# ARANGE Deliverable D2.1

## Improved and tested forest models for case study regions


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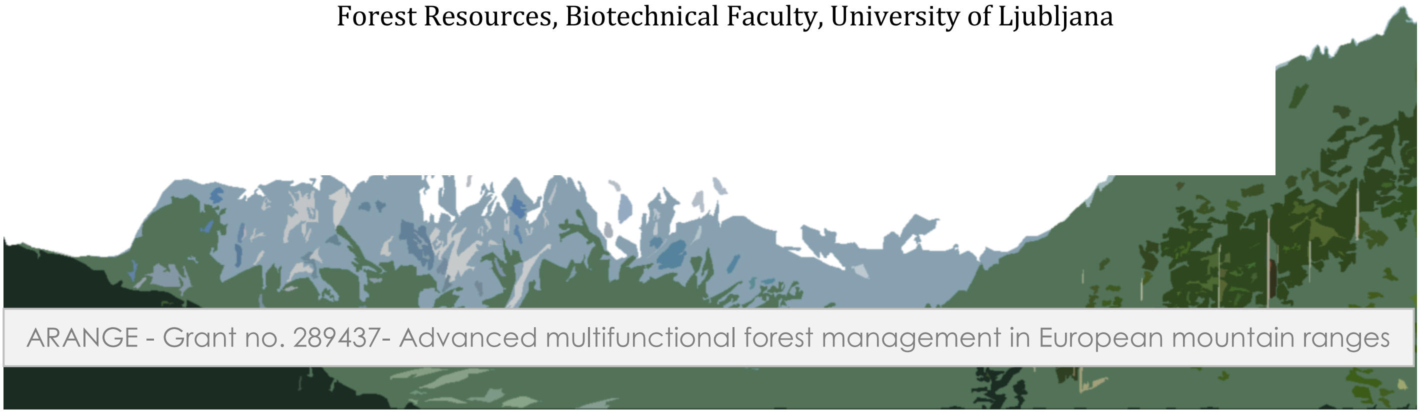

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Abstract:

Forest models are valuable tools that permit us to simulate forest dynamics at high accuracy and detail at different spatio-temporal scales. This is important to evaluate the spatial interdependencies of ecosystem goods and services. A wide range of state-of-the-art models of forest dynamics have been developed by the modeling partners of the ARANGE consortium. The set of forest models available in ARANGE includes both stand-level and landscape-level approaches, i.e. PICUS [BOKU]; ForClim and LandClim [ETHZ]; SAMSARA/CAPSIS [IRSTEA]; SILVA-SI/WEKA [UL]; Heureka [SLU]; SIBYLA [NFC]; MOSES [BOKU] and BIOME-BGC [BOKU]. In the first project year, model development and adaptation of the models to the ARANGE Case Study Areas (CSAs) has taken place; some models were applied preliminarily in several ARANGE CSAs, while others were tested mainly in one CSA. Most of the models were improved in terms of their structure and behavior with respect to a range of features. Overall, the forest models available in ARANGE have been tested for a wide range of conditions in the CSAs, and they have been set up so as to be ready for model application in the CSAs under specific site conditions, using measured stand data for model initialization. The next steps will be to define the management regimes so as to be able to simulate realistic forest structure data.

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# 1 Introduction

Within the ARANGE consortium, a wide range of state-of-the-art models of forest dynamics have been developed and are being applied at a range of sites, including PICUS [BOKU]; ForClim and LandClim [ETHZ]; SAMSARA/CAPSIS [IRSTEA]; SILVA-SI/WEKA [UL]; Heureka [SLU]; SIBYLA [NFC]; MOSES [BOKU] and BIOME-BGC [BOKU]. This set of models includes both stand-level and landscape-level approaches, thus permitting us to simulate forest dynamics in ARANGE at high accuracy and detail at different spatio-temporal scales (i.e., up to ca. 100 $km^2$), which is important to evaluate the spatial interdependencies of ecosystem services.

While these models have proven to be valuable tools for studying forest dynamics in various mountain regions, they have not always been applied in and across the case study areas (CSAs) of the ARANGE project. A crucial first step in ARANGE was thus to set up and test the models for the CSAs, preferably against long-term empirical data. Within ARANGE, there is some scope for model improvements, but this will not be a major effort of the project, and model development must be concluded within the first project year.

This Deliverable reports on the state of the models, the model tests conducted, and the plans for further model applications in the CSAs at the end of the first year of the ARANGE project.

# 2 Report by model

## 2.1 ForClim

### 2.1.1 Brief overview of model

#### 2.1.1.1 Model structure

ForClim is a climate-sensitive forest succession ("gap") model that has been developed to simulate forest dynamics over a wide range of environmental conditions. The model operates at the stand level and uses only a minimum of ecological assumptions to capture the influence of climate and ecological processes on long-term forest dynamics. ForClim is currently parameterized for 31 European tree species and has been tested for the representation of natural forest dynamics of temperate forests of the Northern Hemisphere. ForClim can also be used under scenarios of anthropogenic climate change. ForClim is structured into four sub-models: weather, water, plant, and management. The former two provide input variables for growing season temperature, minimum winter temperature and soil moisture based on a stochastic weather generator that is based on long-term monthly climate data and soil characteristics. The plant sub-model is the core of ForClim, where establishment of new trees is simulated based on bioclimatic conditions (see above), light availability and browsing intensity. Tree growth depends on bioclimatic conditions, light availability and nutrient availability. The model is distance-independent. Tree mortality is modeled as a combination of an age-related and a stress-induced component. The latest version of the model features an extensive management submodel, comprising a wide range of silvicultural treatments such as clearcutting, shelterwood, thinning, planting, and others.

#### 2.1.1.2 Input requirements (climate, land surface, forest properties)

| Climate requirements | Environmental/Site variables | Forest data[1] | Management data |
|---|---|---|---|
| Monthly mean temperature<br><br>Monthly mean precipitation | Water holding capacity (mm)<br><br>Available nitrogen (kg/ha*yr)<br><br>Geographical coordinates<br><br>Slope<br><br>Aspect | Minimum: species, number of trees [#], DBH (cm, at single tree resolution)<br><br>Maximum: species, number of trees [#], DBH (cm), tree height (m) all at single tree resolution, LAI, average size of the forest area (ha) | Type of management, number of management phases, starting and ending year of each harvesting phase, timing of harvest actions (cycle length)<br><br>Intensity of the harvest (% of trees) or basal area removed ($m^2$/ha), target diameter (cm), desired density of the sheltering trees (% trees), desired residual basal area ($m^2$/ha), highest diameter class the stand should have and width of diameter class (in case of selection felling) |

### 2.1.2 Model development in ARANGE (finished by M12)

A new iteration algorithm for optimizing Leaf Area Index at the beginning of the simulation (model initialization) was implemented when the model is initialized from field data (which hardly ever contain tree-specific leaf area data). This improvement was important to avoid strong fluctuations of tree numbers at the beginning of the simulation, which resulted from excessive shading. Furthermore, the dbh-height relationship in ForClim was adjusted for a better representation of vertical canopy structure.

[1] if the model is initialized from field measurements (optional); data required at stand scale level, not necessarily spatially explicit.

*Quercus pyrenaica* was added to the pool of European tree species to improve the simulated species composition in CSA_1. Each species requires 15 parameters, including responses to climate (e.g. the lower limit of the degree-day range and minimum winter temperature). The required parameters were estimated from empirical and literature data and were calibrated along elevation gradients in CSA_1 (Valsain). The parameterization of additional tree species is in progress (e.g., *Q. ilex, Pinus nigra*).

Improvements for a higher accuracy of simulated basal area (BA) under conditions of measured BA >50 m²/ha have begun, and will continue outside the scope of ARANGE.

### 2.1.3 Results from preliminary model applications to CSA(s)

ForClim has been applied preliminarily in all ARANGE CSAs. The model was set up using the ARANGE baseline climate (from T1.2). Site variables (soil characteristics, aspect) were provided directly by the case study responsible persons. In the absence of accurate site information, standard values used in other simulation studies were used. To date, ForClim has not been initialized using empirical forest data from the CSAs. With the exception of a few trial simulations, forest management was not simulated. Therefore, simulations conducted to date refer to "potential natural vegetation", which allows for an evaluation of the general suitability of ForClim in the CSAs.

The model was applied in all CSAs along an elevation gradient (with the exception of CSA_5, Sweden), simulating forest growth at different elevations, based on available baseline climate.

The ForClim results by CSA can be summarized as follows:

CS_1 Valsain (Spain): the model simulates a Scots pine forests, mixed with Pyrenean and other oak species <1500 m a.s.l. Although simulated species composition appears reasonable, the model produces very low values of basal area as compared with measured values in some stands. The problem seems to be related to the simulated competition factor and, perhaps, to the water balance submodel (see 2.1.5).

CS_2 Vercors (France): ForClim simulates reasonable values of biomass and basal area along an elevation gradient (Fig. 1, Beech/Silver fir/Spruce forests with 35 m²/ha at 1400 m a.s.l.). Species simulated are those that are present in real forests, but with different proportions, most likely since stands in the CSA are managed.

CS_3 Montafon (Austria): the model reproduces a forest that is highly comparable to the potential natural vegetation (PNV) of the region and also to forest data from some stands (see Fig. 2, Spruce/Silver fir forest with basal area that reaches 40 m²/ha). For a few simulated stands a small underestimation of biomass was observed. The accuracy of the representation will most likely be improved based on the recent model developments.

CS_4 Sneznik (Slovenia): similar as for CS2, the model produces reasonable values of biomass and basal area, with the presence of the correct dominant species. However, species composition is somewhat different and does not agree with data from managed forest stands of the area (e.g. the model exhibits a dominance of spruce at highest elevations whereas real forests are beech-dominated).

CS_5 Vilhelmina (Sweden): only explorative simulations were performed for this CSA. The model does not perform well in boreal environments. The simulated biomass is strongly underestimating real data; the model fails to capture the Northern European conditions for tree growth. It is not planned to pursue these problems further in ARANGE.

CS_6 Kozie Chrbty (Slovakia): ForClim produced results of species composition comparable with the PNV of the region and values of biomass similar to inventoried data (Fig. 3).

CS_7 Shiroka Laka (Bulgaria): in some stands the model simulates a forest composition that is close to stand descriptions provided by the case study responsible (spruce/silver fir-dominated forest with basal area above 35 $m^2$/ha in the altitudinal belt 1500-1800 m a.s.l., with presence of beech at lower elevations).

### 2.1.4 Results from model testing against empirical data in ARANGE

To date, model results have been compared against empirical data for the CSA Eastern Alps (Montafon) only. However, this cannot be considered a comprehensive model test; due to the lack of data on historical management, no management was applied in the simulations. Single tree data for few stands were delivered from the responsible of CS_3. Once empirical data from representative forest stands within each CSAs will be distributed (e.g. species, diameters at single tree or grouped in classes, tree height, etc.), tests could be performed better across all CSAs.

However, ForClim has at least been tested against PNV maps across all CSAs (see section 2.1.3).

### 2.1.5 Plans for future model applications in ARANGE

*Past ES provision/tests of model performance against historical data*

Improve simulation accuracy with the set of environmental variables that will be delivered within WP1 ("Harmonized data framework of environmental variables"), particularly taking into account management regimes in the CSAs using current and historical series of management practices. Test against empirical data of representative stands.

Preliminary model application across most CSAs under the scenarios of regional climate change.

*Final simulations*

The model is undergoing continuous development; a new model version produced in the coming months (outside of ARANGE) will most likely improve the accuracy of the simulations in more than one CSA.

However, ForClim will *not* be applied for simulations CS_5 (Sweden) and will *not* have been calibrated for CS_1 (Spain) *by M12*.

At least one manuscript that describes model application and assessment of ES under climate change in the ARANGE CSAs is planned.

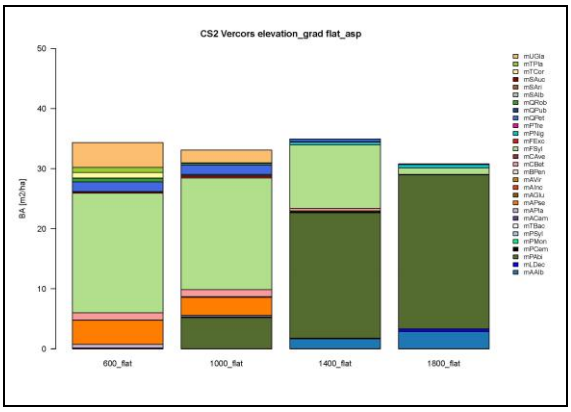


Fig. 1. ForClim simulations in CS_2 (Western Alps) along an elevation gradient (600-1800 m a.s.l.), showing different forest composition and values of basal area.

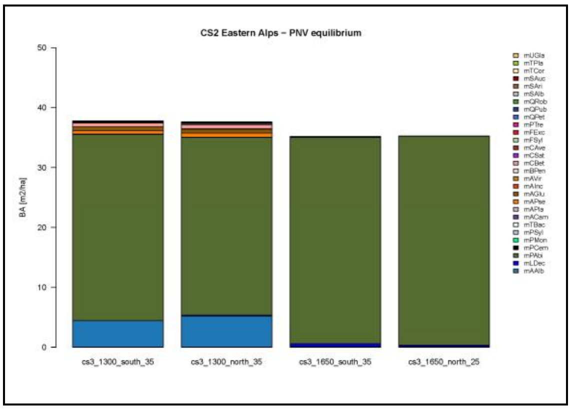


Fig. 2. Simulated forest composition in CS_3 (Eastern Alps): equilibrium state (after 1500 years) in two stands of different aspect (north-south) and slope.

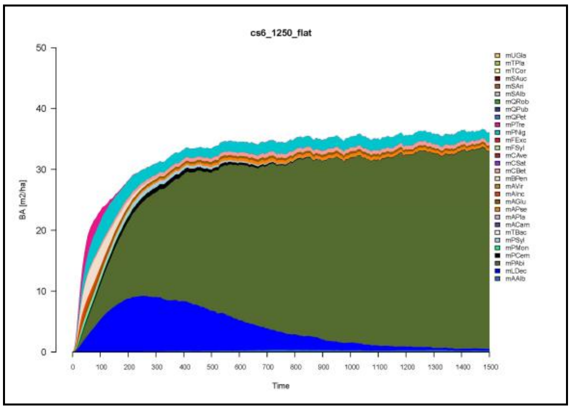


Fig. 3. Results of a simulation of forest dynamics (starting from bare ground) in a stand at elevation 1250 m a.s.l. in CS_6 (Western Carpathians).

## 2.2 LandClim

### 2.2.1 Brief overview of model

#### 2.2.1.1 Model structure

LandClim is a climate sensitive, spatially explicit, forest landscape model that incorporates competition-driven forest dynamics, forest disturbances, and management to simulate forest dynamics on a landscape scale. LandClim simulates forest growth in individual cells using simplified versions of tree recruitment, growth, competition and mortality used in the model ForClim. Forest growth is determined by climatic parameters (monthly temperature and precipitation), soil properties and topography, and the spatially explicit processes of landscape disturbances such as fire, windthrow and bark beetle outbreaks, and forest management. Forest succession processes within each cell are simulated on a yearly time step, while landscape-level processes and disturbances are simulated on a five year or decadal time step. Forest management is implemented at the “management area” scale, with each management area comprised of individually entered and managed forest stands.

LandClim operates on long time scales (tens thousands of years) and large spatial extents (e.g. 100 km2) at a relatively fine scale (grid cells of ca.25 by 25 m). The model has been tested and adapted to the European Alps, North American Rocky Mountains, and Mediterranean forests. Importantly, the fire occurrence in LandClim is an emergent property of the system, depending on forest and climatic state. Fire ignition is currently implemented as a random process that reflects the fire frequency for a specific area. A fire event occurs only if suitable fuel is present in the ignition cell, and the fire is able to spread to at least one adjacent cell. Fire spread and intensity is dependent on climate and topography.

LandClim has been used to explore the importance of disturbances on forest dynamics, the impact of climate change on the procurement of forest ecosystem goods and services, the impact of alternative management strategies, and palaeo-environmental drivers of forests.

#### 2.2.1.2 Input requirements (climate, land surface, forest properties)

| Climate requirements | Environmental/Site variables | Forest data | Management data |
|---|---|---|---|
| Monthly mean temperature<br><br>Monthly mean precipitation | Soil water holding capacity (mm)<br><br>Geographical coordinates<br><br>Slope<br><br>Aspect | Minimum: Forest composition (biomass, BA, etc.), or relative contribution of tree species at the management area or stand level.<br><br>Medium: Tree species specific stem number, biomass and DBH distribution for each management area or stand.<br><br>Maximum: Spatially explicit forest composition data at the resolution of ~ 25 by 25m cells. | For each management area on the landscape: type of management, number of management phases, starting and ending year of each harvesting phase, timing of harvest actions (cycle length)<br><br>Intensity of the harvest (% of trees) or basal area removed ($m^2$/ha), percent of stands entered during each management phase, target diameter (cm), desired density of the sheltering trees (% trees), desired residual basal area ($m^2$/ha), highest diameter class remaining. |

### 2.2.2 Model development in ARANGE (finished by M12)

Our model development work has focused on improving the representation of fire disturbances within the model. This development has proceeded along two lines that take into account the role of climatic as a driving factor influencing fire at a regional scale, and the influence that forest compositional and structure can have on fire occurrence and spread at a local scale. First, by making use of regional fire data and regional projections of increased fire occurrence under climate change in Spain, from Antonio Vazquez de la Cueva, we have parameterized the function that relates fire spread to temperature and drought conditions. Second, we have modified the fire spread equations such that forest structure (species composition and stem density) influences fires spread. We have also been doing model development aimed at improving the model output of forest ecosystem goods and services (EGS) at the stand level. These modifications are continuing and are contingent on the final EGS metrics being agreed-upon by all ARANGE participants.

Model development has also focused on modifying the model structure such that the forest management options and the model output is more amenable with the needs of ARANGE work package 4. In particular, we have allowed for the frequency of disturbances and management to be reduced from once every decade to once every five years. Forest management has also been modified such that for each management area the exact volume of wood to be removed can be specified. This improves upon previous management options, which only allowed the amount of material to be removed to be specified as a % thinning, or as the desired density of stems after management.

### 2.2.3 Results from preliminary model applications to CSA(s)

Model testing and development has primarily been conducted on the CS_1 (Spain), CS_4 (Slovenia) and CS_7 (Bulgaria) landscapes. Preliminary simulations in these case studies have been conducted using the ARANGE base climate data. In CS_1 we have also used simple climate change projections to evaluate fire behavior under increase temperature and decreased precipitation conditions. These simulations were used to improve the parameterization of the fire spread function in LandClim.

Simulations were run with no forest management and with current forest conditions not initialized with empirical forest data. In each CS GIS data provided by the region was used to define the simulation landscape (elevation, slope, aspect), and define “Management Areas” and individual “Stands”. In the Shiroka Laka landscape (CS_7) soil depth and soil moisture holding capacity data was provided for each stand and was used to parameterize soil moisture holding capacity as used in LandClim. In the Valsain landscape (CS_1), empirical data on soil characteristics and moisture holding ability were provided by the CS for representative stands that spanned an elevation gradient. Using these data, we estimated soil depth across the landscape using an elevation and slope based soil depth model. Initial simulations, which included uniform soil depth, projected too much forest biomass at higher elevations (were soil is limiting) and too much Pinus sylvestris at lower elevations.

For the Sneznik landscape (CS_4) LandClim was run with the base 31 central European tree species that LandClim normally simulate. In Valsain (CS_1) we augmented these species with: Pinus halepensis, Juniper sp., Erica aborea, Quercus ilex, and Quercus pyrenaica. In the Shiroka Laka landscape the species set was augmented with Pinus nigra. The parameterizations of these new species have been tested across a range of Mediterranean sites.

In the Valsain, under no management and no fire conditions, LandClim simulates a transition from Quercus ilex, Quercus pyrenaica and Pinus sylvestris dominated forests at low elevations, to Quercus pyrenaica and Pinus syslvestris forests at intermediate elevations, and Pinus sylvestris dominated forest at higher elevations (Figure 4). Under no management conditions the composition of these stands change dramatically through time. At intermediate elevations (~1400-1500 m), under current climate conditions, the proportion of Quercus ilex increases dramatically through time while there are concomitant reductions in total forest biomass. Qurecus ilex primarily replaces Pinus sylvestris, but also decreases the percent composition of Quercus pyrenaica. At low elevations (<1400 m), with no management and no disturbances, Quercus ilex eventually completely outcompetes Quercus pyrenaica and Pinus syslvestris. In contrast, under even moderate fire disturbance regimes tree species diversity is increased. In both the Sneznik (CS_4) and Shiroka Laka (CS_7) landscapes LandClim approximates the expected potential natural vegetation, and captures expected species changes along the CS elevation gradients. In Sneznik, Fagus sylvatica is simulated in too high abundance compared to Picea abies, and this appears to be an issue of using incorrect soil moisture holding capacity values.

### 2.2.4 Results from model testing against empirical data in ARANGE

At the landscape and management area scale, LandClim simulations for the Shiroka Laka (CS_7) landscape have been compared with current stand composition data that was provided by the CS in the GIS files. The current absence of management in LandClim runs hampers the simulation of stand specific forest biomass and species composition. However, as described above, the model captures change in forest composition that is driven by elevation and soil depth, when evaluated at the landscape scale.

### 2.2.5 Plans for future model applications in ARANGE

The application of LandClim will generally remain focused on the three above mentioned CS, until the incorporation of suitable management regimes, and suitable forest initialization data, is complete. Once the incorporation of these factors, and the suitable simulation of forest ecosystem services, is proceeding we will move to simulating Kozie Chrbty in Slovakia (CS_6) and possibly Vercors in France (CS_2) and Montafon in Austria (CS_3).

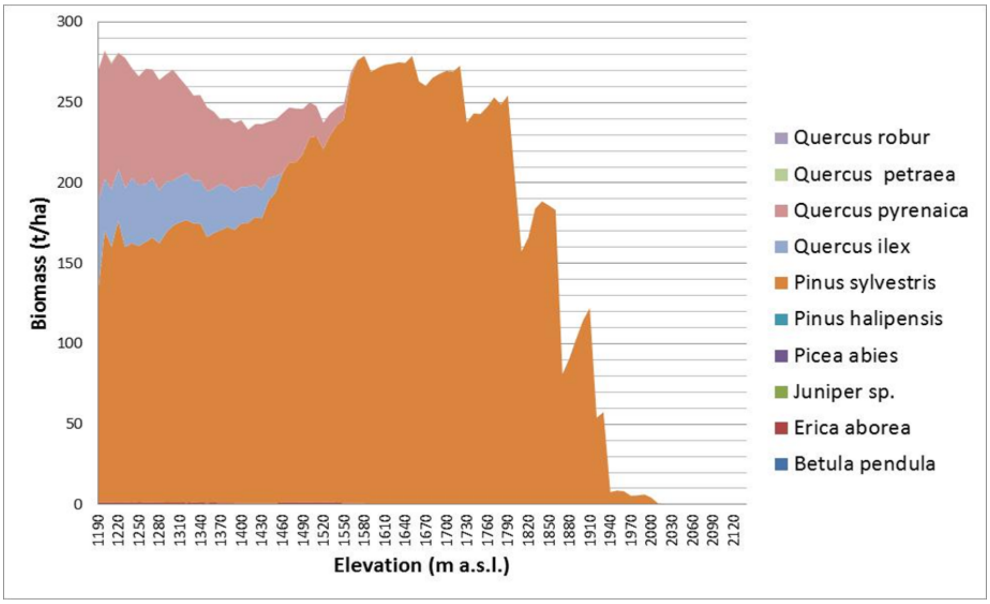


Fig. 4. LandClim simulations of the Valsain (CS_1) landscape. Projected forest composition along the CS elevation gradient after 250 years of forest simulation, under no management and no disturbance conditions.

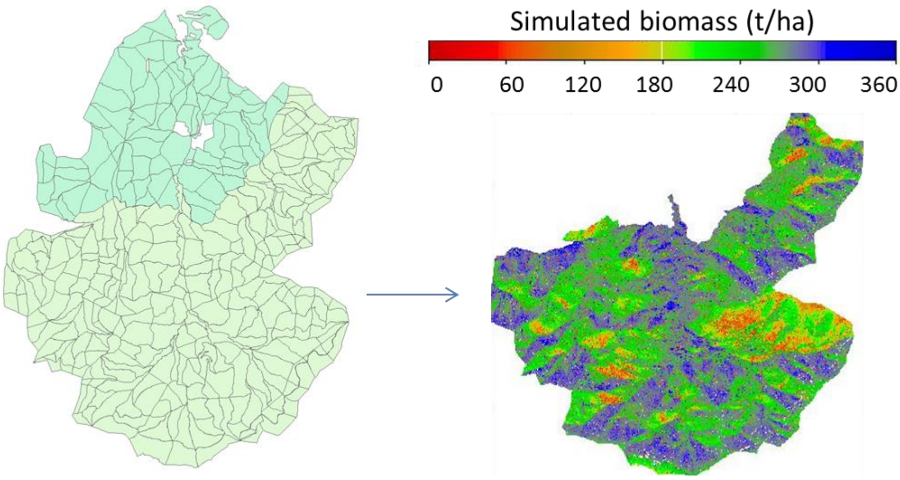


Fig 5. Stand divisions within the Valsain landscape (left) and the spatial representation of simulated forest biomass in each stand and each cell (right).

## 2.3 PICUS

In ARANGE two versions of the PICUS model family will be used. PICUS v1.5 is operated with monthly climate data and has been frequently tested and used for climate change impact assessments and development of adaptation strategies in forest management. PICUS v1.5 will be applied in the Montafon (Austria) and in Shiroka laka (Bulgaria). In the Montafon region the model has been successfully applied in previous projects and no additional evaluation experiments are conducted. PICUS v1.6 is a newly developed (outside ARANGE) variant driven by daily weather data and a detailed plant water relations module. This model version will be used in Valsain (Spanish CSA).

### 2.3.1 Brief overview of model

#### 2.3.1.1 Model structure

##### *2.3.1.1.1 PICUS v1.5*

PICUS v1.5 is a modular forest modelling framework centered around a hybrid patch model which incorporates a number of flexible sub-models for scenario analysis (e.g. forest management, bark beetle damage, rock fall protection, browsing by ungulate game species; Seidl et al. 2005; Seidl et al. 2007; Woltjer et al. 2008). The hybrid model approach aims at combining the strengths of patch models and process based production models while circumventing limitations of the individual approaches (see Mäkelä et al. 2000). The spatial core structure of PICUS is an array of 10 x 10 m patches with crown cells of 5 m in height, up to a maximum height of 60 m. The 10 × 10 × 5 m structural base elements contain all the information on the distribution of tree biomass in space. Tree biomass is evenly distributed within the cells. Contrary to classical patch models (e.g. Shugart 1984; Botkin 1993) interactions between patches are considered with regard to a three-dimensional light regime and spatially explicit seed dispersal. Inter- and intra-species competition, seed dispersal and mortality are modelled based on the approach presented by Lexer and Hönninger (2001). By default 1 ha (10 x 10 patches) is used for the simulations; however other shapes and sizes like spatially explicit stand polygons can be used too based on the 10 x 10 m patches. Stand level net primary production is modelled according to the simplified physiological principles of radiation use efficiency of the 3-PG model (Landsberg and Waring 1997). The hybridisation of both concepts is described in Seidl et al. (2005). Tree population dynamics emerge from growth, mortality and reproduction. The model has been successfully evaluated with regard to the simulation of equilibrium species composition over broad environmental gradients in the Eastern Alps as well as against long-term growth and yield data of uneven-aged, multi-species stands (Seidl et al. 2005).

##### *2.3.1.1.2 PICUS v1.6*

The model PICUS v1.6 incorporates a more detailed physiologically based water cycle module enhancing the assessment of drought conditions and water provisioning ecosystem services (Schimmel et al. 2012). The bucket size is replaced by a layered soil where water percolates through the layers, root distribution in soil layers is considered and affects the uptake of water from soil layers. The transpiration demand is calculated from the Penman-Monteith equation. Snow and water is intercepted in the canopy. Evaporation from tree canopy and the soil is considered as well.

PICUS v1.6 requires input of a time series of daily climate data as in the previous model version and soil data such as pH and plant-available nitrogen (kg $ha^{-1}$ $year^{-1}$). In addition, soil layers characteristics in terms of texture class, thickness (m), unsaturated hydraulic conductance (m $s^{-1}$), texture coefficient and soil water content ($m^3$ $m^{-3}$) at saturation, field capacity and wilting point are required.

The new model version was successfully validated against empirical time series data of soil water content and compared with the previous model PICUS v1.5 (Schimmel et al. 2012). Results revealed that at low water holding capacities and low precipitation the new version provides more sensitive and reasonable values (Schimmel et al. 2012).

### Input requirements (climate, land surface, forest properties)

| Climate requirements | Environmental/Site variables | Forest data | Management data |
|---|---|---|---|
| Monthly or daily values of:<br><br>temperature<br><br>precipitation<br><br>radiation<br><br>vapour pressure deficit | Minimum (static soil): Water holding capacity (mm)<br><br>Plant available nitrogen (kg/ha*yr)<br><br>Latitude<br><br>Maximum:<br><br>Parameter set for the TRACEsoil model<br><br>(for more information please see Seidl et al. 2007) | Minimum: a diameter distribution for each tree species including height information species, number of trees [n/ha], mean DBH [cm], mean height [cm]<br><br>Maximum:<br><br>list of single tree data:species, DBH (cm), tree height (cm), crown length (cm), coordinates | Minimum:<br><br>type of management, year of management,<br><br>intensity (stem number or basal area or volume)<br><br>Maximum:<br><br>Spatially explicit management,<br><br>list of trees to be removed |

## 2.3.2 Model development in ARANGE (finished by M12)

Parameterization of black pine (*Pinus nigra Arnold subsp. nigra*) which was not yet included in the species set of PICUS v1.5. Adjustment of soil drought tolerance for Norway spruce (*Picea abies*).

The newly improved model PICUS v1.6 was used to evaluate the growth of *Pinus sylvestris* and *Quercus pyrenaica* in Valsain (Spain). For PICUS v1.6 the calibration experiments were conducted with the set of *Pinus sylvestris* parameters gathered in a previous study with PICUS model (Seidl et al. 2010, 2011), excluding the potential height growth function which was derived from yield and inventory data in Spain. *Quercus pyrenaica* is not currently available in PICUS v1.6, thus the ecologically similar *Quercus robur* set of parameters was used as starting conditions. Specific changes were potential height growth function and stomatal conductance (m $s^{-1}$).

## 2.3.3 Results from preliminary model applications to CSA(s)

### 2.3.3.1 PICUS v1.5 in Shiroka Laka

To evaluate the performance of the models under the environmental conditions of the Bulgarian case study two approaches have been used.

*a) Calculation of potential natural vegetation (PNV) along the local site gradient (see Table 1):*

Model runs starting from bare ground with external seed input have been conducted for a period of 1000 years. Resulting temporal development of basal area and species-shares were analysed and compared to local expert knowledge.

The model depicts the PNVs very well, with beech dominating at the lower sites and spruce dominating at sites with an elevation higher than 1500m, while black pine dominates at the dry sites. This is in accordance with local PNV information. Some minor issues still need to be resolved in the transition zone at 1250m elevation because beech is too competitive during regeneration phase (Fig. 2).

*b) Productivity calculations along the local site gradient:*

For this purpose mono-species stands (age 10, stem number 2000) were simulated 150 years for all relevant species in the CSA (Tab. 3). As an overall pattern, trees do not show a very pronounced reaction to increasing elevation levels (decreasing temperature), but show highest productivity, as expected, on the site at 1750m a.s.l. on rich Cambisol.

Tab 1: Characterization of the study sites. Abbreviations: MAT = Mean annual precipitation; WHC = soil water-holding capacity; and Nav = plant-available nitrogen.temperature; MAP = Mean annual precipitation.

| Site no. | elevation [m] | MAT [°C] | MAP [mm] | soil type | WHC [mm] | pH | Nav [kg/ha*yr] |
|---|---|---|---|---|---|---|---|
| 1 | 1000 | 11.2 | 910 | Cambisol | 170 | 6 | 50 |
| 2 | 1250 | 9.8 | 930 | Leptosol (Rendzic) | 80 | 8 | 30 |
| 3 | 1250 | 9.8 | 930 | Leptosol (Rendzic) | 120 | 7.5 | 40 |
| 4 | 1250 | 9.8 | 930 | Cambisol | 180 | 6.5 | 60 |
| 5 | 1250 | 9.8 | 930 | Cambisol | 150 | 5.5 | 45 |
| 6 | 1250 | 9.8 | 930 | Cambisol | 200 | 5.5 | 65 |
| 7 | 1750 | 7 | 975 | Cambisol | 220 | 5.5 | 75 |
| 8 | 1750 | 7 | 975 | Cambisol | 170 | 5.5 | 55 |
| 9 | 2000 | 5.6 | 1000 | Cambisol | 170 | 4.5 | 50 |
| 10 | 2000 | 5.6 | 1000 | Mollic Cambisol | 220 | 5 | 70 |

A set of three sites has been selected for the evaluation experiments. The 3 chosen sites (No. 4, 8 and 9) are comparable with regard to water and nitrogen supply along the elevation gradient in the CSA. The model runs were compared to expert knowledge and yield table information.

For spruce general growth patterns fit very well to observed local values (Fig. 1). There are some minor deficiencies in depicting drought stress tolerance on dry sites and therefore competitive weakness against beech and pine, which in general is a plausible pattern.

For black pine problems persist in parameterization because there is a discrepancy concerning height growth from yield table to the presented empirical data which show different height/diameter ratios and dominant heights (field data for tree heights exceed yield table information by far). The latter may explain the different results in growth in Table 2 for black pine.

Because of a lack in detailed information about the yield table management (in general thinning from below) and unrealistically high stem numbers for some species in young age classes (e.g. fir site class 3 starts with 44.068 stems at age 20), PICUS could not exactly mimic yield table growth patterns, however stayed in a plausible range. However the comparison of total gross growth showed a good fitting of the model for the CSA, with some underestimation for the very dry sites at lower elevation (Tab. 3).

Fir shows good results regarding to total gross growth, some alterations in the model are necessary to meet the expected diameter growth. Scots pine performs similarly well.

For beech the model simulated reasonable results along the site gradient, although total gross growth values tend to be a bit lower than expected (Tab. 3) According to local experience beech should not appear at elevations higher than 1500 m a.s.l. However, for beech such a pronounced gradient due to decreasing mean temperature could not be reproduced by the current model version and is also not plausible under the given environmental conditions. Other factors possibly limiting the occurrence at higher elevations such as historical/current pasture activity, snow break and storm damages have not been included in the experiments.

Tab 2: Comparison of simulated total gross growth to yield tables estimates.

| site | species | total gross growth/ha after 100 years [$m^3$ stem] | | | average height after 100 years [m] | | |
|---|---|---|---|---|---|---|---|
| | | PICUS 1.5 | yield tables | delta | PICUS 1.5 | yield tables | delta |
| | fir | 884 | 1011 | -13% | 25.6 | 25.3 | 1% |
| | black pine | 965 | 786 | 23% | 27.2 | 24.5 | 11% |
| site 4 | spruce | 994 | 1115 | -11% | 26.1 | 26.5 | -2% |
| | beech | 635 | 744 | -15% | 18.7 | 24 | -22% |
| | Scots pine | 761 | NA** | | 22.6 | NA** | |
| | fir | 588 | NA | | 21.6 | NA | |
| | black pine | 802 | NA | | 24 | NA | |
| site 8 | spruce | 839 | 872 | -4% | 23.8 | 21.6 | 10% |
| | beech | 402 | NA | | 16.5 | NA | |
| | Scots pine | 667 | NA | | 21.2 | NA | |
| | fir | 410 | NA | | 18.9 | NA | |
| | blackpine | 717 | NA | | 22.4 | NA | |
| site 9 | spruce | 697 | 663 | 5% | 21.9 | 17.9 | 22% |
| | beech | 297 | NA | | 15.1 | NA | |
| | Scots pine | 607 | NA | | 20.1 | NA | |
| | | $R^2$ | 0,50 | | $R^2$ | 0,82 | |

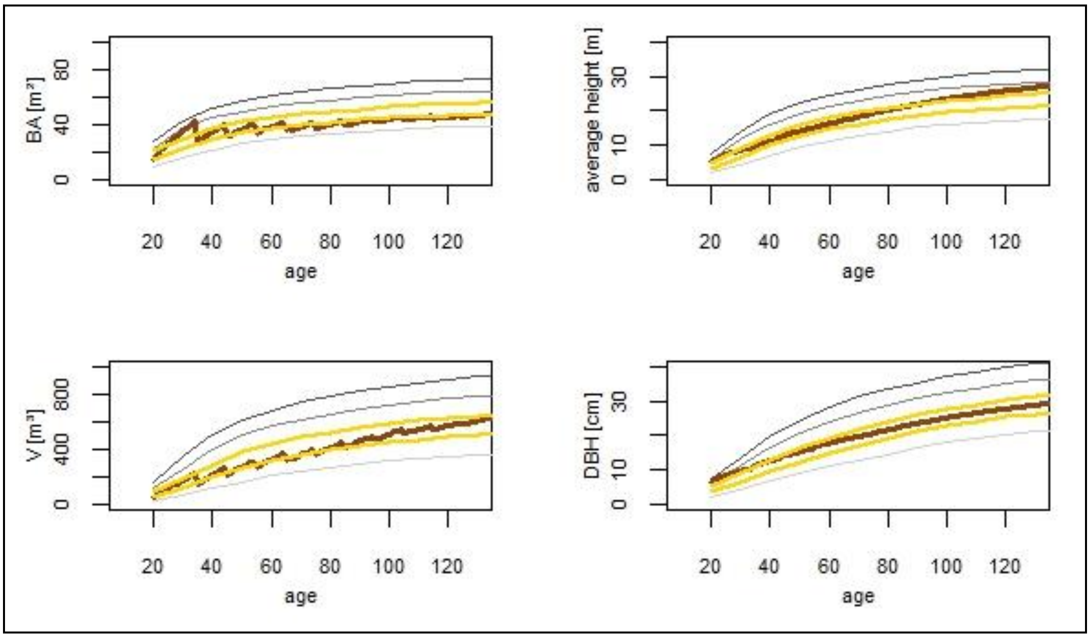


Fig. 6: Temporal development of important indicators. BA = basal area, V = stem volume of standing trees, DBH = diameter at breast height). Grey shades show variable developments according to local yield tables. Yellow lines = yield tables, brown lines = PICUS.

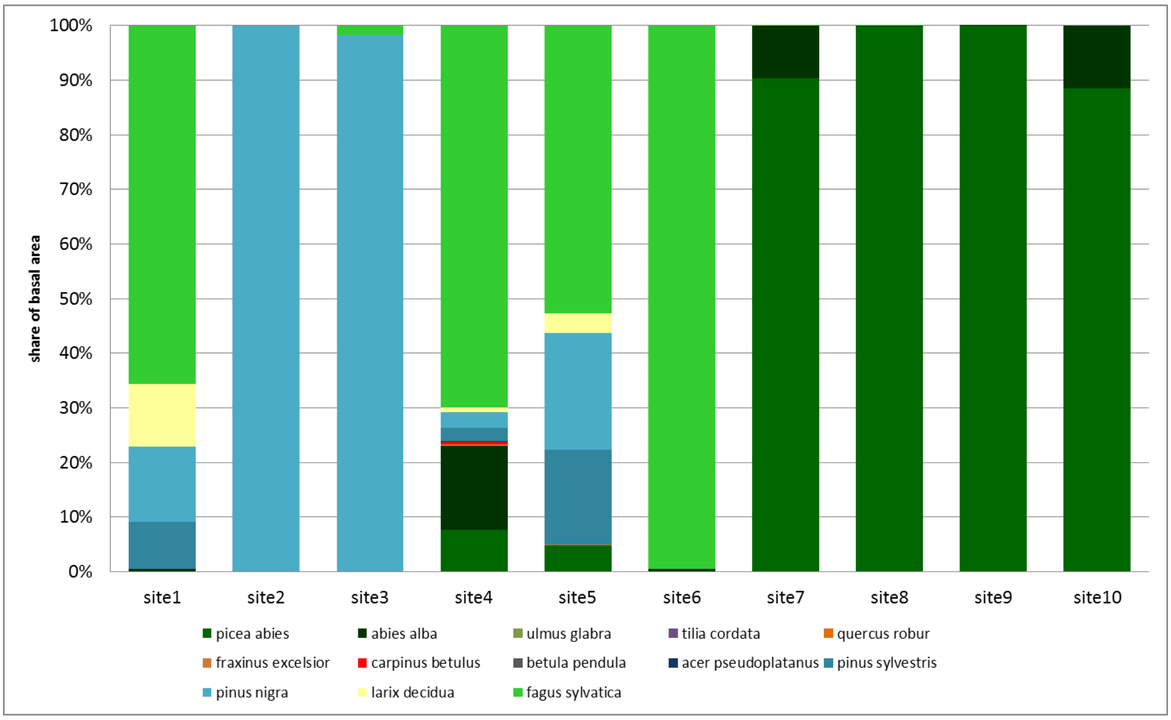


Fig. 7: Potential natural vegetation (mean basal area shares for 500 year period after 1000 year simulation with PICUS). site 1 PNV: *Fagus sylvatica*, site 2 PNV: *Pinus nigra* (admixed *Fagus sylvatica* and *Pinus sylvestris)*, site 3 PNV: *Pinus nigra* (admixed *Fagus sylvatica* and *Picea abies*), site 4 PNV: *Picea abies*, *Abies alba* (admixed *Fagus sylvatica* and *Pinus nigra*), site 5 PNV: *Picea abies*, *Pinus sylvestris* (admixed *Fagus sylvatica*), site 6 PNV: *Picea abies*, *Abies alba*, site 7, site 8 and site 9 PNV: *Picea abies*.

### 2.3.3.2 PICUS v1.6

To evaluate the performance of the hybrid model, several study sites across Sierra de Guadarrama in Valsain were employed (Table 3).

Daily climate data was based on stochastic 100-year time series de-trended from the period 1961 to 1990 in Valsain region which integrates the internal ARANGE climate dataset. Soil data were provided by Marta Pardos from Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria (INIA) in Madrid (Spain).

Tab 3. Characterization of the study sites. Abbreviations: MAT = Mean annual temperature; MAP = Mean annual precipitation; WHC = soil water-holding capacity; and Nav = plant-available nitrogen.

| Site no. | Gradient description | Elevation (m) | Site ID | MAT (°C) | MAP (mm) | pH | WHC (mm) | $N_{av}$ (kg ha$^{-1}$ year$^{-1}$) |
|---|---|---|---|---|---|---|---|---|
| 1 | Moderate | 1250 | 1250_m | 12.4 | 1116 | 4.1 | 102 | 47 |
| 2 | Good | | 1250_g | | | 4.1 | 92 | 78 |
| 3 | Moderate | 1500 | 1500_m | 10.6 | 1241 | 4.5 | 75 | 47 |
| 4 | Good | | 1500_g | | | 4.7 | 78 | 75 |
| 5 | Moderate | 1750 | 1750_m | 8.9 | 1366 | 5.6 | 77 | 40 |
| 6 | Good | | 1750_g | | | 3.8 | 85 | 73 |
| 7 | Moderate | 2000 | 2000_m | 7.1 | 1491 | 5.6 | 61 | 40 |
| 8 | Good | | 2000_g | | | 4.5 | 60 | 50 |

The model evaluation experiments comprised (a) tests of model response to environmental gradients and (b) tests of model response to management.

*a) Environmental gradient sensitivity estimates*

Simulation runs were initialized with a 10-year-old pure stand without management interventions and run over 200 years. Study sites covered a climate gradient along an elevation range as well as a fertility gradient (moderate and good) (Table 3). The target variables analyzed were average diameter at breast height (m), dominant height (m), stem number (ind ha$^{-1}$), volume (m$^3$ ha$^{-1}$) and basal area (m$^2$ ha$^{-1}$).

*b) Growth/productivity of managed forests along environmental gradient*

Simulations were initialized with yield table data and run over 100 years. Results were compared with independent data regarding mean annual increment ($m^3$ $ha^{-1}$ $year^{-1}$) and dominant height (m) at 100 years (Marta Pardos, personal communication). In the case of *Quercus pyrenaica* no information about management was provided, thus simulations without management interventions across the environmental gradient were directly compared with the expected productivity and growth from yield tables over 100 years (Marta Pardos, personal communication).

Results indicated a realistic response to the environment sensitivity experiment over 100 years: productivity and growth are higher in lower elevations (higher mean annual temperature) and in good sites (higher plant-available nitrogen (Nav) and soil water holding capacity (WHC)) (Tables 4 and 5).

Tab. 4. Comparison of simulated *Pinus sylvestris* dominant height and mean annual increment to expert and yield table data. Abbreviations: MAI =Mean annual increment over 100 years.

| Site no. | Site ID | Observed dominant height (m) | Predicted dominant height (m) | Yield table MAI ($m^3$ $ha^{-1}$ $year^{-1}$) | Predicted MAI ($m^3$ $ha^{-1}$ $year^{-1}$) |
|---|---|---|---|---|---|
| 1 | 1250_m | 26 | 25.7 | 12.8 | 9.7 |
| 2 | 1250_g | 29 | 27.3 | 14.6 | 12.9 |
| 3 | 1500_m | 23 | 22.6 | 10.8 | 8.0 |
| 4 | 1500_g | 26 | 25.1 | 12.8 | 9.4 |
| 5 | 1750_m | 20 | 21.1 | 9.1 | 6.9 |
| 6 | 1750_g | 23 | 25.4 | 10.8 | 11.2 |
| 7 | 2000_m | 17 | 19.6 | 7.5 | 5.6 |
| 8 | 2000_g | 20 | 20.7 | 9.1 | 6.8 |

Tab. 5. Comparison of simulated *Quercus pyrenaica* dominant height and mean annual increment to yield table data.

| Site no. | Site ID | Yield table dominant height (m) | Predicted dominant height (m) | Yield table productivity (Mg ha$^{-1}$ year$^{-1}$) | Predicted productivity (Mg ha$^{-1}$ year$^{-1}$) |
|---|---|---|---|---|---|
| 1 | 1250_m | 13.4 | 14.6 | 2.5 | 2.1 |
| 2 | 1250_g | 17 | 16.3 | 3.2 | 2.9 |
| 3 | 1500_m | 11.6 | 12.6 | 2.1 | 1.4 |
| 4 | 1500_g | 13.4 | 14.9 | 2.5 | 2.3 |

The comparison against long term growth and yield data of *Pinus sylvestris* revealed good correspondence between yield table values and predictions of dominant height ($R^2$=0.90) (Fig. 6, a) and mean annual increment ($R^2$=0.78). Similarly, *Quercus pyrenaica* showed good correspondence between yield table data and predicted values of dominant height ($R^2$=0.88) and productivity ($R^2$=0.93).

Overall, species productivity was moderately underestimated. Dominant height did not show a tendency: in some sites was underestimated and in others was overestimated (Tab. 4, 5).

### 2.3.4 Results from model testing against empirical data in ARANGE

Neither in Valsain nor in Shiroka laka empirical data were readily available for model evaluation purposes, with the exception of selected stand top height measurements that were used to (i) assign yield tables to the sites, and (ii) directly compare simulated height development with observations. In Task 2.3 it is planned to use historical forest inventory and management data from 1-2 selected case studies for further model evaluation.

### 2.3.5 Plans for future model applications in ARANGE

No species-specific volume functions were available for *Pinus nigra*, for all other species the Austrian volume equations were used. If possible, regional equations for stem volume will be used in an updated model version.

Further development of the species parameters will improve simulated productivity and growth of *Pinus sylvestris* and *Quercus pyrenaica* in Sierra de Guadarrama (Spain).

## 2.4 BIOME-BGC

### 2.4.1 Brief overview of model

#### 2.4.1.1 Model structure

Biome-BGC is a mechanistic process model. It does not directly simulate trees; it simulates pools and fluxes of carbon, nitrogen, water and energy of an ecosystem. The model runs on a daily time step. It is driven by meteorological data, such as daily minimum and maximum temperature, incident solar radiation, vapor pressure deficit and precipitation. Vegetation specific properties of the modelled ecosystem are listed in an ecophysiological parameter set. Over the years, parameter sets for the main tree species in Europe as well as general parameters for conifer and deciduous tree species were developed and implemented. In addition, the spin-up simulation and a simple management-routing were developed and implemented. Atmospheric $CO_2$ content, nitrogen deposition and fixation, aspect, elevation and physical soil properties (depth, texture) influence the simulation process.

In the model, total ecosystem carbon storage is governed by the balance between NPP and heterotrophic respiration (Rh). Rh is regulated by decomposition activity, the seasonal input of vegetation biomass into litter and soil organic matter pools, the annual mortality rate and management. Since there is no spatial structure within the model, management is defined by the proportion of removed biomass in the different plant compartments.

The main difference of a Biome-BGC simulation compared to a tree population model is that BGC is not initialized with the current stand conditions. It mimics the stand according to the input (site parameters, weather data) and algorithms that simulate growth. That is why a comparison between the simulated and observed current stand (carbon, volume, etc.) is already a key result. So, terrestrial/measured data are needed only for comparison, not for initialization. BGC uses a self-initialization or spinup procedure with pre-industrial $CO_2$ and nitrogen deposition values and very small amount of carbon in the leaf and stem pools in the beginning. The spinup uses a dynamic mortality routine to simulate a virgin forest and is stopped, once the soil carbon pool is in a steady state. This usually takes some thousand years. After the spinup, the forest is in a steady state and can be seen as a representative of a virgin forest. After the spinup, historic land-use is simulated over several rotations according to information on historic management of the stand. After that, the actual stand is simulated. Therefore the stand age is needed. Thinnings are applied according to the management history of the stand or related to stand density indices (crown competition factor, stand density index).

#### 2.4.1.2 Input requirements (climate, land surface, forest properties)

| Climate requirements | Environmental/Site variables | Forest data | Management data |
|---|---|---|---|
| Daily values of minimum and maximum temperature, precipitation, solar radiation, vapor pressure deficit and daylength. | Latitude, elevation, soil texture (proportion of sand, silt and clay), effective soil depth, pre-industrial and industrial nitrogen deposition and nitrogen fixation. | Dominant tree species, age of the current stand, if possible: potential natural vegetation. | Current management regime (thinning intensity, thinning interval).<br><br>Management in the past (before plot establishment). Any information about the management or management strategy before the current plot establishment is useful, like was it a clear-cut system or continuous cover forestry... |

### 2.4.2 Model development in ARANGE (finished by M12)

No development activities were planned within the ARANGE project.

### 2.4.3 Results from model testing against empirical data in ARANGE

We did a first simulation run on 53 stands of the Montafon case study area to show the overall simulation procedure. Please be aware that this is only a 'proof of concept' and we still have to set up some parameters to get a proper result. Figure 9 shows the result of the spinup vs. the observed data. Since the spinup output defines a potential of a fully stocked stand, it is of course higher than the observed values.

Figure 10 shows stands with a low density which have a higher difference between the potential and the observed volume. Therefore we defined the harvesting according to the stand density. In this case, we thinned a certain proportion (30 %) every 40 years. Stands with a low density were thinned more recently than stands with a high density index. Figure 11 shows the result after the harvesting.

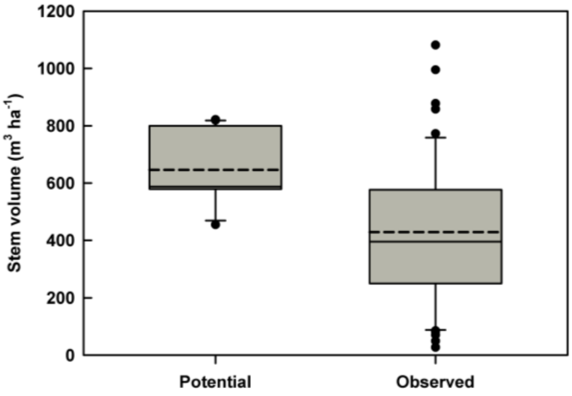


Fig. 9: Potential stem volume after the spinup vs. observed volume.

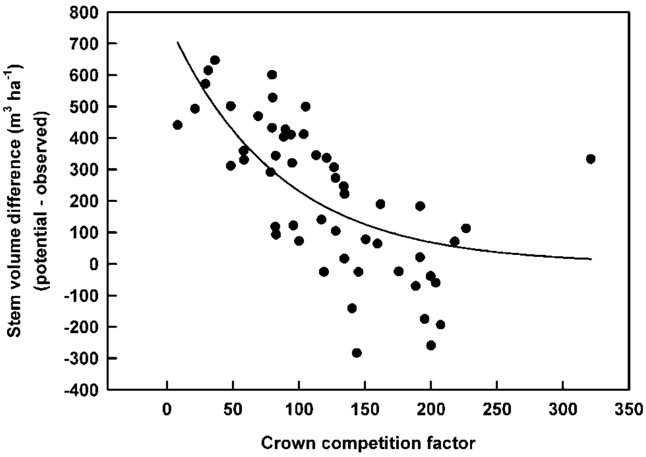


Fig. 10: Difference of potential and observed volume against the stand density (crown competition factor).

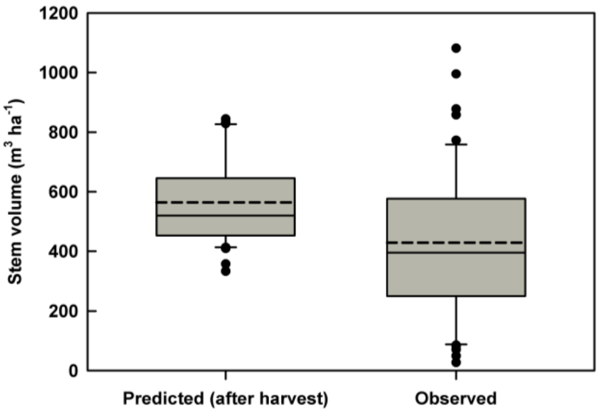


Fig. 11: Predicted and observed volume after harvesting.

### 2.4.4 Plans for future model applications in ARANGE

As seen in the previous sections, BGC is able to simulate the current carbon stocks in the Montafon case study region. This modelling strategy is planned to be applied to all case study regions on the representative stand types (RST). Additionally to the current carbon simulations, BGC can be used to simulate the no-management scenario for the RSTs to show the potential carbon storage of the case study regions. The benefit of using a process model is that the carbon can be simulated and is not calculated with biomass expansion factors from simulation results as it is usually done in tree population models. Not only the above ground biomass can be simulated, also belowground carbon storage variables are available that can be used to describe the overall carbon storage of the ecosystem. The plan is to use the BGC model for the carbon simulations with both, the business as usual and the no management variants. The BGC results can be used to check the reliability of other forest models that estimate the carbon with biomass expansion factors from their simulation result. The carbon should be estimated under current weather conditions and with different climate change scenarios.

## 2.5 Heureka

### 2.5.1 Brief overview of model

#### 2.5.1.1 Model structure

The Heureka system includes a suite of software for analysis and planning of multi-purpose forestry. The core of the system is built on simulator for simulating tree and stand development. The growth and yield models are empirical non-distance dependent individual tree models. Optionally, an area based model can be used for guiding stand development (basal area growth) and the estimated growth is then distributed on individual trees by using the individual tree growth model. The empirical growth model can be adjusted for effects of a changing climate based on analysis performed by the process based model BIOMASS. So far a limited number of climate scenarios are possible to apply. Models simulating even-aged as well as uneven-aged management are included. For even-aged management regeneration by planting or natural generation with seed trees can be applied. Around this growth and yield simulator three central software are built for different purposes; StandWise for stand-level management analysis, PlanWise for forest-level planning and RegWise for regional scenario analysis. StandWise is a simulator in which the user interactively controls management actions in 5 year time steps. PlanWise includes a treatment program generator which generates a (small or large) set of potential management alternatives for each stand. For finding preferred forest level solutions (e.g. on an estate or company level) an optimization tool is available. RegWise is a regional scale simulator estimating cutting potential etc. and forest development primarily based on National Forest Inventory data. Heureka handles timber and bio-fuel production, carbon sequestration, biodiversity (a GIS tool for estimating suitable habitat for a set of species) and recreation. A separate tool for multi-criteria decision analysis (PlanEval) is also developed.

#### 2.5.1.2 Input requirements (climate, land surface, forest properties)

| Climate requirements | Environmental/Site variables | Forest data | Management data |
|---|---|---|---|
| Altitude, latitude, region, and maritime or continental climate (mainly taken by location)<br><br>The empirical growth functions can adjusted for climate scenarios (only ECHAM5_A1B implemented so far). | Soil moisture<br><br>Soil type<br><br>Vegetation type | Basically data are needed on three levels:<br>• Stand<br>• Plot<br>• Individual tree<br><br>In case only stand mean values are available, the system can simulate individual trees given assumptions on stem diameter distributions. | If interactive simulation (StandWise) the user controls timing and performance of silvicultural actions & cuttings. If automatically generating a set of potential management alternatives for each stand (PlanWise), the framework for silvicultural actions & cuttings is to be specified (e.g. min/max age and height for thinnings and age for final felling). In large scale simulations (RegWise) management prescriptions are set up assigning a management schedule for each specified forest type. |

### 2.5.2 Model development in ARANGE (finished by M12)

Development of the Heureka system during 2012 related to ARANGE has concerned ecosystem services: forest fuel, nature conservation (tree retention), and carbon budgets. Most parts (including funding) have been performed in collaboration with other projects.

In Sweden forest fuel is used to a large extent for heating but also for producing electricity. Forest fuel is today extracted mainly form tops and branches ("harvest residues") but harvesting of whole trees in young forests is a potential for increased forest fuel production. During the lifetime of a stand such a harvest could combine and replace late pre-commercial thinning and the first commercial thinning. Harvesting cost functions and forest fuel and timber pricelists for such operations have been implemented.

Tree retention (dispersed or in patches) is broadly used to maintain forest composition and structure aiming at maintained biodiversity in managed forests. When harvesting a stand the mortality will – mainly due to windfall – increase in retained patches. Such a link between the action in the stand (final felling) and its consequences on the trees in the retention patch have been implemented.

By keeping track of biomass changes due to forest growth, cuttings and soil processes carbon budgets can be analyzed by the Heureka system. Earlier the user had to calculate carbon content in trees from biomass values manually but a function is now added summarizing total carbon automatically. Moreover, the implementation of the soil carbon model (the Q-model) has been tested and compared by running the model separately outside the system.

### 2.5.3 Results from preliminary model applications to CSA(s)

The Swedish CSA – Vilhelmina – is located in the northern Sweden (64°30’ north). In northern Scandinavia (northern parts of Norway, Sweden and Finland) reindeer herding is a large scale land use. The reindeers spend summer foraging in high altitude non-forested mountains and migrate to forest land in winter, migrating routes typically of hundreds of kilometers. Grazing of ground lichens in forest land during the winter is crucial and often a bottle neck. Many forest operations, such as soil scarification, the creation of dense young forest and cuttings have negative impacts on reindeer herding. There is, however, a potential to decrease such negative impact by adaptation and planning of forest management. Studies modeling different forest management options in winter grazing land adapted to reindeer herding in CS_5 Vilhelmina (Sweden) are ongoing. One scientific paper is in preparation.

In a larger spatial scale (part of Vilhelmina rural district/municipality, 134 000 ha) Heureka have been used to analyze different forest management alternatives: today’s management practices versus more intensified and less intensified management, respectively (Figure 12). The latter management alternative strives for a management better adapted to nature conservation objectives and reindeer herding. Forthcoming ARANGE studies are, however, supposed to be applied on a smaller geographical scale.

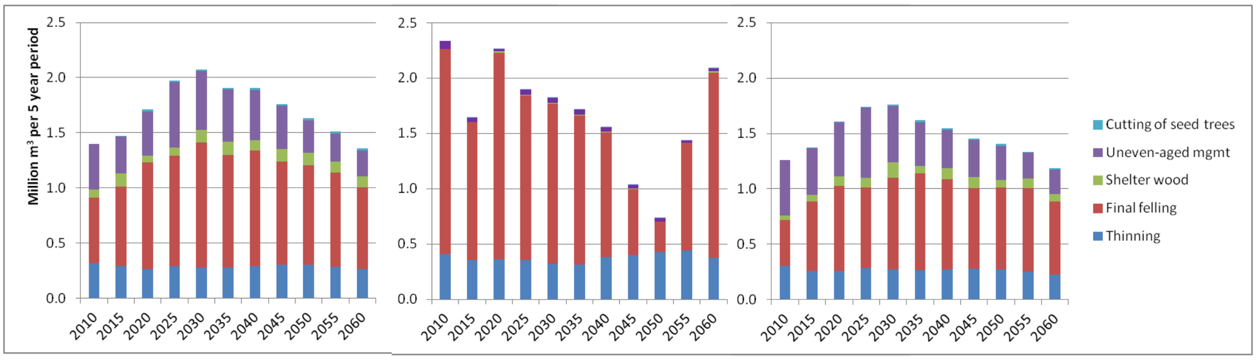


Fig. 12. Potential harvest in the Swedish CSA (part of Vilhelmina rural district/municipality, 134 000 ha) given today’s management practices (left), given a more intensified management (middle) and given less intensified management (right), the latter management being better adapted to nature conservation objectives and reindeer management . “Shelter wood” means final felling of a stand leaving a shelter wood. Forthcoming ARANGE studies are supposed to be applied on a smaller geographical scale.

### 2.5.4 Results from model testing against empirical data in ARANGE

Prior to the ARANGE project, the growth and yield models have been tested on data from long term experimental plots in CS_5 Vilhelmina (Sweden).

### 2.5.5 Plans for future model applications in ARANGE

The Heureka model will mainly be applied in the CS_5 Vilhelmina (Sweden). The growth and yield models have correction factors available in the system thereby to some extent making them possible to apply outside the range of the empirical data on which they are based. It has, among others, been discussed to test them on (high altitude) Scots pine in the CS_1 Valsain (Spain).

## 2.6 MOSES

### 2.6.1 Brief overview of model

#### 2.6.1.1 Model structure

MOSES (MOdelling Stand rESponse) is a single tree growth model. Since MOSES is designed to be a classical growth and yield model, it is currently not sensitive to climate change impacts but does address stand structure and changes in tree growth derived from silvicultural management options. This allows us to demonstrate the impacts of changes in tree species composition and/or management options on the resulting stand dynamics by changing the input assumptions according to the results of other "climate sensitive" models.

MOSES consists of a diameter and height increment model, a dynamic crown model and logistic models for (i) individual tree mortality and (ii) regeneration predictions. The interaction of the trees is defined by a distance-dependent competition index. MOSES includes the sub-module STANDGEN to generate the necessary missing input parameters for model initialization (tree coordinates). Data for calibration consisted of 57000 growth periods of individual trees (increment and mortality data) and came from permanent investigative plots across Austria, Switzerland and parts of Germany. The model extensively validated using 225000 repeated tree observations across different mixtures, stand types, age structures, management regimes etc. across Central Europe. Parameter sets exist for Norway spruce, Fir, Larch, Scots pine, Stone pine, Oak and Beech as well as for Sitka spruce in Scotland and Oak in Greece. Input data for MOSES can be tree lists (Census), data from angle count sampling points (ACS) or surveys. Different management algorithms are integrated in MOSES (high thinning, low thinning, random thinning, clear-cutting).

#### 2.6.1.2 (climate, land surface, forest properties)

| Climate requirements | Environmental/Site variables | Forest data | Management data |
|---|---|---|---|
| - | Site index per tree species | DBH, height (optional), height to the live crown (optional)<br><br>Census: tree coordinates<br><br>ACS: distance and species of the nearest neighbor tree<br><br>Survey: basal area or number of trees per hectare and species standard deviation of the DBH, parameters for species mixture and aggregation | Thinning intensity (removed proportion of basal area, number of trees or volume), year of the thinning. |

### 2.6.2 Model development in ARANGE (finished by M12)

There is no model development planned. However since MOSES follows the potential growth concept similar to other models used within ARANGE, one could easily couple the potential estimates to changes in climate which would allow some adjustments to changes in climate. Note that the model was never intended to be climate sensitive.

### 2.6.3 Results from preliminary model applications to CSA(s)

The model has been widely tested in Switzerland and Austria. Another test run was done for uneven-aged mixed species forest in Croatia. This application also revealed unbiased and consistent result (see Figure 13).

### 2.6.4 Plans for future model applications in ARANGE

Currently MOSES is planned to be implemented for uneven-aged mixed species forest in Slovenia (one of the case study regions within ARANGE). The idea is to use forest inventory data to assess the changes in structure and productivity as it may vary by site and forest management options. Potential climate related impacts may be addressed due to different assumptions in the species proportion and structure; note that the model is currently not climate sensitive but changes of the forest structure derived from other climate sensitive models can be used to initialize MOSES that can further be used to analyze the impacts.

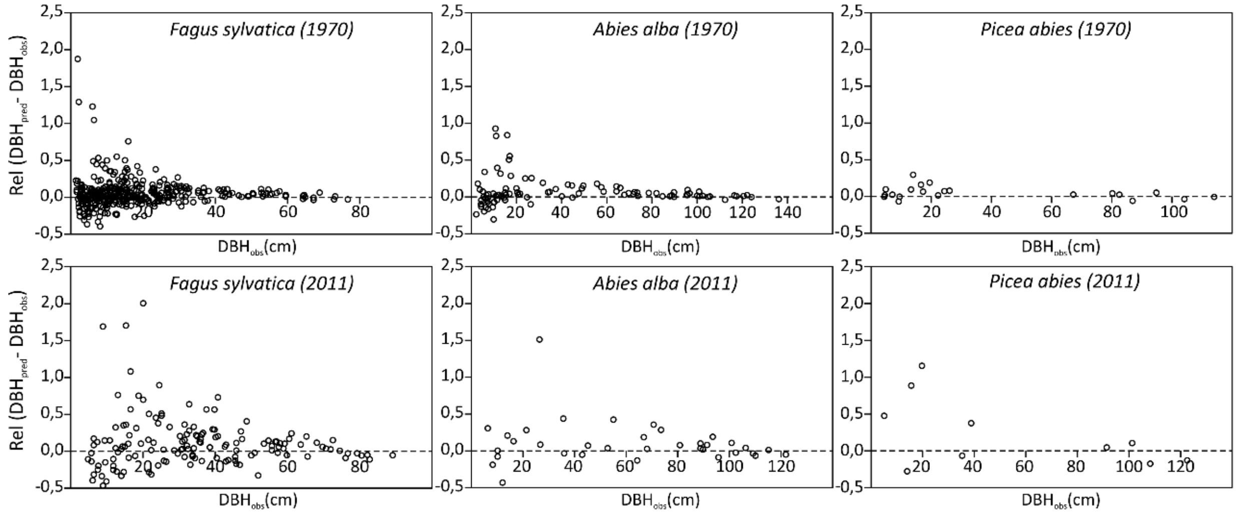


Fig. 13: MOSES validation runs for diameter increment predictions in uneven-aged mixed beech, fir and spruce forests in Croatia. This suggests that the model is also applicable for ecosystem types beyond the calibration areas.

## 2.7 Samsara

### 2.7.1 Brief overview of model

#### 2.7.1.1 Model structure

Samsara2 is an individual-based and spatially explicit model to simulate the dynamics (regeneration, growth and mortality) of mixed and uneven-aged mountain forest stands. Every process in the model has been calibrated empirically for Silver fir (*Abies alba*) and Norway spruce (*Picea abies*) stands, within the montane elevation belt of the Northern Alps. Competition for light is calculated within a stand based on light ray interception by tree crowns. Annual diameter increment of individual trees depends on their size and on the amount of light intercepted by their crown during the growing season. Individual effects modulate tree growth to represent the variability of individual tree response to light. Natural mortality depends on tree diameter and on a competition index defined as the basal area of neighbouring trees larger than the subject tree within a radius of 15m. Seeds are produced by adult trees in relation to their basal area and dispersed randomly within the stand. Seedling germination, growth and survival depend on the light reaching the ground calculated in the center of 25 m² cells. Seedlings are transformed in trees with a crown participating to light interception when they reach the diameter thresholds of 7.5cm. Samsara2 is implemented in the simulation platform Capsis4 that hosts more than 30 forest simulation models developed in several countries and provides common visualization, simulation and forest management tools. These tools allow simulate detailed silviculture strategies, varying both the characteristics of harvested trees and their spatial arrangement within a stand. Ecological factors other than light such as climate and site conditions are not directly taken into account in Samsara2. Contrary to the other models used in the ARANGE project, Samsara2 has not been designed to simulate stands representing every situations found in a landscape.

It is more devoted to the detailed analysis of the interactions between stand structure, silviculture and dynamics of specific hotspots where the goals of production, biodiversity preservation and protection against hazards are combined at the stand scale.

#### 2.7.1.2 Input requirements (climate, land surface, forest properties)

| Climate requirements | Environmental/Site variables | Forest data | Management data |
|---|---|---|---|
| No input required | Empirical parameters for growth, mortality and regeneration adapted to the species and location. | Minimum: distribution of dbh per species.<br><br>Detailed: table of trees with their species, dbh, and coordinates x,y,z. | To reproduce past management: annual number of trees and volume harvested.<br><br>To analyse new management options: harvest limit diameter ; thinning limit diameter ; min/standard/max cut basal area in a single harvest operation; max proportion of harvest and thinned basal areas allowed ; regulation factor for species composition, aggregation and repulsion factor to regulate harvest spatial distribution. |

### 2.7.2 Model development in ARANGE (finished by M12)

Forest dynamic processes: The regeneration submodel for spruce and fir was improved to simulate better the response of spruce and fir seedlings to light levels corresponding to gaps ranging from the size of a single tree to areas of several hectares. The natural mortality submodel was improved to match better the observations of the French National Forest Inventory.

Management: An important work was done to develop the two automatic silviculture simulation algorithms necessary for the historical evaluation work on historical data and for the simulation experiments. The first algorithm mimics past management of unevenaged stands based on harvests reports in N and V (published). The second algorithm simulates flexible unevenaged management by varying harvest limit diameter, harvest volume, max % harvest among trees of corresponding size, max % thinning among trees of the corresponding size, spatial aggregation, composition regulation. (in revision)

Outputs: A submodel of wood decay was developed. Indicators of herb species richness were calibrated on data from the French National Forest Inventory. Both these outputs are necessary to analyse the impact of management on biodiversity.

### 2.7.3 Results from preliminary model applications to CSA(s)

Samsara2 has been calibrated for spruce-fir uneven-aged forests of the mountain climatic level of the Alps and for intermediate levels of fertility. Applications of the model are made in a theoretical framework in which demographic and management parameters are varied within ranges covering the gradients observed in the Alps but not necessarily related to a specific case study. However, the results will interest directly the case studies where spruce-fir mountain forests are found: CS_2 (Vercors), CS_3 (Montafon), CS_4 (Sneznik), CS_6 (Kozie Chrbty), CS_7 (Shiroka Laka).

### 2.7.4 Results from model testing against empirical data in ARANGE

The ability of Samsara2 to reproduce observed forest dynamics has been tested using stand data from the forest of Queige (located not far from case study CS-2, Vercors and providing historical data series of high quality). Starting from inventories made in 1930, we have simulated forest dynamics and management up to 1980, and compared the simulated stands to observations in 1980 (Fig. 14).

When using mean estimates of demographic parameter values, the average bias (difference between prediction mean and observation mean) per decade of simulation (average time length between two harvests) is of 5.4% for stem density, 4.8% for basal area and 0.06% for quadratic mean diameter. These biases are highly variable from one stand to the other in a same forest.

We have conducted a sensitivity analysis of the predictions made on the forest of Queige, using a Latin Hypercube Sampling scheme to make the demographic model parameters vary within their uncertainty range. The uncertainty of model predictions is very high, especially for basal area (~ 25 $m^2$/ha), however mean predictions are reasonable. Simulated stand structure after 50 years has been shown to be most sensitive to spruce growth parameters in this forest. We are currently expending this work to other situations.

### 2.7.5 Plans for future model applications in ARANGE

Simulation experiments have been started to analyse the effect of uneven-aged forest stand management on wood production and biodiversity. The experiments focus on the hotspot represented by spruce-fir uneven-aged forest at the mountain level. They are intended to provide a general understanding of the patterns of relations between management parameters at the stand level (limit harvest diameter, composition regulation etc…) and production vs biodiversity indicators at the stand level. The management parameters to which these ecosystem services are the most sensitive will be identified. The ranges of management strategies compatible with both services will be characterized.

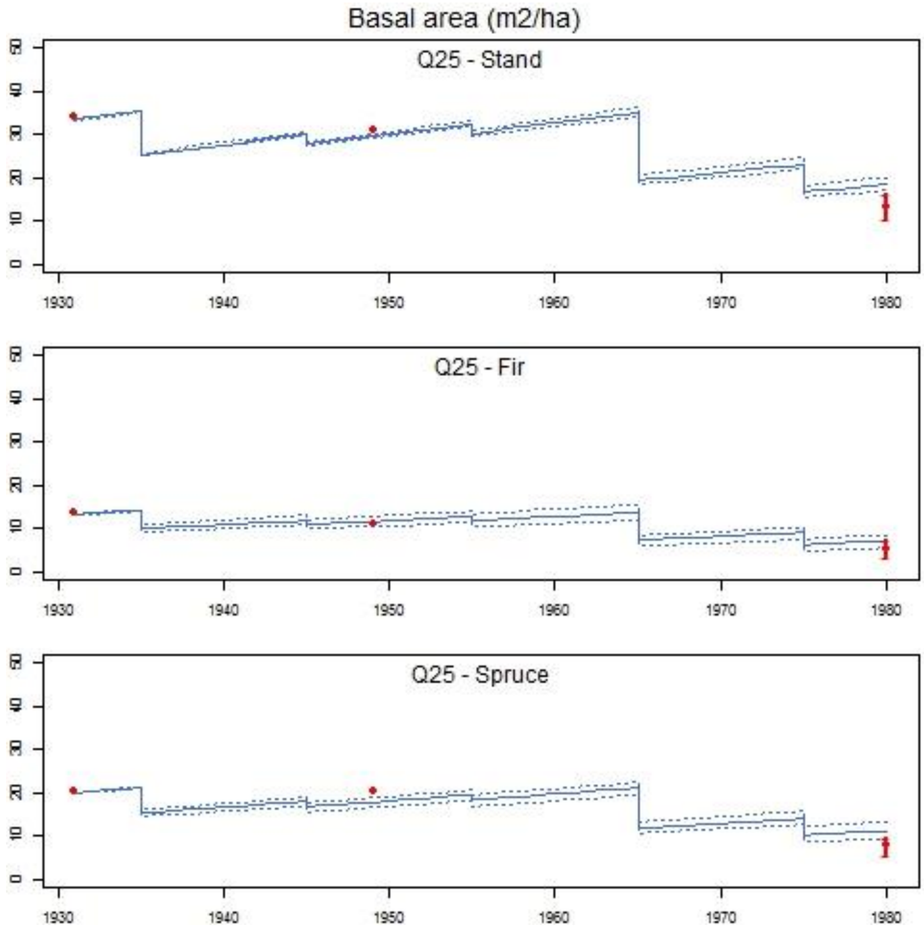


Fig. 14: Simulated dynamics of the stand Queige-25 (blue) compared to observations (red).

## 2.8 SILVA-SI

### 2.8.1 Brief overview of model

#### 2.8.1.1 Model structure

SILVA-SI is a spatial information system, consisting of historical data on forests and forest management and environmental/site and climate variables. It represents a platform for developing different statistical models of forest stand development. Unlike most of the models within the group of “ARANGE models”, SILVA-SI is not a process based forest growth model. It covers the entire forest area of Slovenia (11,400 km$^2$, 32.597 compartments). The forest data in SILVA-SI are basic data on the state of forest stands (Table of input requirements) at the compartment level (32.597 compartments, average area approx. 34 ha). For the part of the ARANGE CS (Dinaric Mountains), SILVA-SI is based on the sub-compartment level (165 sub-compartments, average area approx. 19 ha). The data at the national level are available for the period 1970-2010 and for the case study for the period 1912-2004. The forest data were acquired from various sources, mostly through forest inventories; this is a combination of a field description of all stands and of tree measurements (dbh ≥ 10 cm) at permanent 500 m$^2$ sampling plots (N = 100.178) with a dominant sampling network size of 250 m × 250 m and 250 m × 500 m (Poljanec et al., 2010).

The historical data (from 1912 to 1974) for the case study were collected from different archival sources (e.g. forest management plans, forest maps). The forest inventory data for the last 100 years (Klopcic et al., 2010; Klopcic and Boncina, 2011) were completed with site variables (e.g. digital elevation model, site and soil map; see Table of input requirements) and compiled in the database.

To date, the data from SILVA-SI have been used for different statistical modelling at different spatial levels. Binary logistic regression, GLM, and Artificial neural networks (ANN) were applied to analyze changes in stand structure and species composition in past decades and to detect relevant influential factors. Furthermore, at the country level the multi-target regression trees were employed (Boncina et al., 2011) to determine the main variables that influence the temporal dynamics of the growing stock and tree species composition.

#### 2.8.1.2 Input requirements (climate, land surface, forest properties)

| Climate requirements | Environmental/Site variables | Forest data | Management data |
|---|---|---|---|
| Mean annual precipitations (mm),<br><br>Mean annual temperature (°C) | Elevation (m),<br><br>Variation of elevation within the compartment or sub-compartment,<br><br>Inclination (°),<br><br>Aspect,<br><br>Rockiness (%),<br><br>Latitude, longitude<br><br>Bedrock<br><br>Relief (e.g. top of the hill, bottom of the hill, slope) | Forest area,<br><br>Growing stock (GS) ($m^3$ $ha^{-1}$),<br><br>GS of tree species or proportion of tree species usually grouped into 10 main tree species groups,<br><br>Proportion or GS of the small (dbh=10-29 cm), medium (dbh=30-49 cm) and large (dbh≥50 cm) trees in the GS,<br><br>Stand type and/or development phases | Annual removed GS ($m^3$ $ha^{-1}$),<br><br>Annual allowable cut ($m^3$ $ha^{-1}$),<br><br>Management system<br><br>Forest openness (m $ha^{-1}$) |

### 2.8.2 Model development in ARANGE

To date, our work was divided into two main activities. Firstly, the changes of stand structure and tree species composition in the CS area as well as the influential factors were analyzed with basic statistical methods. Secondly, changes of stand volume and tree species composition in the past and their prediction for the next decade were modelled with General linear model (GLM, stepwise procedure), and afterwards evaluated in the context of two main forest management goals: timber production and biodiversity.

We set the growing stock at the end of the management planning period (GS 1964, GS 1974, GS 1984, GS1994 and GS 2004) for each period as target (dependent) variables. Stand parameters at the beginning of each management planning period, management activities in that period and environmental variables (Table of input requirements) were used as the descriptive variables. Since the variability of climate parameters could not have been recorded along the altitude gradient in the CSA due to the absence of meteorological measurement stations along this gradient, the temperature and precipitations were not included in the model development.

In addition to the total growing stock, the growing stock of Silver fir and European beech at a specific point in time were modelled, using the independent variables from the presented data set (Table of input requirements), unless some of the predictors were not available for the period being modelled. First, we learned the model on the data for the period 1954-2004 and evaluated the model fit. To predict the growing stock and tree species composition for the next decade (year 2014), we kept the structure of the model using all independent variables for the year 2004 and replacing realized cut with the annual allowable cut for the period 2004-2013 as proxy for future management activities.

For the evaluation of the generated models and for the selection of the exploratory and predictive models, we used quantitative (e.g. R-square, root mean squared error), qualitative and contextual criteria (expert validation of the model based on statistical models previously developed in the CSA).

### 2.8.3 Results from preliminary model applications to CSA(s)

SILVA-SI has been applied in the Dinaric Mountains CSA only. The results from the previous statistical modelling were important for expert validation of the GLMs developed within the ARANGE and are also briefly reported here. The results of SILVA-SI based modelling applied within the ARANGE 2.1 task can be summarized as follows.

The development of the diameter structure of forest stands in the part of CSA (Leskova dolina) clearly showed a shift in the diameter distribution towards large-diameter trees (dbh ≥ 50 cm); in the period 1912-2004, the number of large-diameter trees increased for 54 trees $ha^{-1}$ and the number of small-diameter trees (dbh = 10–29 cm) dropped for 171 trees $ha^{-1}$. In Leskova dolina fir was the dominant species throughout the study period, but its proportion dropped by 16 % in the 1964–2004 period; the proportions of beech and spruce substantially increased in the studied period.

The set of explanatory GLMs for timber production showed reasonable performance. The main predictors of the total GS at the end of each inventory period were: 1) parameters describing the state of the forest at the beginning of the inventory period (i.e. the initial GS, the initial proportion of small diameter trees, and the initial proportion of broadleaves), 2) management activities during the examined period (the annual removals), 3) the elevation gradient and 4) the forest openness in the compartment.

The models simulating changes in tree species composition showed different performances (yet only two most common tree species in the CSA were considered – the GS of silver fir and the GS of European beech). While model for silver fir showed a high performance ($R^2$=0.810), the performance of the model simulating changes of the GS of European beech was much lower ($R^2$=0.591). The main explanatory variables for the GS of silver fir were 1) the GS of silver fir at the beginning of the inventory period, 2) site conditions (elevation, inclination and rockiness) and 3) the annual removals of conifers. The GS of European beech was explained by 1) the initial GS of beech, 2) the proportion of small diameter broadleaved trees at the beginning of the inventory period, 3) the elevation and 4) the forest openness in the compartment.

The forecasted total GS seemed to be slightly underestimated according to the expert evaluation and past modelling results. The comparison of predicted values with inventory data confirmed that. The predicted values of changes in GS of European beech and of silver fir showed reasonable good values. Even so, further testing and development of the models is needed.

### 2.8.4 Plans for future model applications in ARANGE

Due to an insufficient model fit for some of the GLM models based on the SILVA-SI database, we plan to:

- improve a simulation accuracy with the set of forest management and wildlife variables that will be acquired from different sources;
- apply and refine other models from the ARANGE consortium to the Dinaric Mountains CSA (e.g. MOSES);
- compare the SILVA-SI statistical model-based forecasts (the GLM models developed in ARANGE and the previously developed models) to the forecasts made by process-based models applied within the ARANGE project in the CSA Dinaric Mountains.

## 2.9 SYBILA

### 2.9.1 Brief overview of model

#### 2.9.1.1 Model structure

The SIBYLA growth and yield model (Fabrika & Ďurský 2005, 2006) is based on the Silva simulator (Pretzsch et al. 2002), and is an individual-tree, distance-dependent model. It is an empirical, ecological niche-based model that simulates the growth of individual trees, and it evaluates inter- and intra-specific competition among trees. SIBYLA was parameterised and validated using forest inventory data from Germany, Switzerland and Slovakia. The model is parameterized for 5 main European forest tree species – Norway spruce, Silver fir, Scots pine, European beech and oak (*Quercus* sp.); other species can be simulated on the basis of their ecological and morphological similarity with the aforementioned species and using calibration functions.

The model consists of the following sub-models: stand structure generator, mortality submodule, competition sub-module, growth sub-module, thinning sub-module, regeneration submodule (under development) and analytical sub-module which derives summary information on simulated stands, including various indices of stands` structure (yield, biomass and carbon, diversity, cost&benefit). The growth sub-model was originally designed by Pretzsch & Kahn (1998). Growth responses to respective environmental parameters were formalized according to Kahn (1994). The mortality sub-model was described by Ďurský et al. (1996) and Ďurský (1997). Because the model's growth and mortality routines are climate sensitive, the model is well suited for modelling the impacts of climate change on forest development (Hlásny et al 2011). Simulations are usually run for one rotation, regeneration routine which is under development now, allows for unlimited number of consecutive simulations. Stochastic mode can be used to allow for producing more robust simulations. The model can simulate several cutting and thinning techniques, typically applied in Central Europe. The following treatments can be applied: thinning from below, thinning from above, neutral thinning, method of future crop trees, method of target diameter, method of target frequency curve and method of a cutting element.

#### 2.9.1.2 Input requirements (climate, land surface, forest properties)

| Climate requirements | Environmental/ Site variables | Forest data | Management data |
|---|---|---|---|
| number of growing degree days, annual temperature amplitude (°C), mean air temperature IV-IX (°C), precipitation totals IV-IX (mm), deMartone index of aridity (mm.°C$^{-1}$) | $CO_2$ content (ppm), $NO_x$ content (ppb), soil nutrition(0–1), soil moisture (0-1) | Stand can be initialized using tree data positions and dimensions; stand design can be generated using stand data such as species composition, age and diameter structure; or using combinations of these approaches | By default, the growth simulator applies the model of decennial thinning percentage, in which the percentage is related to stand age of all simulated tree species, site classes, and degrees of stand density. |

### 2.9.2 Model development in ARANGE (finished by M12)

Regeneration module has been missing in Sibyla simulator, thus the simulations were limited to one forest life-cycle; forest biomass and carbon were underestimated in stands where natural regeneration occurs. During 2012 data from Slovak National Forest Inventory (NFI) (2005-2006) have been analyzed and parameters of natural regeneration for main forest tree species that occurred on NFI plots have been derived. Effect of parameters such as seed purity, germination rate, seed year frequency, etc. was taken from the literature. The regeneration module is climate sensitive what makes it suitable for climate change impacts studies. Test runs have been evaluated. Implementation of natural regeneration module to Sibyla simulator has started in 2012, and it is expected to be finished in early 2013 to be ready for use in ARANGE CSAs.

Further, development of the framework for multimodel assessment of forest biomass and carbon pools based on Sibyla and BiomeBGC simulations have been addressed. The approach integrates the outputs of both models produced under an ensemble of climate change scenarios, several model assumptions, and considering models stochasticity. Exchange of several quantities during the simulation stage, and way for the integration of simulation outputs, were proposed and tested. Among others, transfer of soil water content, and dead biomass decomposition rates based on BiomeBGC simulations are used to enhance the Sibyla-based simulations. The approach is implemented as series of scripts in the SQL. Finally, an approach to the decomposition of the uncertainty of final estimates, based on the Generalized Linear Models, have been proposed (following Olesen et al. 2007) and tested. This aims at the breakout of the uncertainty of final estimates, and attributing this uncertainty to factors such as models architecture, climate change scenarios, time periods addressed and inherent models stochasticity.

### 2.9.3 Results from preliminary model applications to CSA(s)

We performed a range of simulations in Slovakia which partly cover the CS_6 (Kozie chrbty, Slovakia). This experiment was to explore the effects of climate change on forest production and carbon cycle, and to designate generic response functions of forest production to climate change for Central Europe (Figure 15). As CS_6 is presently dominated by Norway spruce, and future management supposes increasing the share of broadleaved, mainly of European beech, this knowledge will be used in the CSA to optimize the simulation design.

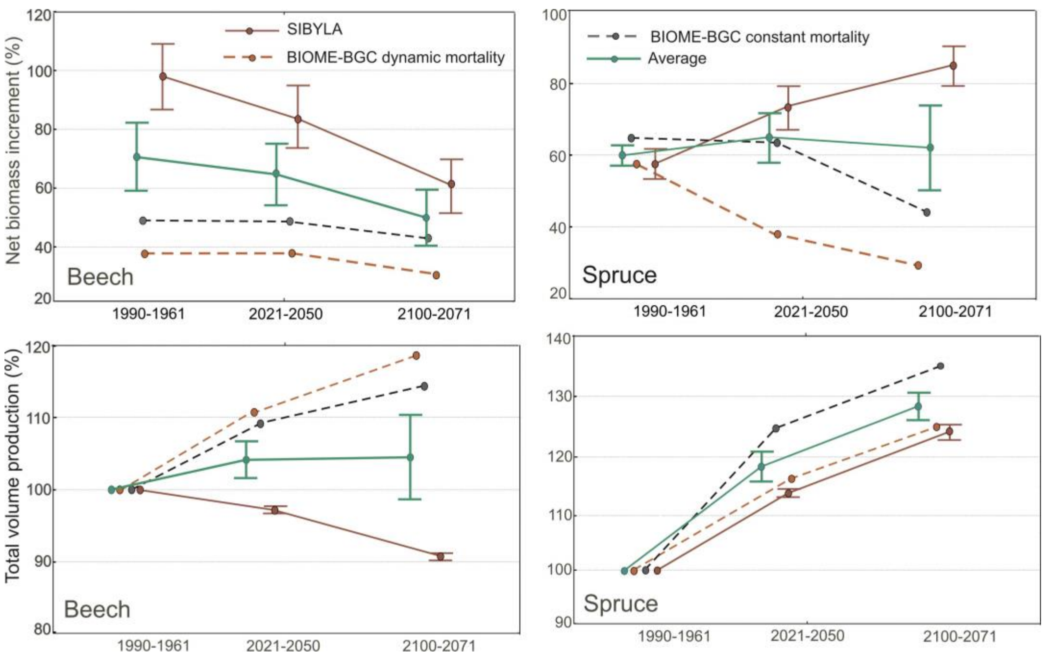


Fig. 15: Response of European beech and Norway spruce growth to changing climate across vegetation zones in Central Europe. Simulations are based on Sibyla tree growth simulator. Zones 4 to 7 cover CSA 6.

The other experiment focused of more detailed investigation of forest production and carbon cycle by the integration of Sibyla and Biome-BGC simulations of mountain Norway spruce stands

(Figure 16); data from European forest monitoring plots were used for the calibration. Results of this experiment are transferable to CSA.

Experiment focused on the simulation of forest stands development under various thinning regimes was performed in the Czech Republic; structure of calibration data was similar to data which are intended for use in the CSA. During this experiment, a specific approach to initial stand definition has been developed, based on the combination of tree positions generation and setting exact positions of trees which remained in a stand after several thinning periods. This approach will be used in the CSA.

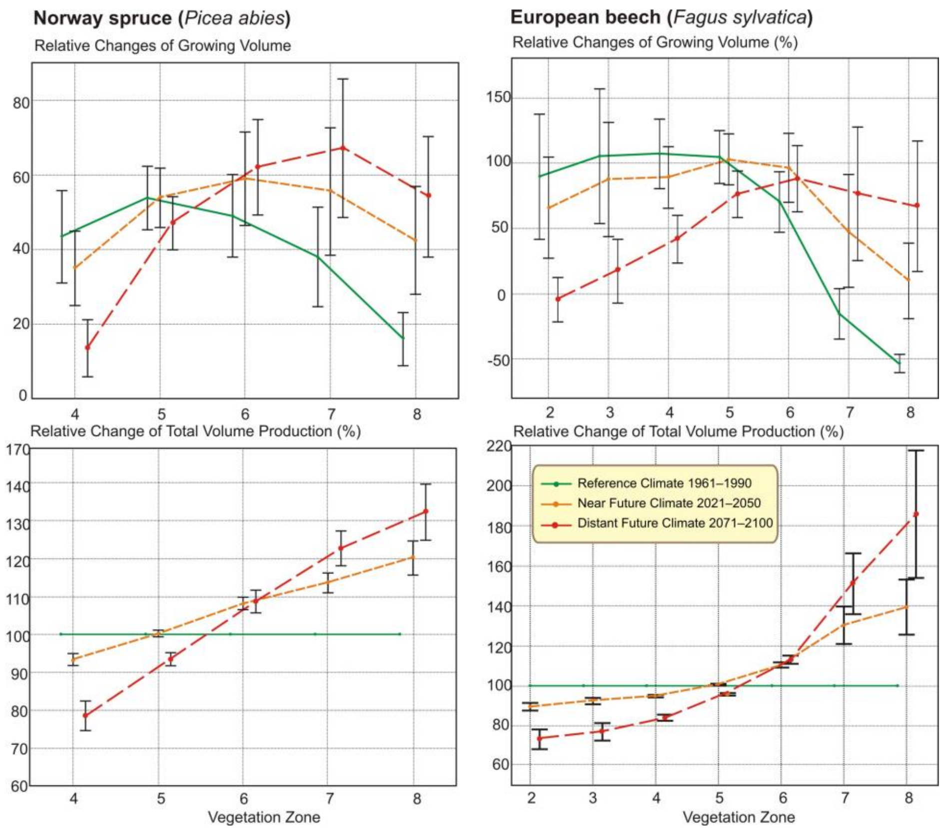


Fig. 16: Multi-model assessment of net biomass increment and total volume production of unmanaged mountain Norway spruce stand in Slovakia based on Biome BGC and Sibyla simulations. The results are transferable to CSA.

## 2.9.4 Results from model testing against empirical data in ARANGE

There are 14 experimental plots in the CS_6 for which the historical data on stand development and management is available, and which are expected to be used for CSA specific simulations. Initial design of all plots has been set up in the Sibyla simulator, including definition of site parameters; stand definition was based on field campaign from autumn 2012 when detail stand data were collected. Historical data on forest management and disturbances specific to each plot has been collected as well. The oldest records go approximately to 1960, time series length and data quality is variable. These data were organized to time series of volume extracted from the plots so as they can be used in the simulation of stand development under BAU management. Climate change scenarios were taken from simulations performed in the ARANGE project, and all climatic variables needed to run the Sibyla simulations (cf. Table in section 2.9.1) were prepared. Plot-specific calibration using historical data and present-day measurement has not been done yet. Finally, test simulation runs under no-management scenario were run.

### 2.9.5 Plans for future model applications in ARANGE

The model is expected to be applied primarily for simulation of forest stands development in CS_6 (Kozie chrbty, Slovakia), and supposedly in CS_3 (Montafon, Austria) and CS_4 (Sneznik, Slovenia) where we suppose the present model parameterisation be valid, and model calibration using plot data from the CSAs thereof could allow for producing reliable estimates.

In CS_6, simulations of forest development at 14 experimental plots with historical data available will be performed under various managements, alternative to the present one, and climate change scenarios. The presence of secondary spruce forest suffering from the large-scale decline supposes us to focus on forest conversion oriented management scenarios, and considering strongly stands hazard rating in management scenarios proposed. Several approaches to the upscaling of simulation outputs to the entire CSA will be tested, and links between final stand structures and set of ecosystem services and functions (mainly round wood and fuel wood production, carbon sequestration and biodiversity support) will be investigated.

# 3 Conclusions

The present compilation documents that the forest models available in ARANGE have been set up and tested for a wide range of conditions in the CSAs of the project. We conclude that the goals of Task 2.1 of the project have been reached, and model application in the CSAs can begin. The next steps will be to define the management regimes (both past and future) so as to be able to simulate realistic forest structure data.

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