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1. Executive Summary

In this deliverable D4.1 (Harmonized management rules and model output) report, we have i) introduced the open-source versions of PICUS, GOTILWA+, SIMA, and LMDzOR models with their underlying definitions and new functionality, and ii) described the harmonized definitions for forest management rules and output variables. This makes it possible to simulate sustainable forest management practices and facilitate comparisons of simulation outputs by different models in different regions and climate projections.

2. Introduction

The overall objective of the INFORMA project is to increase and share the science-based knowledge on multi-objective sustainable forest management (SFM) under climate change. More specifically, it will address the trade-offs and synergies between different management objectives, considering the environmental integrity, social acceptability, and economic feasibility, while maintaining carbon sinks, supporting genetic diversity and biodiversity conservation, and maintaining soil water resources in different European regions under changing climate. Concretely in WP4, INFORMA aims to propose spatially explicit portfolios of best regional multipurpose SFM practices for different future climate projections (RCPs), considering regional conditions and the need to adapt to and mitigate climate change at the same time with sustainable provisioning of multiple ecosystem services essential for human livelihoods and wellbeing. Overall, SFM requires spatially diverse forest management strategies that acknowledge all carbon pools, emissions, and removals simultaneously to provide longer-term and larger mitigation benefits, while supporting the provisioning of biodiversity and other ecosystem services at the same time.

Numerical models may be useful tools in forest management planning. However, such models have typically been developed and validated for different management purposes and considering specific biogeographical regions, which makes it difficult to apply them in different regions without re-parametrisation and validation of models. This holds also on forest simulation models PICUS, GOTILWA+ and SIMA and climate model LMDzOR, which we use in WP4 in model-based analyses to quantify impacts, trade-offs, and synergies of sustainable forest management under different climate projections. Specifically in Task 4.1 of WP4, we aim to harmonise the description of management rules and related output variables of PICUS, GOTILWA+, SIMA and LMDzOR models.

In this D4.1 (Harmonized management rules and model output) report, we introduce first the open-source versions of PICUS, GOTILWA+, SIMA, and LMDzOR models with their underlying definitions and new functionality. Secondly, we describe the harmonized definitions for forest management rules and output variables, which are required to simulate SFM practices and facilitate comparisons of simulation outputs by different models in different regions and climate projections. Specific focus was given on harmonization of model output variables such as carbon, nitrogen and water cycling, as well as structural diversity indices at the stand and landscape level.

3. Outlines for PICUS, GOTILWA+, SIMA, and LMDzOR models

In this chapter, we introduce the forest simulation models: PICUS, GOTILWA+ and SIMA, and the climate model LMDzOR and their underlying processes, key input and output variables, and forest management options (see Tables 1-3).

PICUS model. The forest model PICUS version 1.5 (Lexer and Hönninger, 2001; Seidl *et al*., 2005; Irauschek *et al*., 2017a, see Figure 1), henceforth referred to as PICUS, is a hybrid of the classical gap model components and process-based stand-level NPP algorithms (Landsberg and Waring, 1997). The spatial core structure of PICUS is an array of 10 x 10 m patches with vertical crown cells of 5 m in height. Interactions between patches are considered via a three-dimensional light model and spatially explicit seed dispersal. The basic simulation unit is the individual tree. Each tree is located on a patch, however the exact location within a patch is not defined. The

growth of trees is estimated in a two-step approach. First, based on the potential growth concept and environmental modifiers for temperature, water supply, nutrient supply and light a preliminary estimate is calculated. Stand-level NPP is estimated with a model of light use efficiency (Landsberg and Waring, 1997), which depends on intercepted radiation, temperature, precipitation, vapor pressure deficit, soil water and nutrient supply. Distribution of assimilates to individual trees is then based on the relative competitive success of the individual trees inferred from the preliminary growth estimates. Individual tree mortality depends on age and stress conditions. Spruce bark beetles, windstorms and ungulate browsing are disturbance factors that are explicitly considered. Natural tree regeneration considers seed production and distribution, germination, and establishment. Up to the height of 130 cm seedlings are simulated with a height class approach. Beyond that threshold, they are regarded as individuals in the tree population (Irauschek *et al*., 2017b). A soil model adressing the decomposition of organic materials follows C and N through the ecosystem and can be switched on for specific analysis tasks. PICUS includes a flexible management module enabling the implementation of silvicultural treatments at the tree level depending on tree attributes and patch location. The model includes 17 parameterized tree species and has been validated (Seidl *et al*., 2005; Didion *et al*., 2009) and applied in numerous studies all over Europe (Lexer *et al*., 2002; Maroschek *et al*., 2015; Pardos *et al*., 2015; Zlatanov *et al*., 2017). The model input and output variables and management rules are shown in Tables 1-3.

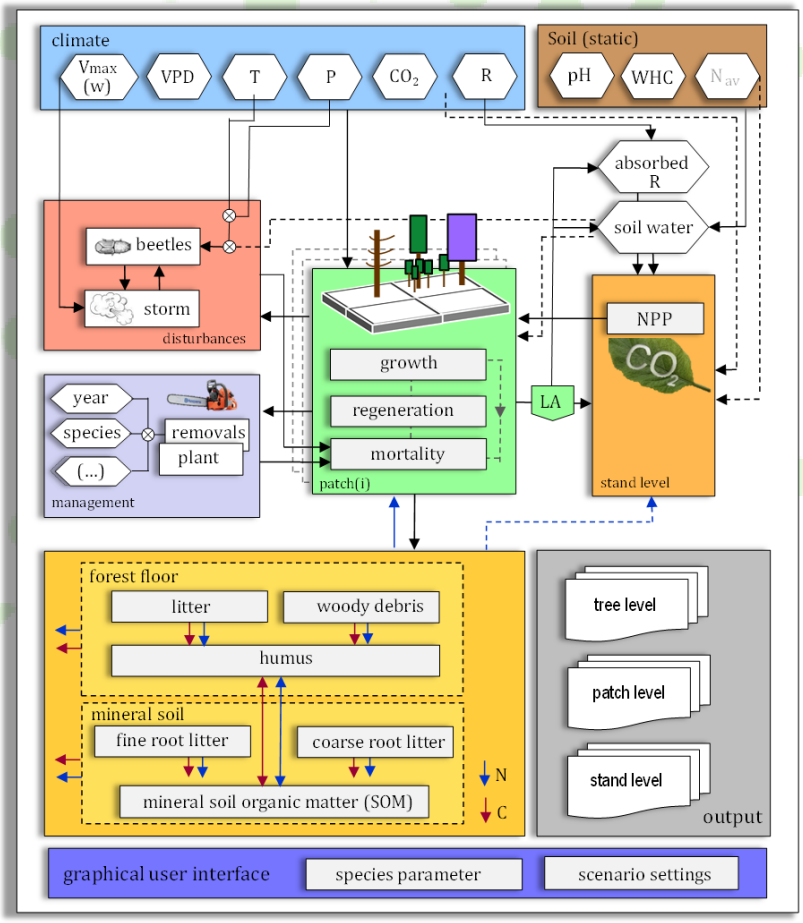

Figure 1. Schematic representation of PICUS model components.

GOTILWA+ model. GOTILWA+ (**G**rowth **O**f **T**rees **I**s **L**imited by **WA**ter, http://www.creaf.uab.es/gotilwa/, Gracia *et al*., 1999; Keenan *et al*., 2009; Nadal-Sala *et al*., 2017, Figure 2) is a process-based forest simulation model. It simulates daily carbon and water fluxes, and tree growth and stand development for a mono-specific multi-cohort forest stand. It allows to simulate both forest management and transient climate conditions. GOTILWA's performance has

been extensively validated in different European forests (e.g. Kramer *et al*., 2002; Morales *et al*., 2005; Keenan *et al*., 2010; Mahnken *et al*., 2022). Also, the model has been widely used for projecting forest development throughout the globe (e.g. Sabaté *et al*., 2002; Keenan *et al*., 2009; 2010; Reyer *et al*., 2017; Bugmann *et al*., 2019; Nadal-Sala *et al*., 2019; 2021). To run a simulation, GOTILWA+ requires as input data: a) daily meteorological drivers and atmospheric CO_2 concentration); b) stand characteristics; c) tree physiology parameters (i.e. photosynthetic and stomatal conductance, specific growth and maintenance respiration rates); d) allometric relationships between DBH and tree structural organs, and e) stand-specific conditions including soil hydrology and composition, soil respiration fluxes; and f) forest management.

Forest management is implemented in GOTILWA+ as an array of pre-defined successive interventions on forest structure that remove trees from the system. These interventions are implemented as inputs to the model. GOTILWA+ allows to simulate forest management both in plantations and in mature forests, with both even-aged and uneven-aged criteria. Interventions can be applied based on different forest structure variables, and they require as an input the intensity of the intervention, as well as the type of thinning applied. GOTILWA+ keeps track of the diameter class of the wood extracted, allowing the differentiation of its potential commercial use. Finally, after each thinning regeneration can occur, as forest management open gaps in the forest canopy and saplings can grow due to incoming radiation. The model input and output variables and management rules are shown in Tables 1-3.

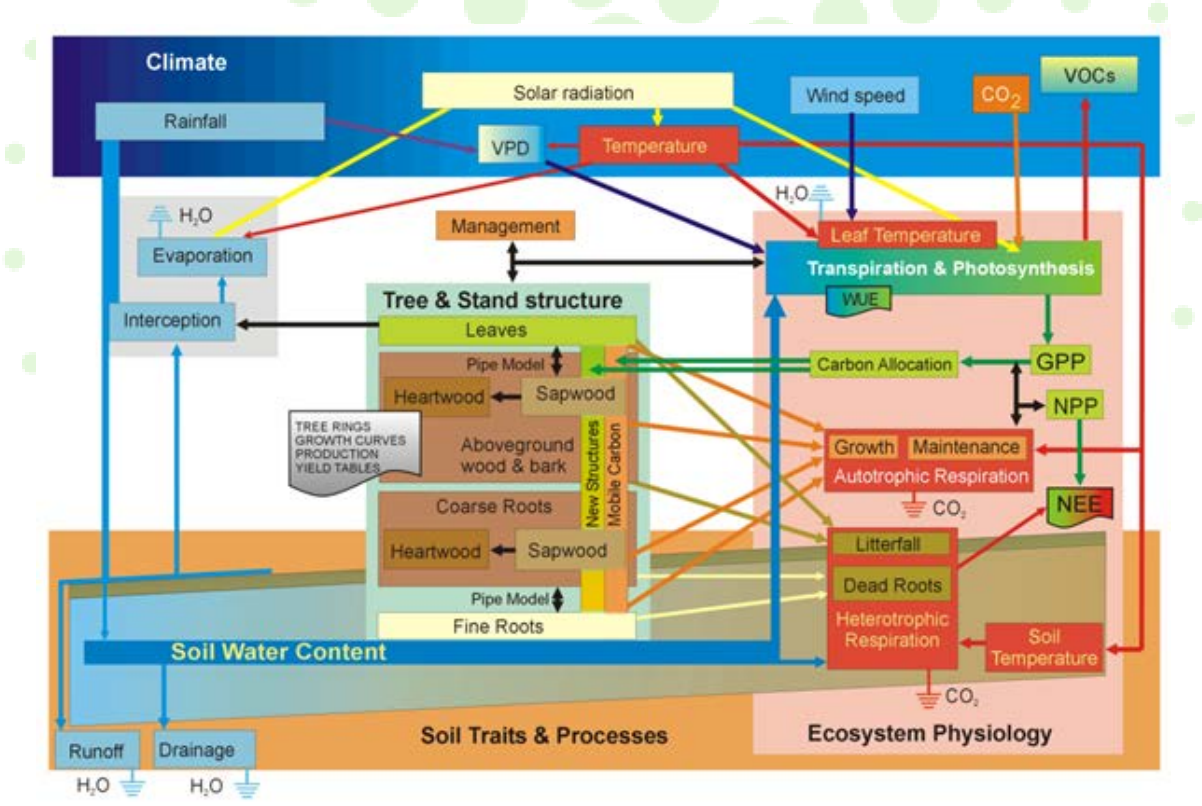

Figure 2. Scheme of the GOTILWA+ model processes and assumptions.

SIMA model. A gap-type forest ecosystem model SIMA (Kellomäki *et al*., 2008, 2018, 2019) simulates forest growth and dynamics as controlled by forest management and environmental conditions (climate and site) for the main boreal tree species (alone or as a mixture) throughout Finland. The diameter growth of trees is calculated as a function of the potential (maximum) diameter growth, which is scaled from 0-1 to meet the prevailing growing conditions (i.e. multiplier

1 = no reduction and <1 = reduction of diameter growth), i.e. the temperature sum (Tsum, degree days, d.d. >5ºC), light availability (along a vertical light gradient), soil moisture and supply of nutrients (e.g. nitrogen on mineral soils) (Figure 3). Additionally, the diameter of the tree and the atmospheric carbon dioxide (CO_2) concentration affect the potential diameter growth. Tree height is calculated based on tree diameter, and temperature sum (of current climate), to take into account also latitudinal genotype differences. The mass of tree organic matter (foliage, branches, stem, and roots) is calculated based on height and diameter. The probability of tree mortality is affected mainly by stand basal area and density, and maximum age of trees, but it may increase if the diameter growth is too low for two consecutive years. Litter from any living organ and the mortality of trees transfer carbon and nutrients into the soil, where litter and humus (soil organic matter) decay and release nutrients for tree growth and CO_2 is emitted into the atmosphere. The model simulations are carried out with a time step of one year on an area of 100 m^2, based on the Monte Carlo technique (i.e. birth and death of trees are stochastic events). Each simulation is repeated several times to determine the convergence of the mode (usually the mean value is used in data analysis. The model input and output variables and management rules are shown in Tables 1-3.

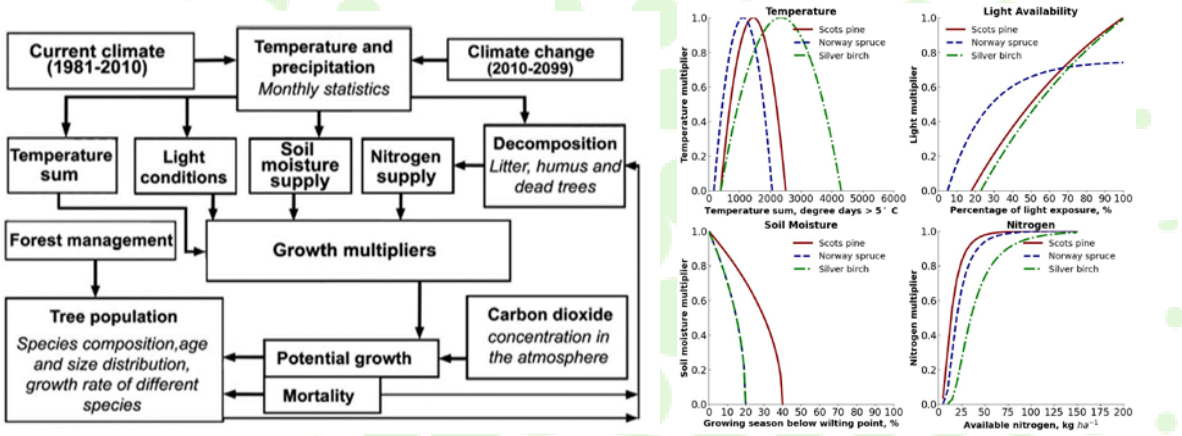

Figure 3. Outlines for SIMA model and its growth multipliers.

LMDzOR model. LMDzOR is a land-atmosphere model configuration of the IPSL (Institut Pierre Simon Laplace) Earth System Model. LMDzOR consists of a coupling between the LMDz atmospheric model and the ORCHIDEE land surface model (Figure 4). In this configuration, which will be used in task 4.6, sea surface temperature, sea ice extent and atmospheric composition are prescribed through external files. 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 climate effects of changes in the land surface and the effects of climate change on the land surface itself. 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. The land-only configuration, which will be used in Tasks 4.4 and 4.5, receives from the so-called forcing files the atmospheric conditions such as temperature, humidity, and wind, to mention a few. 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.

In the land-only configuration (Tasks 4.4 and 4.5), the user provides files describing the boundary conditions, namely the (initial) vegetation distribution, a soil map, the atmospheric CO2 concentration, and a river network map as well as the climate forcing. ORCHIDEE then uses these inputs to calculate its prognostic variables (Figure 4) focusing on the terrestrial water cycle, the surface energy balance, biogeochemical processes, and anthropogenic activities. The

biogeochemical processes, which are the focus of INFORMA, 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. *In the coupled configuration (Task 4.6)*, the user also needs to provide files describing the (initial) vegetation distribution, a soil map, and a river network map but the climate forcing now comes from LMDz as is the atmospheric CO2 concentration. The hydrological, energy and biogeochemical pools and fluxes calculated in ORCHIDEE (Figure 4) are passed to LMDz where they are accounted for in the calculation of the climate. Energy, water, carbon, and nitrogen exchanges between ORCHIDEE and LMDz are calculated at a 15-minute time step. In a zoomed set-up, the resolution over Europe is ~50 x 50 km.

Large-scale climate models such as LMDzOR require a limited number of contrasting forest management systems that are expected to be relevant on the spatial scale (e.g., 50 x 50 km) of global and regional modelling studies. LMDzOR allocates part of the carbon from photosynthesis to a user-defined number of diameter classes (the default is 3). The use of diameter classes introduces stand structure into LMDzOR which is the basis of the forest management strategies implemented in LMDzOR. 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 systems 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 LMDzOR model.

LMDzOR 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 the 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 LMDzOR whereas product and energy substitution should be accounted for through postprocessing. The model input and output variables and management rules are shown in Tables 1-3.

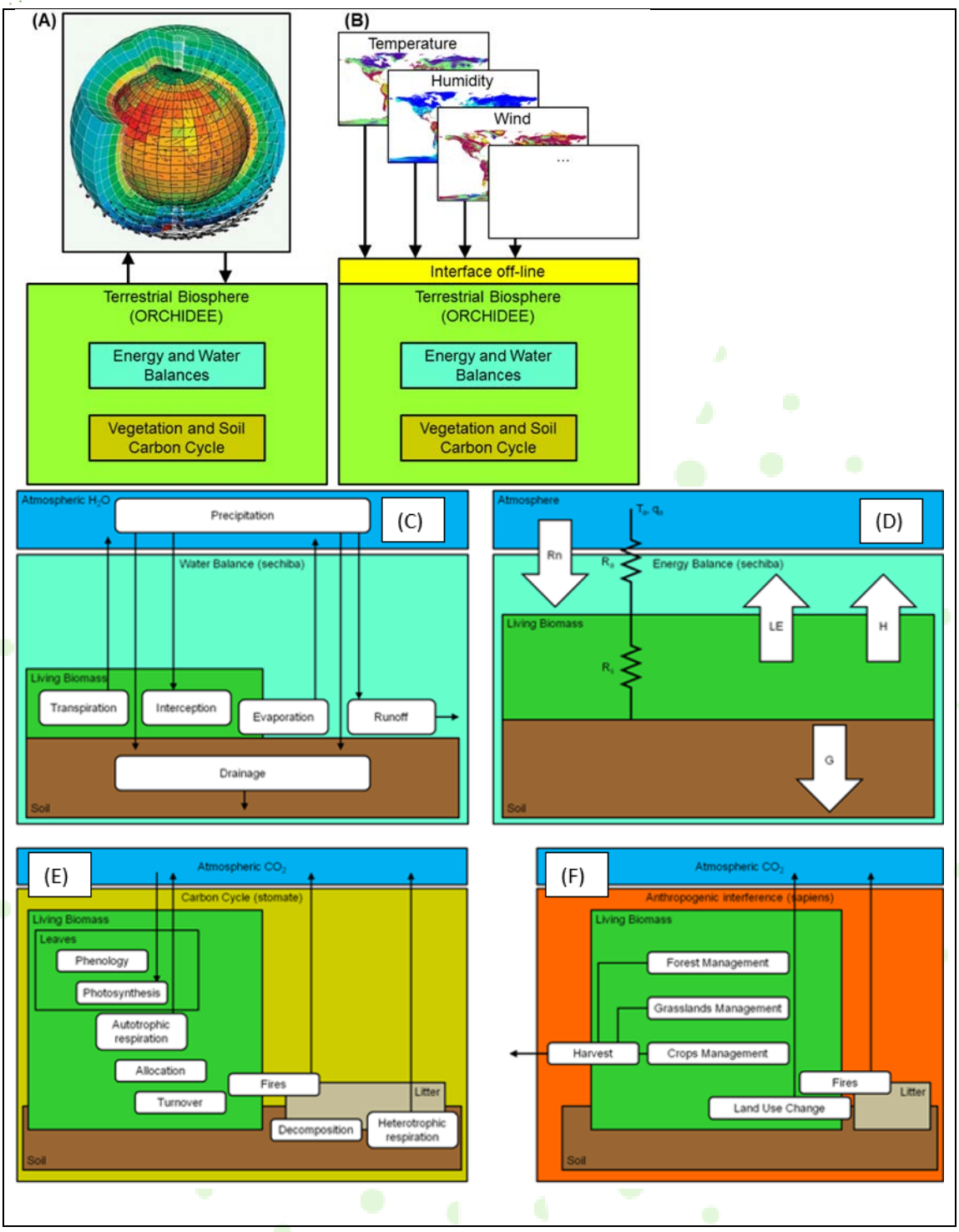

***Figure 4**. Overview of the configurations of the ORCHIDEE model: (A) Shows the coupled configuration in which the two-way interaction between the land and the atmosphere is accounted for. The land surface conditions affect the climate simulations which in turn affect the land surface conditions. (B) the land-only configuration in which the climate forcing affects the land surface but the simulated land surface conditions do not affect the climate forcing. Both configurations will be used in INFORMA. The coupled configuration will be used in the simulations for Task 4.6 and the land-only configuration will be used in Tasks 4.2-4.5. Processes represented in the ORCHIDEE model: (C) Main hydraulic processes simulated in ORCHIDEE, (D) Main energy fluxes and pools simulated in ORCHIDEE, (E) Main biogeochemical processes simulated in ORCHIDEE, and (F) Main anthropogenic processes simulated in ORCHIDEE.*

Table 1. Input data required by PICUS, GOTILWA+, SIMA and LMDzOR; N.a. = not available.

Input data	PICUS	GOTILWA+	SIMA	LMDzOR
Climate forcing	Daily point-based min and max temperature (°C), precipitation (mm), VPD (kPa), global radiation ($MJ \cdot m^{-2} \cdot day^{-1}$), max windspeed (m/s) (if available). Available *climate data (Austria): RCP2.6, RCP4.5 and RCP8.5 scenarios plus historic climate (1980-2021) at regional scale.*	Daily point-based min and max temperature, precipitation, relative humidity / vapor pressure in the atmosphere, wind speed and radiation. *Climate data (Spain): Downscaled daily data of P, Tmin and Tmax available from the Spanish Meteorological Agency (AEMET) at a 5x5 km grid resolution, for the scenarios Historic, RCP4.5, RCP6.0, RCP8.5. The availability of the radiation and atmospheric water vapor pressure for the same period.*	Monthly point-based mean temperature (°C), monthly precipitation (mm), annual atmospheric CO_2 concentration (ppm). Available *climate data (Finland): FMI: 10 km x 10 km. Time horizon: 2010-2100. Present climate: 1981-2010. Future pathways: RCP2.6, RCP4.5 and RCP8.5 (multi-model means for 28 GCM runs). Monthly mean temperature, monthly precipitation, annual atmospheric CO_2 concentration. Also, for some GCMs RCP4.5 and RCP8.5 (HadGEM2-ES, MPI-ESM-MR, CanESM2 and MIROC5): Daily min and max temperature* (°C), *air pressure (Pa), precipitation (inc. Snow, mm), relative humidity (%), incoming radiation* ($MJ\ m^{-2}\ day^{-1}$).	Daily rasterized climate variables (atmospheric temperature (K), air humidity (%), wind speed (m/s), pressure (Pa), rain (mm) and snow (mm), and global radiation ($W\ m^{-2}$) for the time horizon of the simulation. For the model spinup CRU-JRA from 1901-2015 will be used. For spinups with disturbances, detrended CRU-JRA will be used. *Historical data: CRU-JRA. Future climate: IPSL-CM simulations for AR6.*
Vegetation distribution	Point-based information on stand type; within each stand tree-level information, spatially explicit at 10x10m resolution (patch scale)	Point-based information on tree species and DBH classes (every 5 cm) distribution in each stand.	Point-based information on tree species, with DBH (at 1.3 m above stem base, in cm, possibly cohorts) and number of trees per hectare (trees/ha) per tree species (and cohorts if available) in each stand.	Single map with the fraction of forest in each grid box (unitless; 0-1) as well as the PFTs in each grid box. The base layer is ESA CCI land cover for 2015 which is further processed to meet the LMDzOR requirements.
Soil properties	Point-based information on water holding capacity (maximum soil depth 100cm), plant available Nitrogen (kg/ha*yr) , soil pH	Point-based information on soil depth, stoniness, and soil C content (% weight) in the organic horizons.	Point-based information on site fertility type, amount of organic matter ($Mg\ ha^{-1}$ (Tons) affecting available nitrogen, soil type (e.g., sand, clay, etc) affecting water holding capacity (= field capacity, cm/30 cm soil depth) and wilting point (cm /30 cm soil depth), inducing drought).	Single initial map with Sand, loam and clay content (%) and pH (unitless). The model is parameterized for the 12+1 USDA soil classes. Data: USDA soil map.
Topography	N.a.	Average slope in the stand.	N.a.	Single initial map DTM (m a.s.l.).
N-inputs	Nitrogen deposition (annually) if full soil model is switched on	N.a.	Nitrogen deposition ($kg\ N\ ha^{-1}$) (annually) and forest fertilization e.g. ($kg\ N\ ha^{-1}$ if applied)	Annual deposition maps ($g\ N\ m^{-2}\ y^{-1}$) for the time horizon of the simulation. Maps provided by NMIP cover 1860-2015.
Initial state of stand/FMU	Required input: Point-based information on species and diameter distribution in the first year of the simulation, qualitative info on species mingling pattern, height-diameter relation; generated initial forest state: tree-based, spatially explicit at 10x10m (patch scale)	Point-based information on tree species and diameter distribution in the first year of the simulation.	Point-based information on species and their diameter (cm) (cohorts) in the first year of the simulation. (Also, data for calibration of height (m) prediction based on diameter in SIMA model, if available).	Single initial map of the mean diameter (m) for the first year of the simulation horizon. Currently working on a nudged spinup procedure based on the Pucher *et al*. (2022) map. Due to data sparsity all PFTs within a grid box get the same initial diameter. Suitable for large scale gradients across Europe but too rough for national simulations.
Forest management	Information on present day (historic) forest management is used for control simulations.	Point-based information on present day forest management is used for control simulations.	Point-based information on present day forest management is used for simulations.	Single initial map [1] of present-day forest management (currently 5 different management systems) is used for control simulations.

[1] LMDzOR: A European map based on McGrath *et al*., 2015, distinguishes unmanaged, thin & fell and coppice. As an alternative a global reconstruction (unpublished) based on Hurtt v2 could be used. The benefit of using D4.2 for these maps seems small given the targeted spatial domain (and the very small share of the FMU therein). LMDzOR requires also as input land use history: Annual rasterized maps of vegetation fraction and species distribution from 1900 to 2015. Accounting for different land use scenarios in INFOMRA future simulations open and needs to be assessed whether feasible. Hurtt v2, used within the AR6 context. A European product, i.e., Hoffman *et al*. (2021), could be used.

Table 2. Management options (rules) by PICUS, GOTILWA+, SIMA and LMDzOR; N.a. = not available

Aceglass management	**PICUS**	**GOTILWA+**	**SIMA**	**LMDzOR**
Clearcut followed by planting of seedlings	Year / dimension of trees at which clearcut occurred, density and composition of the planted seedlings (n/ha) (also spatial distribution at 10x10m resolution; also in combination with natural regeneration	Year in which clearcut occurred, density of the planted seedlings	Diameter (cm) of dominant trees or stand age (years) at the time of the clearcut, followed by planting the desired number of seedlings per hectare of selected tree species (Scots pine, Norway spruce or silver birch); also in combination with natural regeneration	Basal area (m^2 ha^{-1}) and relative density (unitless, 0-1) at the time of the clear cut. A new stand of the same or another plant functional type is established.
Clearcut followed by natural regeneration	Seeds either from parent trees on-site only or with external seed input as an addon	Year at which clearcut occurred, density of the initial natural regeneration	N.a. (Natural regeneration (Scots pine, Norway spruce or silver/downy birches) could be used to provide additional seedlings in the planted stand (or in a Norway spruce stand with selective cuttings)	Basal area (m2 ha^{-1}) and relative density (unitless, 0-1) at the time of the clear cut. A new stand of the same plant functional type is established.
Tending of seedling stand (Precommercial thinning)	Tree removals to regulate mixture or density until the target mixture or density is obtained (residual n/ha per species)	Tree removals to regulate mixture or density until the target mixture or density is obtained	Tree removals to regulate mixture or density until the target mixture or density is obtained	Tree removals to obtain target basal area and relative density
Thinning from below	Standard: tree removals as relative volume share from a stand level removal value (m3/ha) in 5 relative diameter classes; any other removal scheme can be implemented	Target biomass / stem density / wood volume / basal area extracted; can also be implemented as target for remaining biomass / stem density / wood volume / basal area	Tree removals start from smallest diameter (height) classes. Thinning could be done based on dynamic thinning rules (stand basal area (m^2 ha^{-1}) thresholds before and after thinning versus stand dominant height (i.e. mean height of 100 largest trees in a stand) or by using fixed years for thinning and giving thinning intensity in terms of % for basal area removal (species by species)	Relative density (unitless, 0-1) after thinning. Tree removals start from the smallest diameter class.
Thinning from above	Standard: tree removals as relative volume share from a stand level removal value (m3/ha) in 5 relative diameter classes; any other removal scheme can be implemented	Target biomass / stem density / wood volume / basal area extracted; can also be implemented as target for remaining biomass / stem density / wood volume / basal area	Tree removals start from the smallest diameter (height) classes. Thinning based on dynamic thinning rules (stand basal area thresholds before and after thinning versus stand dominant height) or using fixed years and thinning intensity as % of basal area removal	Relative density (unitless, 0-1) after thinning. Tree removals start from the largest diameter class.
Forest fertilization	N.a.	N.a.	Nitrogen fertilization on upland soils, kg N ha^{-1} at a certain year	Nitrogen fertilizer, gN m^{-2} y^{-1} added
Unevenaged management	Single-tree and patch-level cutting schemes	Selective single-tree cutting schemes removal of trees mostly from upper and middle canopy layer	Selective single-tree cutting schemes, removal of trees mostly from upper and middle canopy layer	Selective single tree cutting schemes, removal mostly from upper and middle canopy layer, removal target a prescribed relative density (unitless, 0-1).
Salvage logging after storm	Yes; biomass compartments which are salvaged can be specified	N.a.	N.a.	Salvage logging is applied to managed forests. Dead wood is left on site in unmanaged forests.
Monoculture or species mixtures (tree	Any mixture of eligible species can be simulated (ca. 20 tree	Only monocultures can be simulated	Both possible	Only monocultures can be simulated (plant functional types)

species)	species calibrated)			

Table 3. Description of selected common outputs (variable groups) available by PICUS, GOTILWA+, SIMA and LMDzOR. N.a. = not available.

Output variables	**PICUS**	**GOTILWA+**	**SIMA**	**LMDzOR**
Tree/stand characteristics	Height (m), diameter (cm) at breast height, growth of stem volume, volume (m3/ha*yr), basal area (m2/ha), number of trees per hectare, biomass separately for different organs (total and by tree species; (kg/ha), standing and ground dead wood (m3/ha)	Dominant height, average diameter at breast height, growth of stem volume, standing volume, basal area, tree density, aboveground and belowground biomass (total, also tree compartments)	Height (m), diameter at breast height (cm), growth of stem volume($m^3\ ha^{-1}\ y^{-1}$), volume($m^3\ ha^{-1}$), basal area($m^2\ ha^{-1}$), number of trees per hectare, biomass separately for different organs (total and by tree species), standing and ground dead wood (Mg ha^{-1})	Dominant height (m), dominant diameter (m), average diameter (m), average height (m), growth of stem volume ($m^3\ m^{-2}\ y^{-1}$, standing volume ($m^3\ m^{-2}$), basal area ($m^2\ ha^{-1}$), tree density (trees m^{-2}), aboveground and belowground biomass (gC m^{-2}) total and for the different tree compartments), recruitment (gC $m^{-2}\ y^{-1}$), mortality (gC $m^{-2}\ y^{-1}$), damage volumes (gC $m^{-2}\ y^{-1}$)
Carbon dynamics	Carbon in trees, standing deadwood, organic layer, soil (kg/ha)	Net Ecosystem Exchange, Gross primary productivity, Net primary productivity	Carbon in trees, soil, and total (Mg C ha^{-1}), Net Ecosystem Exchange (sum of CO_2 emissions from soil and CO_2 uptake by trees) (g $Co_2\ m^{-2}$)	Net ecosystem exchange, gross primary productivity, net primary productivity, net biome production, autotrophic respiration, heterotrophic respiration (all in gC $m^{-2}\ y^{-1}$)
Timber and energy wood	Any tree biomass compartment (stem, branches, leaves) (kg/ha)	Wood yield, wood yield per DBH class	Timber in terms of saw logs and pulpwood ($m^3\ ha^{-1}$), and energy biomass (also biomass fractions) (Mg ha^{-1})	Wood yield per diameter class (gC $m^{-2}\ y^{-1}$), wood product pools (gC), emissions from wood product pools (gC y^{-1}); Post-processing: material and energy substitution (gC y^{-1})
Available nitrogen for growth	N.a.	N.a.	Available nitrogen in soil (kg N ha^{-1}), atmospheric deposition, N fertilization (kg N ha^{-1})	Available nitrogen in soil (gN m^{-2}), atmospheric deposition (gN $m^{-2}\ y^{-1}$), fertilization (gN $m^{-2}\ y^{-1}$)
Available water in soil	Water balance calculation (mm)	Soil water content, interception, drainage, runoff (all in mm y^{-1})	Water balance between precipitation and evapotranspiration, number of dry days	Water balance between precipitation, transpiration, evaporation, run-off, interception, and drainage (all in mm y^{-1}).
Structural diversity indices	N.a., Post hoc calculation on individual tree (cohort) data possible	N.a., Post hoc calculation on individual tree (cohort) data possible	N.a. Post hoc calculation on individual tree (cohort) data possible	N.a. Post hoc calculation on individual tree (cohort) data possible
Tree water use	Evaporation, transpiration	Transpiration, water use efficiency in wood production	Evapotranspiration with its components: evaporation, transpiration, and interception (mm yr^{-1}), also: Run-off = Precipitation-Evapotranspiration (mm yr^{-1})	Transpiration coupled to stomatal conductance and thus photosynthesis (mm gC^{-1})

4. Harmonized forest management rules and output variable definitions of models

We introduce here the common and harmonized forest management options (rules, Table 4) and output variables available by each model (Table 5). Based on these, it can be evaluated which kind of comparisons are possible, considering management options at stand level and simulation outputs, respectively, between models in different case study areas. The PICUS model will be run for the Alpine, Boreal and Continental Forest Management Units (FMUs), the GOTILWA+ model for the Mediterranean, Continental and Atlantic FMUs and the SIMA model for Boreal,

Alpine, and Atlantic FMUs. All models can simulate typical management options used for age class forestry and uneven aged forestry as shown in Table 4. However, the criteria used for timing and intensity of different management options will vary between models as well as tree species which they can simulate either as single tree species stands or mixtures.

Table 4. The harmonized forest management rules simulated by PICUS, GOTILWA+, SIMA, and LMDzOR.

Ageclass forestry	**Models**
Final harvest / regeneration methods:	
1. *Clear cutting*: All trees removed from the forest; criteria for timing of final felling: stand age, basal area or mean DBH	PICUS, GOTILWA+, SIMA, LMDzOR
2. *Uniform shelterwood system*: share of canopy trees removed in one or more consecutive cuts, final cut removes residual canopy trees	PICUS, GOTILWA+
3. *Irregular shelterwood system:* patch cuts, enlargement of patches until all canopy trees have been harvested	PICUS
4. *Shelterwood strip system*: Shelterwood cut in strip of 2 tree lengths (20% of volume removed, all dimensions) followed by removal of shelter (100%) 10-20 years later	PICUS
Forest Regeneration:	
1. *Natural*: Natural seeding	PICUS, GOTILWA+, SIMA, LMDzOR
2. *Artificial – planting*: Seedlings	PICUS, GOTILWA+, SIMA, LMDzOR
3. *Planting/Natural seeding together*	PICUS, SIMA, GOTILWA, LMDzOR
Tending measures in youth and thicket stage:	
1. Young stand tending (pre-commercial thinning) is typically done to regulate mixture or density until target mixture or density is obtained, and seedlings left following tending belong to upper and intermediate canopy storey	PICUS, GOTILWA+, SIMA, LMDzOR
Thinning in the pole and mature stand:	
1. *Thinning from below (=low thinning):* Removal of trees starts from lower layer of a canopy (suppressed and intermediate trees), removal percentage, e.g. based on basal area of trees	PICUS, GOTILWA+, SIMA, LMDzOR
2. *Thinning from above:* Removal of trees starts from upper (and middle) layer of a canopy (dominant and codominant trees), removal percentage, e.g. based on basal area of trees	PICUS, GOTILWA+, SIMA, LMDzOR PICUS, GOTILWA+, LMDzOR
3. *Combination from above and from below:* Removal of trees from all canopy layers	PICUS, GOTILWA+, SIMA, LMDzOR
4. *No thinning:* no trees are removed from a stand (only final felling optionally)	
Unevenaged forestry	
1. Selective thinning, removal % of basal area until target (removal of trees mostly from upper and middle canopy layer, depending on removal intensity)	PICUS, GOTILWA+, SIMA, LMDzOR
Monoculture or tree species mixtures PICUS: Any mixture of eligible species can be simulated (ca. 20 tree species calibrated), tree species include e.g. *Picea abies, Abies alba, Larix decidua, Fagus sylvatica, Acer pseudoplatanus* GOTILWA+**:** Only monocultures. Regeneration is possible. Tree species include: *Quercus ilex subsp. ilex* or *Quercus humilis, Fagus sylvatica; Pinus sylvestris; Pinus nigra; Pinus halepensis; Pinus pinaster* SIMA: Both possible to simulate, tree species include *Pinus sylvestris*, *Picea abies* and *Betula* spp. (silver/downy birches) LMDzOR: Only monocultures, model uses plant functional types which combine parameters of different tree species with similar leaf traits growing in the same biome.	

Table 5. Harmonized output variables with their short names and units used in PICUS, GOTILWA+, SIMA, and LMDzOR models. N.a = output variable not available; Tbi = to be included.

Variable	Scale	LMDZOR	PICUS	GOTILWA+	SIMA
Basal area (m^2 ha^{-1})	stand level	BA (m^2 m^{-2})	BasalArea_m2_ha (m^2 ha^{-1})	BA (m2 ha^{-1})	BA (m^2 ha^{-1})
Standing volume (m^3 ha^{-1})	stand level	WOOD_VOL (m^3 m^{-2})	Volume_m^3_ha V (m^3 ha^{-1})	STV (m^3 ha^{-1})	V (m^3 ha^{-1})
Wood increment (m^3 ha^{-1} y^{-1})	stand level	WOOD_VOL_INC (m^3 m^{-2} day^{-1}) (gross incr.)	AnnualGrowth_m^3_ha (gross) (m^3 ha^{-1} yr^{-1})	WDP (kg ha^{-1} yr^{-1})	VG (m^3 ha^{-1} yr^{-1}) (gross incr.)
Stand density (trees ha^{-1})	stand level	IND (trees m^{-1})	Stems_ha (n/ha)	NStemsha (trees ha^{-1})*	N (trees ha^{-1})
Stand density (trees ha^{-1})	DBH class	N.a	Stems_ha_DBH (n/ha)		N.a (may be provided)
Height of dominant trees (m)	stand level	HEIGHT_DOM (m)	DomHeight_m (m)	DomHeight_m (m)	HD (m)
Quadratic tree diameter (m)	stand level	DIAMETER (m)	DBHm (cm)	DBH_cm (cm)	DBH (cm)
DBH (m)	DBH class	N.a	N.a	Defined as the DBH for each class (cm)	N.a (may be provided)
Wood harvest (m^3 ha^{-1} y^{-1})	Stand level	CUM_WOOD_HAR (m3 m^{-2} y^{-1})	CumRemovedVolumem^3_ha (m^3 ha^{-1} y^{-1})	CumYield_m^3ha (m^3 ha^{-1})	cumTimber (m^3 ha^{-1})
Wood harvest (m^3 ha^{-1} y^{-1})	DBH class (5 cm interv/ species)	N.a	Tbi	As wood harvest, but per DBH class	N.a
Aboveground living biomass (gC m^{-2})	Stand level	TOTAL_AB_M_INV_c (gC m^{-2})	ForestC_kg_ha (kg C ha^{-1})	Abovegroundbiomass_ MgMOha (MgMO ha^{-1})	ABW (Mg C ha^{-1})
Belowground living biomass (gC m^{-2})	Stand level	TOTAL_BE_M_INV_c (gC m^{-2})	N.a	Belowgroundbiomass_M gMOha (MgMO ha^{-1})	BLW (Mg C ha^{-1})
Total living biomass (gC m^{-2})	Stand level	TOTAL_M_c (gC m^{-2})	N.a	totalbiomass_MgMOha (MgMO ha^{-1})	SBM (Mg C ha^{-1})
Lying dead wood (gC m^{-2})	Stand level	LITTER_WOD_AB_c (gC m^{-2})	ForestDeadC_kg_ha	N.a	GDW (Mg C ha^{-1})
Standing dead wood (gC m^{-2})	Stand level	N.a	N.a	N.a	SDW (Mg C ha^{-1})
Litter excl. dead wood (gC m^{-2})	Stand level	EXC_LITTER_M_c	N.a	N.a	Litter (Mg C ha^{-1})
Litter incl. dead wood +organic soil (gC m^{-2})	Stand level	INC_LITTER_M_c	N.a	OrganicSoilCarbon_Mg Cha	GDW + SDW + Litter + OrgSoil (Mg C ha^{-1})
Organic soil (g C m^{-2})	Stand level	??	??	??	OrgSoil (Mg C ha^{-1})
Mineral soil (gC m^{-2})	Stand level	TOTAL_SOIL_c	SoilC_kg_ha	InorganicSoilCarbon_Mg Cha	MSoil (Mg C ha-1)
Transpiration (mm $year^{-1}$)	Stand level	transpir	N.a	Transpiration_mm (mm $year^{-1}$)	Transp (mm $year^{-1}$)
Evaporation (mm $year^{-1}$)	Stand level	latent	N.a	Transpiration (mm) + Interception (mm)	Evap (mm $year^{-1}$)
Interception (mm $year^{-1}$)	Stand level	inter	N.a	Interception_mm (mm $year^{-1}$)	Intercep (mm $year^{-1}$)

5. Open-source versions of models

We show in Table 6 information regarding the availability of open-source versions of different models.

Table 6. Licenses of the different models used in INFORMA.

Model	License	Quality checks	Current approach for publications and citation
PICUS	N.a.	Coded in C++. Source code available upon request.	N.a
GOTILWA+	CeCill. The CeCILL grants users the right to copy, modify, and distribute the licensed software freely. It excludes commercial usage.	Coded in Visual Basic 6. GOTILWA+ benchmark against measurements has been evaluated recently in Nadal-Sala *et al.*, (2019) and in Mankhen *et al.*, (2022). It is subject to periodical revision and outputs consistency checks.	Cite as model version. Main citations are: Gracia *et al.*, (1999) and Nadal-Sala *et al.*, (2017)
SIMA	N.a.	Coded in Fortran (model) and Visual Basic (user interface). Source code available upon request.	N.a.
LMDzOR	CeCill. The CeCILL grants users the right to copy, modify, and distribute the licensed software freely. It excludes commercial usage.	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.	Permanent doi of model code. E.g. 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).

6. Discussion

We introduced in this D4.1 report the open-source versions of PICUS, GOTILWA+, SIMA, and LMDzOR models and their underlying definitions and new functionality added in the course of INFORMA so far (or which will be still added to facilitate comparisons of simulation outputs under different management regimes and climate projections between the different models). The harmonized definitions for forest management rules and output variables described in this report facilitate the direct comparisons of simulation outputs by different models under various management regimes and climate scenarios. We did not try to uniformise the model's management rules (and criteria) as such, instead, we aimed to ensure that the different models use the same definitions for different management options. This was done because management rules and criteria may also differ largely depending on tree species and management approaches in different biogeographical regions.

Based on this work, we are better aware of possible limitations and possibilities for the models' comparison and use, e.g. tree species and management options as well as model outputs available by different models. Because forest simulation models PICUS, GOTILWA+ and SIMA were originally developed for different bio-climatic regions and management purposes, there is little overlap between the models in terms of tree species. All these models are capable of simulating monocultures, but only PICUS and SIMA models can simulate mixtures of tree species. For models dealing with large spatial domains like the climate model LMDzOR, the real tree species diversity is too high to parameterize all species in a single model. For that reason, plant functional types are used instead, which further complicates the comparison of regional and global models.

In a next step, we will run idealized simulations to verify the ability of the land-only configuration of the LMDzOR model to reproduce the sensitivities of PICUS, GOTILWA+ and SIMA to

management regimes and climate projections (Task 4.4). The models will also be further parameterized, if necessary, to simulate a wide variety of forest management alternatives in the study cases under different climates (Task 4.2). The PICUS model will be run at stand level for the Alpine, Boreal and Continental FMUs, the GOTILWA+ model for the Mediterranean, Continental and Atlantic FMUs and the SIMA model for Boreal, Alpine, and Atlantic FMUs. The comparison of models' performance in neighbouring biogeographical regions will employ stand level simulations with selected (available by models) tree species with and without forest management under different climate projections. PICUS, GOTILWA+ and SIMA will be run both at the stand and FMU levels in biogeographical regions for which they have been parametrised and evaluated using various forest management objectives and regimes and climate projections in simulations to suggest best SFM strategies at the stand and regional levels (Tasks 4.2 & 4.5). LMDzOR climate model will be used to quantify the climate impact of SFM strategies suggested in different regions and climate projections (Task 4.6).

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