppice systems could be mimicked by defining when cuts are made, and with which intensity, as well as the regeneration speed. However, the growth rate and biomass allocation of coppice forests is different from high forests and specific data for coppice forests are currently lacking. Coppice could therefore be modelled with EFISCEN-Space, but appropriate data for implementing coppice management in the model are currently lacking.

6.8.2 ORCHIDEE

Coppicing of the aboveground biomass is decided on stem diameter. At harvest, the root system is left intact, and, in between coppicing, no wood is harvested. Note that at present it is not possible to simulate coppicing with-standards in ORCHIDEE. In ORCHIDEE, stands under short rotation management are limited to poplar (Populus spp.) and willow (Salix spp.) forests. Stands are harvested at a prescribed age. Following a set number of harvest cycles, the root system is uprooted and the whole stand is replanted. When the stand is coppiced (or uprooted for short rotation coppice the stand can be replaced by one out of four options – (i) a stand of a different species with the same silvicultural system; (ii) the same species with a different silvicultural system; (iii) a different species with a different silvicultural system; or replanted with (iv) the same species and tended with the same silvicultural system as before.

6.8.3 ECOSSE

Short rotation management are limited to poplar (Populus spp.) and willow (Salix spp.) forests. The re-established of the crop occurs after a 20-year period (the estimated productive lifespan of the crop) and it does not involve further cultivation.

6.9 Continuous cover forestry

6.9.1 EFISCEN-Space

Continuous cover forestry can be simulated by EFISCEN-Space as a continuous series of thinnings. The threshold to start thinnings should be lower than under thin and fell forestry, to keep the stand more open to facilitate continuous recruitment. The thinnings are specified to be from above, to mimic the process of selectively removing larger trees to facilitate recruitment and keep a wide diameter distribution. In addition, a specified fraction of any trees above the target diameter will be removed. All thresholds can vary by species and region within Europe and can be defined by the user.

6.9.2 ORCHIDEE

If the relative density index approach is combined with recruitment, continuous cover forestry can be simulated. This approach is currently under development.

6.9.3 ECOSSE

Continuous cover forestry resembles thinning with respect to its effect on the soil C pool, and therefore it can be simulated by ECOSSE by altering the amount of organic material on the soil surface.

6.10 Change rotation length

6.10.1 EFISCEN-Space

A change in rotation length in EFISCEN-Space can be simulated by increasing the target diameter when final felling will occur.

6.10.2 ORCHIDEE

The ORCHIDEE model does not prescribe the rotation length. The rotation length is an emerging property of: (i) the relative density index, (ii) the maximum diameter, and (iii) tree growth. The rotation length can easily be changed by decreasing or extended by increasing the stand diameter at which the final cut will occur.

6.10.3 ECOSSE

The ECOSSE model does not prescribe the rotation length. Changing rotational length will have an impact on tree growth and subsequently, on litter. Therefore, the ECOSSE model can simulate the impact of changing rotation length on soil carbon and nitrogen dynamics by altering the litter quality and quantity associated with the change in rotational length.

7. References

Arets EJMM, Schelhaas MJ. (2019). National Forestry Accounting Plan. Submission of the Forest Reference Level 2021-2025 for the Netherlands. Ministerie LNV, 2019. 75 p.

Bellassen, V., Le Maire, G., Dhôte, J. F., Ciais, P. & Viovy, N. (2010). Modelling forest management within a global vegetation model-Part 1: Model structure and general behaviour. Ecol. Modell. 221, 2458–2474.

Bowditch, E., Santopuoli, G., Binder, F., del Río, M., La Porta, N., Kluvankova, T., Lesinski, J., Motta, R., Pach, M., Panzacchi, P., Pretzsch, H., Temperli, C., Tonon, G., Smith, M., Velikova, V., Weatherall, A., Tognetti, R. (2020). What is Climate-Smart Forestry? A definition from a multinational collaborative process focused on mountain regions of Europe. Ecosystem Services 43, 101113.

Bradbury NJ, Whitmore AP, Hart PBS, Jenkinson DS (1993) Modelling the fate of nitrogen in crop and soil in the years following application of 15N-labelled fertilizer to winter wheat. J Agr Sci 121: 363-379.

Coleman K, Jenkinson DS (1996) RothC-26.3 - A model the turnover of carbon in soil. In: Powlson DS, Smith P, Smith JU (ed) Evaluation of soil organic matter models using existing long-term datasets. NATO ASI Series I, vol. 38. Springer, Berlin, pp 237–246.

Dondini M, Jones EO, Richards M, Pogson, M, Rowe RL, Keith AM, Perks, M.P., McNamara NP, Smith, J.U. and Smith P (2015). Evaluation of the ECOSSE model for simulating soil carbon under short rotation forestry energy crops in Britain. GCB Bioenergy, 7: 527-540.

Ducoudré, N. I., K. Laval, and A. Perrier (1993), SECHIBA, a new set of parameterizations of the hydrologic exchanges at the land-atmosphere interface within the LMD atmospheric general circulation model, Journal of Climate, 6, 248– 273.

Duncker, P. S., Barreiro, S. M., Hengeveld, G. M., Lind, T., Mason, W. L., Ambrozy, S., & Spiecker, H. (2012). Classification of forest management approaches: a new conceptual framework and its applicability to European forestry. Ecology and Society, 17(4).

Fortin, M., Ningre, F., Robert, N., and Mothe, F. (2012). Quantifying the impact of forest management on the carbon balance of the forest-wood product chain: A case study applied to evenaged oak stands in France, Forest Ecol. Manage., 279, 176–188.

Härkönen, S., Neumann, M., Mues, V., Berninger, F., Bronisz, K., Cardellini, G., Chirici, G., Hasenauer, H., Koehl, M., Lang, M., Merganicova, K., Mohren, F., Moiseyev, A., Moreno, A., Mura, M., Muys, B., Olschofsky, K., Del Perugia, B., Rørstad, P.K., Solberg, B., Thivolle-Cazat, A., Trotsiuk, V., Mäkelä, A., (2019). A climate-sensitive forest model for assessing impacts of forest management in Europe. Environmental Modelling & Software 115, 128-143.

Jandl, R., Ledermann, T., Kindermann, G., Freudenschuss, A., Gschwantner, T., Weiss, P. (2018). Strategies for Climate-Smart Forest Management in Austria. Forests 9.

Järvenpää, M., Repo, A., Akujärvi, A., Kaasalainen, M., & Liski, J. (2015). Bayesian calibration of Yasso15 soil carbon model using global-scale litter decomposition and carbon stock measurements. Manuscript in preparation. www. syke. fi/projects/yasso.

Jenkinson DS, Hart PBS, Rayner JH, Parry LC (1987). Modelling the turnover of organic matter in long-term experiments at Rothamsted. INTECOL Bulletin 15:1-8.

Jenkinson DS, Rayner JH (1977). The turnover of organic matter in some of the Rothamsted classical experiments. Soil Sci 123: 298–305.

Krinner, G., N. Viovy, N. de Noblet-Ducoudré, J. Ogée, J. Polcher, P. Friedlingstein, P. Ciais, S. Sitch, and I. C. Prentice (2005), A dynamic global vegetation model for studies of the coupled atmosphere-biosphere system, Global Biogeochemical Cycles, 19, GB1015.

Larsen, J.B., Angelstam, P., Bauhus, J., Carvalho, J.F., Diaci, J., Dobrowolska, D., Gazda, A., Gustafsson, L., Krumm, F., Knoke, T., Konczal, A., Kuuluvainen, T., Mason, B., Motta, R., Pötzelsberger, E., Rigling, A., Schuck, A., (2022). Closer-to-Nature Forest Management. From Science to Policy 12. European Forest Institute.

Lieth H (1975) Modeling the primary productivity of the world. In: Primary Productivity of the Biosphere (ed. Lieth H, Whittaker RH), pp. 237–263. Springer Berlin Heidelberg, Springer-Verlag, New York.

Luyssaert, S., Hessenmöller, D., von LXpke, N., Kaiser, S., and Schulze, E. D. (2011). Quantifying land use and disturbance intensity in forestry, based on the self-thinning relationship, Ecol. Appl., 21, 3272–3284.

Mason, W.L., Diaci, J., Carvalho, J., and Valkonen, S. (2021). Continuous cover forestry in Europe: usage and the knowledge gaps and challenges to wider adoption. Forestry, cpab038.

Matthews JD, (1991). Silvicultural systems. Clarendon Press, Oxford.

Nabuurs, G. J., Päivinen, R., Schelhaas, M. J., Pussinen, A., Verkaik, E., Lioubimow, A., & Mohren, F. (2001). Nature-oriented forest management in Europe: modeling the long-term effects. Journal of Forestry, 99(7), 28-33.

Nabuurs, G.J., J. van Brusselen, A Pussinen. M.J. Schelhaas. (2006). Future harvesting pressure on European forests. European Journal of Forest Research. 126: 391–400

Nabuurs, G.J., D.C. van der Werf, N. Heidema and I.J.J. van der Wyngaert. (2007). Ch 13. Towards a High Resolution Forest Carbon Balance for Europe Based on Inventory Data. In Freer Smith et al. (Eds). Forestry and Climate Change. OECD Conference, Wilton Park. Nov 2006. p 105-111.

Nabuurs, G.-J., Delacote, P., Ellison, D., Hanewinkel, M., Hetemäki, L., Lindner, M., Ollikainen, M. (2017). By 2050 the Mitigation Effects of EU Forests Could Nearly Double through Climate Smart Forestry. Forests 8, 484.

Nabuurs, G.J., Verkerk, P.J., Schelhaas, M.J., González Olabarria, J.R., Trasobares, A., Cienciala, E. (2018). Climate-Smart Forestry: mitigation impacts in three European regions. From Science to Policy 6.

Nabuurs, G.J., G.M. Hengeveld, D.C. van der Werf and A.H. Heidema (2010). European forest carbon balance assessed with inventory based methods — An introduction to a special section. Forest Ecology and Management 260: 239–240.

Nabuurs, GJ., Verweij, P., Van Eupen, M. et al. (2019). Next-generation information to support a sustainable course for European forests. Nat Sustain 2, 815–818.

Naudts, K. et al. (2015). A vertically discretised canopy description for ORCHIDEE (SVN r2290) and the modifications to the energy, water and carbon fluxes. Geosci. Model Dev. 8, 2035–2065.

Polcher, J., McAvaney, B., Viterbo, P., Gaertner, M.-A., Hahmann, A., Mahfouf, J.-F., Noilhan, J., Phillips, T., Pitman, A.J., Schlosser, C.A., Schulz, J.-P., Timbal, B., Verseghy D., and Xue, Y. (1998). A proposal for a general interface between land-surface schemes and general circulation models. Global and Planetary Change, 19:263-278.

Repo, A., Järvenpää, M., Kollin, J., Rasinmäki, J. & Liski, J. (2016). Yasso15 graphical user-interface manual.

Schall, P. and Ammer, C. (2013). Can land use intensity be reliably quantified by using a single self-thinning relationship?, Ecol. Appl., 23, 675–677.

Schelhaas MJ, Fridman J, Hengeveld GM, Henttonen H, Lehtonen A, Kies U, Krajnc N, Lerink B, Ní Dhubháin A, Polley H, Pugh TAM, Redmond J, Rohner B, Temperli C, Vayreda J, Nabuurs GJ, (2018a). Actual European forest management by region, tree species and owner based on 714,000 re-measured trees in national forest inventories. PLoS ONE 13(11): e0207151.

Schelhaas MJ, Hengeveld GM, Heidema N, ThXrig E, Rohner B, Vacchiano G, Vayreda J, Redmond J, Socha J, Fridman J, Tomter S, Polley H, Barreiro S, Nabuurs GJ, (2018b). Species-specific, pan-European diameter increment models based on data of 2.3 million trees. Forest Ecosystems 5:21.

Schelhaas MJ, Hengeveld GM, Filipek S, König L, Lerink B, Staristsky I, de Jong A, Nabuurs GJ (in prep) EFISCEN-Space 1.0 model documentation and manual.

Smith J, Gottschalk P, Bellarby J, Richards M, Nayak D, Coleman K, Hillier J, Flynn H, Wattenbach M, Aitkenhead M, Yeluripurti J, Farmer J, Smith P (2011). Model to estimate carbon in organic soils—sequestration and emissions (ECOSSE) user-manual. University of Aberdeen, UK, pp 1–77.

Smith JU, Bradbury NJ, Addiscott TM (1996). SUNDIAL: A PC-based system for simulating nitrogen dynamics in arable land. Agron J 88:38-43.

Smith, J.U., Gottschalk, P., Bellarby, J., Chapman, S., Lilly, A., Towers, W., Bell, J., Coleman, K., Nayak, D.R., Richards, M.I., Hillier, J., Flynn, H.C., Wattenbach, M., Aitkenhead, M., Yeluripurti, J.B., Farmer, J., Milne, R., Thomson, A., Evans, C., Whitmore, A.P., Falloon, P. & Smith, P. (2010a). Estimating changes in national soil carbon stocks using ECOSSE – a new model that includes upland organic soils. Part I. Model description and uncertainty in national scale simulations of Scotland. Climate Research 45, 179-192.

Smith, J.U., Gottschalk, P., Bellarby, J., Chapman, S., Lilly, A., Towers, W., Bell, J., Coleman, K., Nayak, D.R., Richards, M.I., Hillier, J., Flynn, H.C., Wattenbach, M., Aitkenhead, M., Yeluripurti, J.B., Farmer, J., Milne, R., Thomson, A., Evans, C., Whitmore, A.P., Falloon, P. & Smith, P. (2010b). Estimating changes in national soil carbon stocks using ECOSSE – a new model that includes upland organic soils. Part II. Application in Scotland. Climate Research 45, 193-205. doi: 10.3354/cr00902.

Verkerk, P.J., Costanza, R., Hetemäki, L., Kubiszewski, I., Leskinen, P., Nabuurs, G.J., Potočnik, J., Palahí, M., (2020). Climate-Smart Forestry: the missing link. Forest Policy and Economics 115, 102164.

Viovy, N. (1996), Interannuality and CO2 sensitivity of the SECHIBA-BGC coupled SVAT-BGC model, Physics and Chemistry of The Earth, 21, 489– 497.

Vuichard, N., Messina, P., Luyssaert, S., Guenet, B., Zaehle, S., Ghattas, J. Bastrikov, V., and Peylin, P. (2019). Accounting for carbon and nitrogen interactions in the global terrestrial ecosystem model ORCHIDEE (trunk version, rev 4999): multi-scale evaluation of gross primary production. Geosci. Model Dev., 12, 4751–4779.

Yousefpour, R., Augustynczik, A.L.D., Reyer, C.P.O., Lasch-Born, P., Suckow, F., Hanewinkel, M. (2018). Realizing Mitigation Efficiency of European Commercial Forests by Climate Smart Forestry. Scientific Reports 8, 345.