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Models for Adaptive Forest Management

D 3.2/3.3 Tested model features concerning adaptive management capacity in the various case studies

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Contents

1 Introduction

The objective of this project deliverable is to describe the features concerning adaptive forest management as developed, implemented and tested in the tools as described earlier in D 3.1. Here only the new features are described.

Actual runs and delivery to the toolbox are described in deliverables from Wp 4 resp Wp6.

2 Definitions and terminology used in the description of the forest simulation tools

It is important that the forest simulation tools are described in a similar way and using the same terminology. For this purpose, the terminology from the EFORWOOD project (Tomé et al., 2007), later on also adopted by the COST Action FP0603 “Forest models for research and decision support in sustainable forest management” was adopted here with some adaptations and constitutes the first point of the deliverable.

State variables – Set of variables (at stand and/or tree level) that characterize the forest at a given moment and whose evolution in time is the result (output) of the model. State variables can be: 1) Principal variables if they are the output of the growth modules; 2) Derived variables if they are indirectly predicted based on the values of the principal variables

Driving variables – Variables that are not part of the forest but that influence its behaviour: 1) Environnemental variables (e.g. climate and soil variables); 2) Human induced variables/processes (e.g. silvicultural treatments); 3) Hazards (e.g. pests and diseases, storms, fire)

Forest model – A dynamic representation of the forest and its dynamics, at whatever level of complexity, based on a set of (sub-)models or modules that together determine the dynamic of the forest as defined by the values of a set of state variables. The forest responses to changes in the driving variables are reflected by the predicted dynamic of the forest. Modules, and therefore the models, can be deterministic or stochastic.

Model module – Set of equations and/or procedures that led to the prediction of the future value of a state variable.

Module sub-module or component – Equation or procedure that is part of a model module, contributing to the prediction of a state variable but not having a state variable as output.

Silvicultural system – Sequence of silvicultural operations, including regeneration and felling, that characterize the forest management applied to a stand. Different objectives in forest management (e.g. conservation in semi-natural woodland vs. production of timber in plantations) are likely to lead to the adoption of different silvicultural systems.

Forest management alternative – Sequence of silvicultural operations that are applied to a stand during the rotation (for even-aged stands) or during a cycle (for uneven-aged silviculture). The silvicultural system expresses the “philosophy” behind the type of tending and the forest management alternative the details of the operations.

Management regime, treatments schedule or prescription – Sequence of silvicultural operations that are applied to a stand during the projection period. It may include several silvicultural systems and the transitions between them or even species substitution and/or land use changes.

Scenario – Conditions (climate, forest policy measures, management alternatives, etc) present during the projection period.

Forest simulator – Computer tool that, based on a set of forest models, makes long term predictions of the status of the forests within a well-defined region under a certain scenario of climate, forest policy or management alternatives. Forest simulators usually predict, at each point in time, wood and non-wood products from the forest as well as indicators of sustainable forest management. Forest simulators can be developed to work at different levels of spatial resolution. Stand simulators are focused on the simulation of a stand while landscape/management area simulators are focused on the simulation of all the stands included in a certain well defined region in which the stands are spatially described in a GIS. The simulation can be made on a stand by stand basis or through a grid. In both cases outputs for the whole landscape are also provided, namely sustainability indicators. It allows for the testing of the effect of spatial restrictions such as maximum or minimum harvested areas or maximization of edges. At a larger scale operate the regional simulators that are focused on the simulation of a large region, based on forest inventory data, usually without individualization of each stand. Outputs are usually given by forest type but focused on the whole region. Regional simulators are many times non-spatialized but can also be spatialized, usually through a grid.

Decision support system – Computational infrastructure integrating database management systems with analytical and operational research models, graphic display, tabular reporting capabilities and expert knowledge. The model base management system includes simulators and optimization algorithms that point out for a solution – list of forest management alternatives for each stand.

3 Documentation of Case model improvements

3.1 Northern Boreal

3.1.1 New features of the model

Outlines

Further model development in WP3.2 for the northern boreal study area in the Motive Project is needed in order to provide climate change impact on growth estimates of tree stands into the MONSU planning model (http://fp0804.emu.ee/wiki/index.php/Monsu), developed by Prof. Timo Pukkala, University of Eastern Finland, Finland. MONSU model allows optimizing the management, when aiming at production of timber, sequestration of carbon and minimizing abiotic risks due to wind and snow loading. MONSU generates a number of treatment schedules for each stand in a selected forest area for varying planning periods, including the risks of wind and snow load to damage trees (based on the simulations with HWIND model). Management guidelines for private forests in Finland are behind the management regimes, but tree species choice, regeneration method, intensity and timing of thinning and rotation length can be varied in order to obtain more than one treatment schedule per stand for optimizing of management. Regarding the simulations under the changing climate, the MONSU simulator should be made responsive to the climate change based on the simulations done with the FinnFor model because it has been developed originally for current climate.

Transfer of climate change impacts into Monsu

Regarding the transfer of climate change impacts to MONSU (transfer functions), the following assumptions are made: (i) the response to the climate change is species-specific, (ii) the response to climate change is specific to maturity (size) of trees, (iii) the response is specific to spacing in the tree stand, (iv) the response is specific to the position of trees in the stand, and (v) the response is specific to the site fertility (site type). Consequently:

$$\Delta Growth\ (\Delta d, \Delta h) = f(\text{climate change, tree species, maturity } (h, d), \text{spacing, position, site type}) \quad (1)$$

where d is the diameter and h is the height of a tree. The transfer of climate change impacts into Monsu is based on the relative change in growth (ΔG(REL)), which the change in climate (temperature, precipitation, CO_2) is doing in relation to the growth under the current climate, as modelled separately for D and H,.

$$\Delta d(REL) = \frac{\Delta d(CC)}{\Delta d(CUR)} \quad (2)$$

$$\Delta h(REL) = \frac{\Delta h(CC)}{\Delta h(CUR)} \quad (3)$$

where CC refers to the growth under the climate change and CUR to the growth under the current climate in otherwise similar conditions (tree species, maturity (h, d), spacing, position, site type). The ratio between the growth under the climate change and the current climate provides a correction factor, which is used to correct the growth in Monsu to meet the changes due to the climate change.

The process-based model FinnFor was used in this work to generate the data to construct the correction factors following the outlines given by Equation (1). The model utilizes the main physiological (photosynthesis, respiration, transpiration, water and nutrient uptake) in calculating the growth of trees. Depending on the physiological and growth processes on the hourly, daily and annual basis, the model is parameterized for the main trees species in Finland (*Pinus sylvestris, Picea abies, Betula pendula, Betula pubescens*). The model is exhaustively described earlier (e.g. Kellomäki and Väisänen 1997, Ge et al. 2010). Figure 1 demonstrates how the model is used to generate the data to calculate the factors to correct the growth in Monsu to meet the changes in growth due to the climate change.

In the calculation, the initial tree stands represented varying combinations of tree species of varying size (diameter) growing in stands of varying spacing (stand density) on sites of varying fertility. Furthermore, the trees in the stand were divided in three size cohorts representing varying tree position. The time series of climate scenarios (current climate, changing climate) were cut in short slices (5 years), which were used in calculating the response of each initial tree stand to the current and changed climate for each time slice. This made it possible to identify how young and mature trees in wide and narrow spacing on less fertile and fertile sites grow considering the position of trees in the stand. The calculations were done for Scots pine, Norway spruce and birch in the conditions of the case study area.

Simulations for transfer functions

The density of initial stand varied from 600 – 3000 trees per hectare in steps of 300 trees/ha in such a way that the trees in the stand were divided into three cohorts with the same number of trees/ha in each cohort (e.g. 600 trees/ha = 200 + 200 + 200 trees/ha in each cohort). In the case of small trees, they can grow five years over the whole range of stand density. In the case of large trees, this is an unrealistic assumption. Therefore, the initial densities were selected in such a way that trees of particular size were able to grow in a stand of selected spacing representing the full density over the five year period with no mortality. In the case of Scots pine, the calculations were done for the fertile, medium fertile, poor and very poor sites of *Oxalis-Myrtillus, Myrtillus, Vaccinium and Calluna* types. In the case of Norway spruce and birch, the calculations were done for the sites of *Myrtillus and Oxalis-Myrtillus* types (medium fertile and fertile sites). In each case, the soil was sandy moraine in simulations.

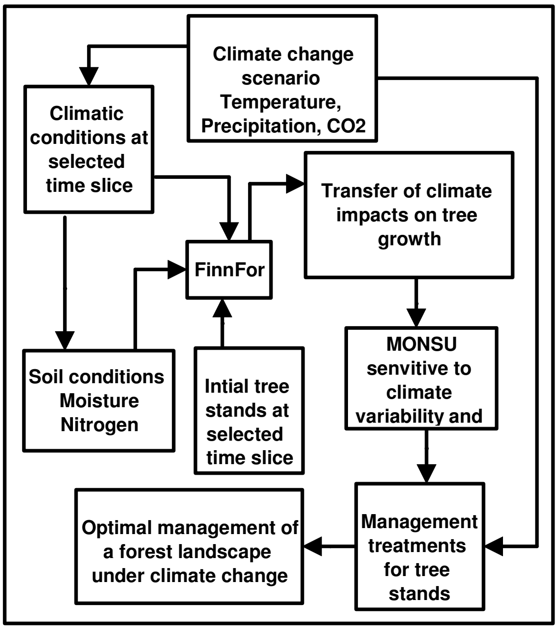


Figure 1. Outlines for the calculations used to define the values of correction factors to introduce the climate change impacts in Monsu.

The climatic and soil factors control the carbon uptake (photosynthetic production) and the consequent growth of biomass and dimensions of trees. Photosynthetic production is specific for tree species and the availability of nitrogen, which controls the nitrogen content of foliage. The constant nitrogen in foliage over the life span of trees are used as given in Table 1. The nitrogen content is linked to the forest site type and further to the fertility of the site.

Table 1. Nitrogen content in foliage used in the calculations.

Species	Site type	Site fertility, H_{100} or H_{50} (birch)	Nitrogen content, %
Scots pine	OMT	30	2.43
	MT	27	1.90
	VT	24	1,30
	CT	18	0.54
Norway spruce	OMT	30	3.74
	MT	27	2.92
Birch	OMT	26	4.68
	MT	24	3.65

Climate scenario

The current climate used in the calculations is that for the Joensuu airport (N 62° 40', E 29° 38', asl 94 m.) in the immediate vicinity of the case study area. The long-term (1961-2000) weather statistics on temperature and precipitation were provided for the Partner 3, who used it in compiling the climate change scenario for the same place. The annual mean values for temperature and precipitation sum for the current climate and the changing climate are shown in Figure 2. The atmospheric CO_2

concentration was for the current climate 369 ppm and in the climate change scenario it increased fairly linearly from the value 369 ppm to the value 703 ppm until 2100.

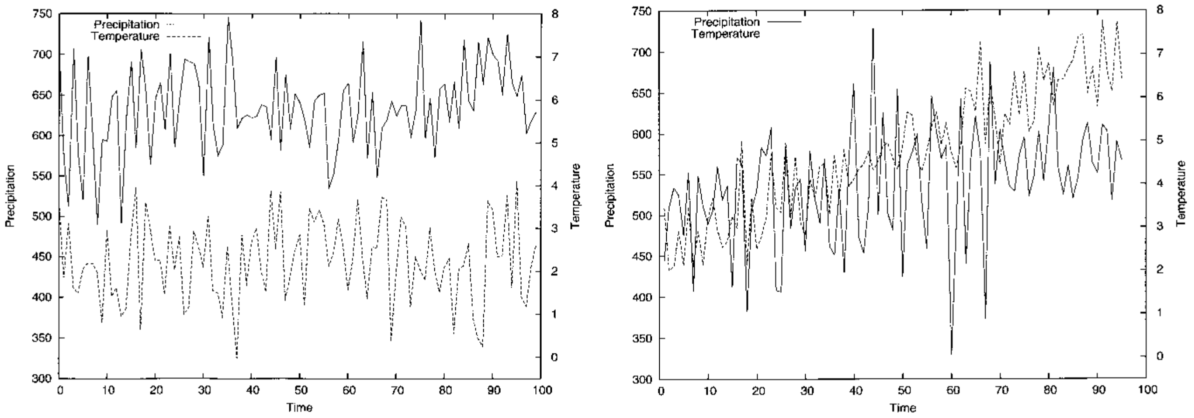


Figure 2. Annual mean temperature and annual precipitation sum for the boreal case study area. A: the current climate from the Joensuu Airport and B: the climate change.

Effects of climate change on tree growth

Figure 3 shows how the correction factor for the diameter growth of Scots pine varies over the 100-year period representing the climate change scenario for 2001-2100.

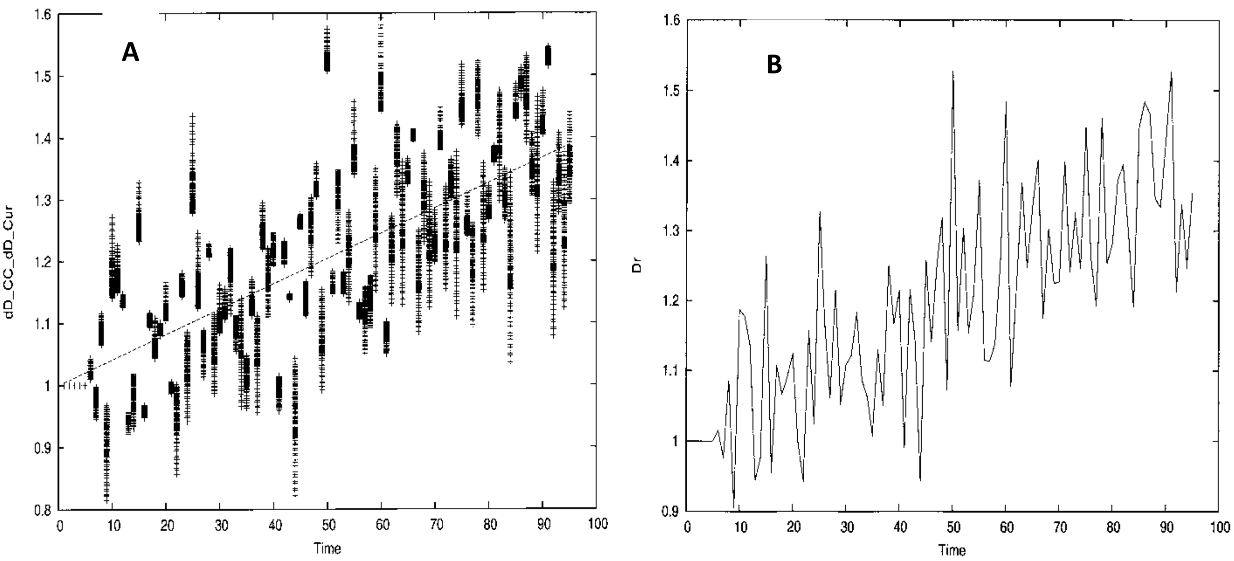


Figure 3. A: Clusters of points represents how all the combinations of initial stands respond to the climate change in a particular slice of time with the given climatic conditions. B: the same as in A, but for the mean values of the correction factors representing each cluster.

Each cluster of points represents how all the combinations of initial stands respond to the climate change in a particular slice of time with the given climatic conditions. It shows that different initial stands respond differently the same climatic conditions, but the response varies substantially following the year-to-year variability in climate. On the other hand, the response is smaller when the spacing is narrow or a tree is suppressed by taller trees.

The climate change increased the radial and height growth of Scots pine in a similar way from 0.36 % per year up to 0.59 % in such a way that the increase was larger on poor sites compared to that on fertile sites (Table 2). The same pattern held for Norway spruce and Silver birch, but in these cases the increase was smaller than that of Scots pine, and the increase in the height growth was smaller than in the radial growth. On the other hand, the increase was larger for birch than for Norway spruce.

Table 2. Change in the radial and height growth as a function of tree species and site type calculated from the material demonstrated in Figure 3.

Species	Site type	Trend for radial growth, % per year	Trend for height growth , % per year
Scots pine	OMT MT VT CT	0.362 0.414 0.523 0.596	0.362 0.414 0.523 0.596
Norway spruce	OMT MT	0.266 0.293	0.262 0.288
Birch	OMT MT	0.328 0.334	0.320 0.326

3.1.2 Incorporation of adaptive management

Regarding the adaptive management to the climate change, the main factors in the MONSU model are the choice of tree species, thinning regime and rotation length, which have a major effect on the growth and yield, carbon sequestration and the vulnerability of forests to snow and wind damages. In the case of thinning and length of rotation, the adaptive management is incorporated through the thinning rules, which are based on the development of the dominant height and basal area. Regarding the rotation length, the timing of terminal cut is defined by a target mean diameter of trees indicating the mature for cut.

The basic idea of thinning rules is presented in Figure 4. Whenever the value of basal area at a given value of the dominant height meets the thinning threshold line, a thinning intervention will take place and the value of basal area will be reduced to the value defined by the line of remaining basal area after thinning. This implies that any change in climatic conditions will automatically adjust the thinning cycle to the changes in growth. In the case of increasing growth, the thinning cycle will be faster and vice versa. This holds also for the rotation length based on the development of mean diameter of trees; i.e. increasing growth make trees earlier mature for cut, but the reduced growth will slow down the maturing for cut.

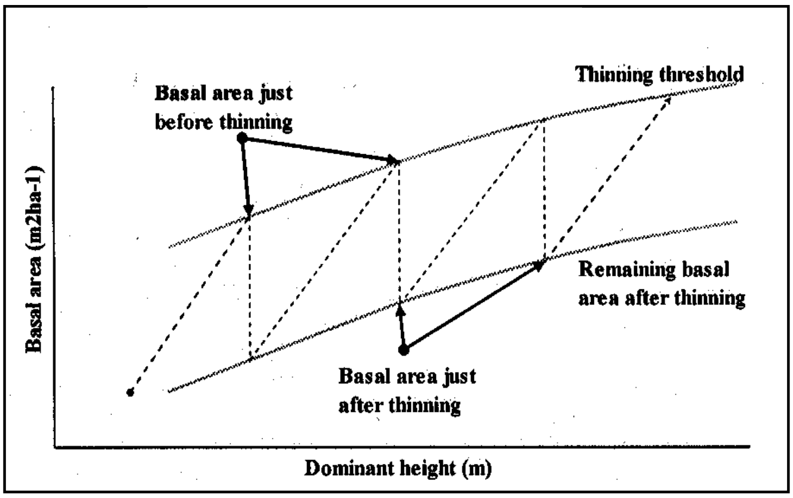


Figure 4. Principles defining the thinning regime based on

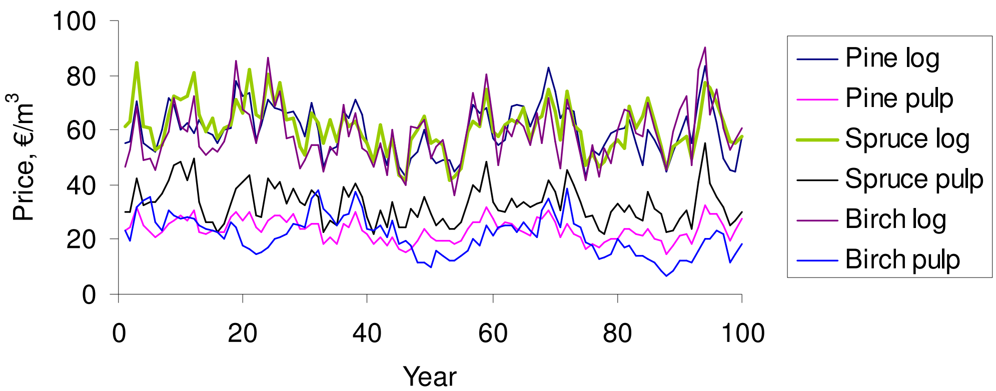
development of dominant height and basal area.

3.1.3 Tests and results under climate change

Climate scenarios into management support systems

The climate scenarios were included into the Newstand and MONSU simulation – optimization systems. MONSU is a landscape level system which uses combinatorial optimization to find the best combination of treatments for different stands. Newstand is a stand level decision support system which uses stochastic optimization with the scenario techniques to find the best anticipatory solutions for stand-level management problems in situations where regeneration, timber prices and tree growth are stochastic. Auto-correlated and cross-correlated scenarios are generated for the prices of different timber assortments and for the growth levels of different trees species (Figure 5). The used models take into account that the growth of different tree species in successive years are correlated.

In the Motive project, the growth trends due to climate change have been modelled for the case study area and these trends were added to the stationary scenarios to produce scenarios that include trends (Figure 6). Simulating each analysed management schedule under several regeneration, growth and price scenarios produces the distribution of the objective function (for instance net present value). Such a management schedule is selected which produces the most favourable distribution of outcomes (e.g. has the highest expected NPV). The corresponding management schedule is the anticipatory optimum.



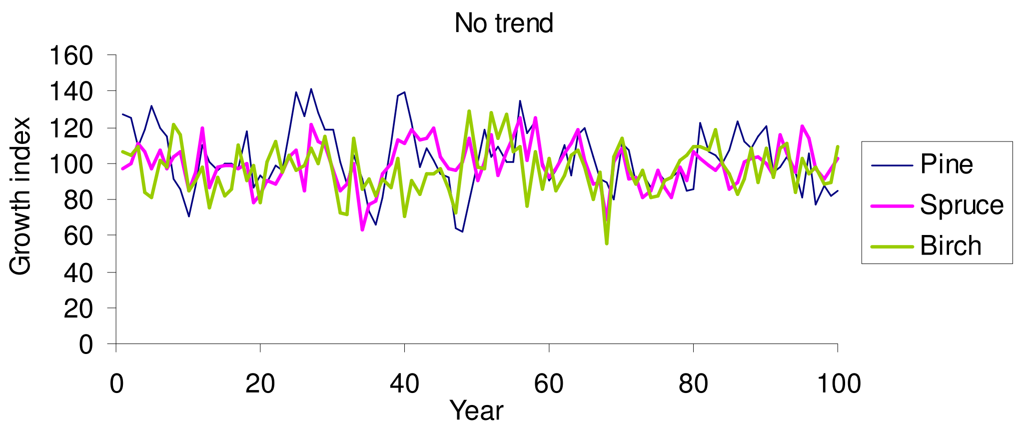


Figure 5. A stochastic timber price scenario and a growth index scenario. Note the temporal correlations and the cross-correlations between assortments and tree species.

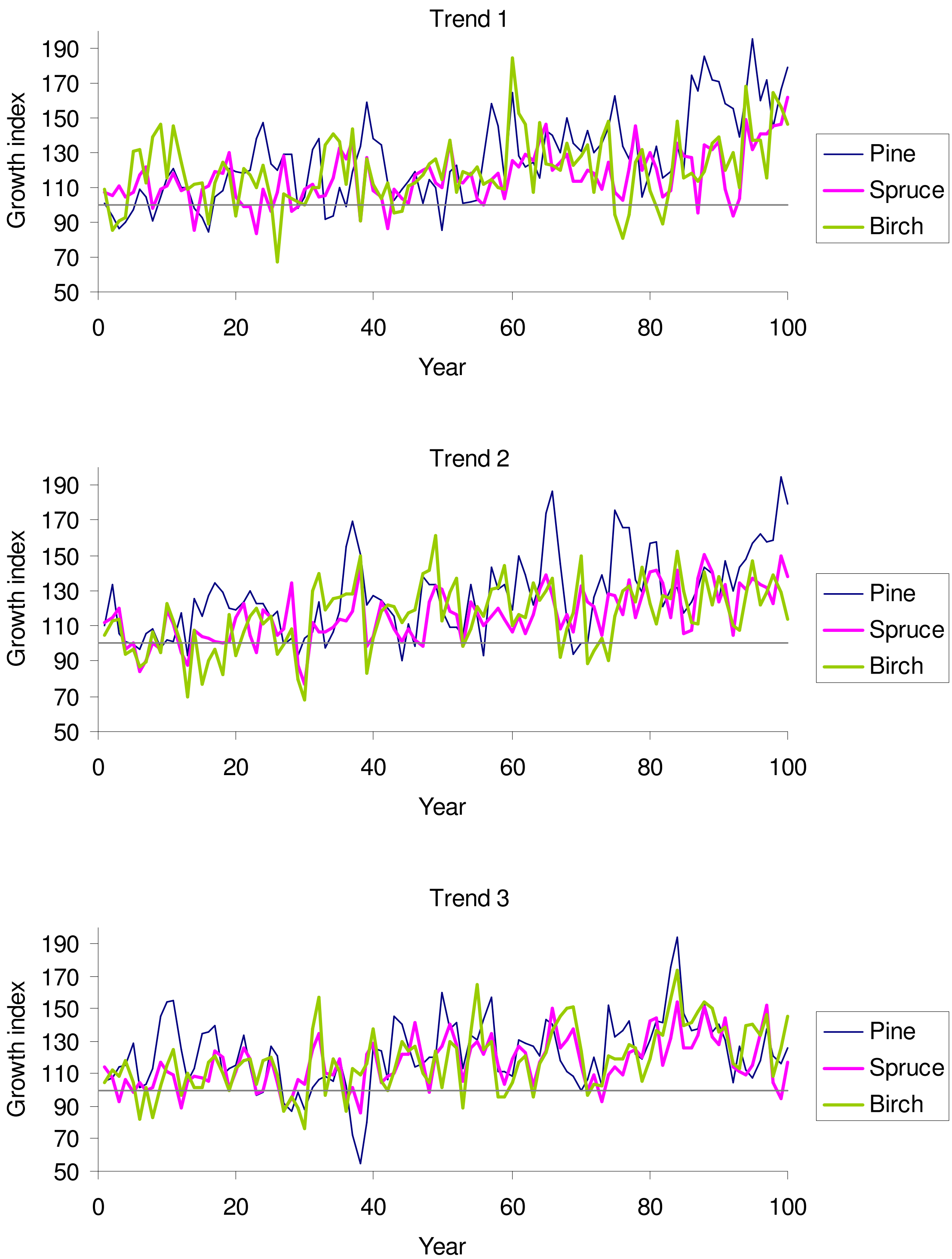


Figure 6. Three stochastic growth scenarios that include a climate-induced trend. The scenarios are for mesic site (MT).

During the Motive project, the Newstand system is developed so that, instead of current anticipatory optima (Figure 7), the system will find rules for the optimal timing of operations. This means that adaptive optimization will be used instead of the current anticipatory optimization. The outcome of optimization will be a rule that tells to landowner how the optimal cutting decision depends of stand structure and timber prices (i.e., when the right moment to cut the stand is and how it should be cut).

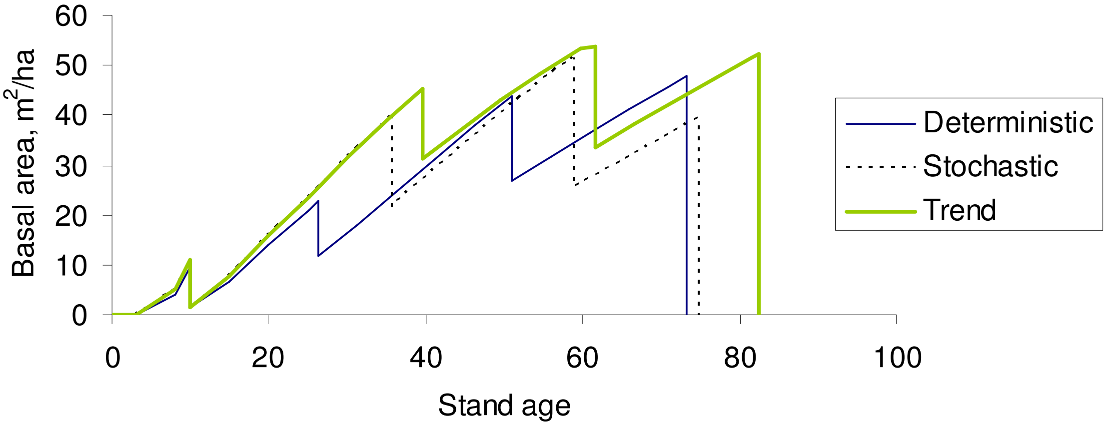
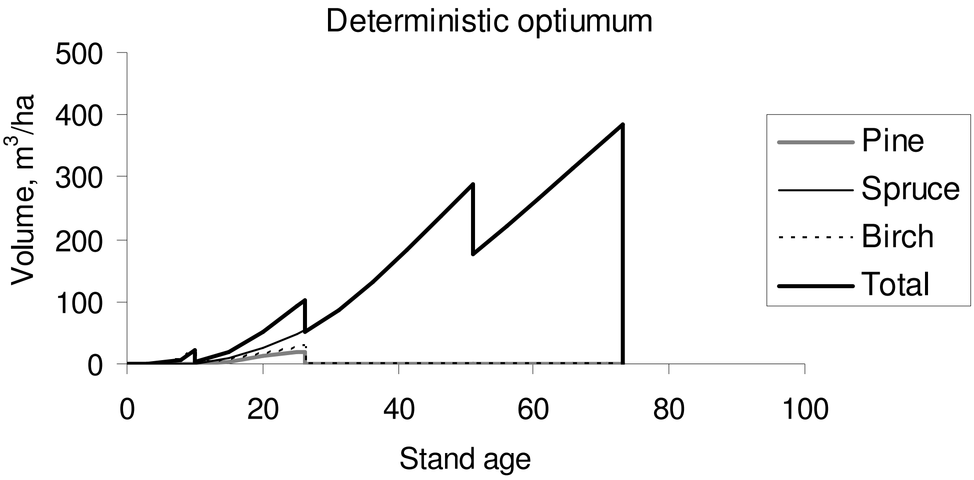


Figure 7. Optimal management schedule according to deterministic optimization without growth trend for climate change, stochastic optimization without growth trend, and stochastic optimization with growth trend in a mesic Norway spruce stand.

Logically, ascending growth trend increases the optimal growing stock volume. It also seems to increase optimal rotation lengths. Using stochastic optimization, instead of deterministic, seems to lead to solutions in which the stand is kept longer as a mixed stand (Figure 8). The optimization shown in Figures 7 and 8 are for a spruce plantation. In the model system, natural regeneration of Norway spruce, Scots pine and birch has been predicted with models.



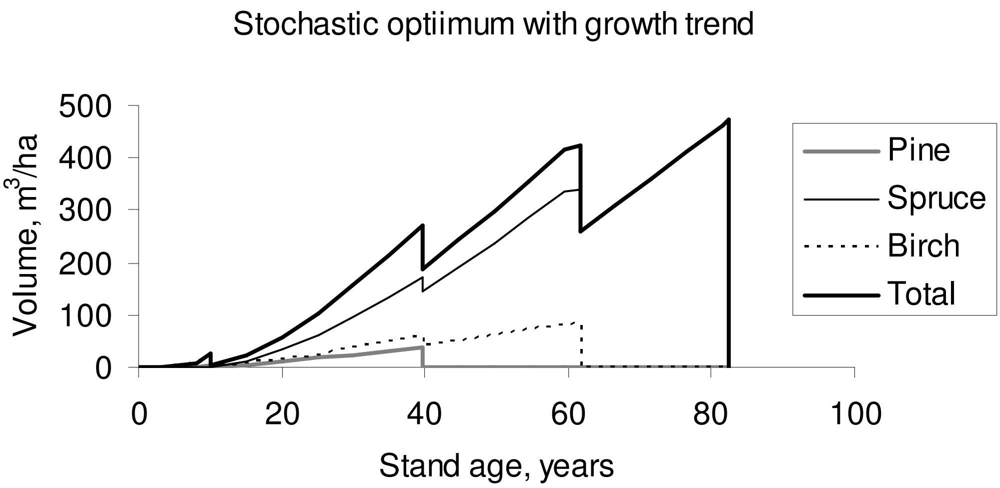


Figure 8. Development of stand volume in a planted Norway spruce stands in a deterministic optimum and in a stochastic optimum, in which the growth trend due to climate change has been taken into account.

3.2 South Boreal

3.2.1 New features of the model

The Forest Time Machine model system

The Forest Time Machine (FTM) is a forest management-unit simulator that was primarily developed to support evaluation and comparison of different forest management strategies (Andersson et al. 2005). In FTM, the development of each individual forest stand is divided into phases, e.g. young, wood producing, or providing seed/shelter, and simulations are run using time steps of five years. For those stands in the young phase, the time taken for the trees to reach a height of 8 m is calculated. In the wood producing phase, basal area and volume growth is calculated using empirical functions (Ekö 1985) based on data from the Swedish National Forest Inventory. Following the wood producing phase, the forest can be clear felled or partially felled. In each of the development phases the site index (SI) is used as one of the independent variables to predict tree growth. The FTM system has recently been modified to enable the gradual adjustment of stand volume growth over time in the projections in response to climate change (Blennow et al. 2010a). These adjustments are mediated by adjustment of the SI in response to changes in net primary production.

For the FTM simulations spatially explicit stand level information is input, including SI (at the start of the simulation period), height above sea level, soil moisture class, ground vegetation type, soil type, regeneration method used, tree species specific values of mean tree height, mean diameter at breast height, the number of stems per hectare, basal area, mean tree age, and history of commercial thinnings made during the rotation period. Future forest operations are specified by assigning a management programme to each stand. A management programme can consist of regeneration, pre-commercial thinning, commercial thinning and regeneration felling. Treatments in a management programme are scheduled through the combination of variables set by the user and functions dependent on SI.

We have

– Implemented routines in FTM for calculation of a stand-wise indicator of recreation value according to Lindhagen (2005).
– Developed and implemented routines in FTM to handle land-use change between agriculture (crop and pasture) and forestry.
– Added and implement routines in FTM for calculation of indicators of forest owner life-style vales.
– Improved the coupling between FTM and WINDA-GALES using GIS (ArcGIS), in order to more easily handle the adaptive management by standardizing formats for data input and output for the models.

The WINDA-GALES model

The WINDA model is an integrated system of models for assessing the probability of wind damage to forest stands (Blennow & Sallnäs 2004). It provides a geographically explicit environment for stand-wise calculation of the probability of exceeding critical windspeeds for wind damage in a landscape. The calculations are sensitive to the stability of the forest as well as to the local wind climate and uses extreme value theory for the statistical calculations. The model can be used to evaluate silviculture strategies and forest planning options with respect to the probability of wind damage. The model was recently modified to enable the calculation of the potential probability of wind damage under a changed climate based on climate scenario data (Blennow & Olofsson 2008) and has been used together with the climate sensitive FTM model (Andersson et al. 2005) to calculate the probability of wind damage under climate change (Blennow et al. 2010a,b).

At exposed stand edges at least 10 m high, the threshold (critical) wind speed required to uproot or break a tree is calculated using a modified version of the HWIND model (Peltola et al. 1999). HWIND calculates this critical wind speed by comparing the applied moment due to the wind with the maximum resistive moment that can be provided before uprooting or stem failure occur. TheWindAtlas andApplication Program (WASP) (Mortensen et al. 1993) is used in WINDA to calculate the critical free-stream wind speed. This is the calculated critical wind speed with the effects of changes in surface roughness and orography removed. Calculated critical free-stream wind speeds are linked to critical geostrophic wind speeds using WASP methodology and Tennekes method (Kristensen et al. 2000). The annual probability of exceeding the critical geostrophic wind speed for each sector is calculated using an extreme value distribution (Gumbel 1958) fitted to a time series of annual maximum wind speeds for each sector. The annual probability of wind damage for each stand is calculated as the aggregated sector-wise maximum value of the probabilities of uprooting and stem breakage, respectively. An ArcInfo polygon coverage holding information on the forest cover of the study area and its surroundings, and a digital elevation model of 50 m resolution are used as input.

The GALES model (Gardiner et al. 2000) has been integrated into a WINDA environment in collaboration with FR (Blennow & Gardiner 2009). The model development has been carried out within the Motive programme and provides a geographically explicit environment for stand-wise calculation of the probability of exceeding critical windspeeds for wind damage in a landscape. The calculations are sensitive to the stability of the forest as well as to the local wind climate. The model can be used to evaluate silviculture strategies and forest planning options with respect to the probability of wind damage. Using climate scenario data and a description of the state of the forest under climate change, the potential probability of wind damage under a changed climate can be assessed. The WINDA-GALES model has extended functionality compared to the WINDA (Blennow and Sallnäs 2004; Blennow & Olofsson 2008) and GALES (Gardiner et al 2000) models, on which it is based.

In WINDA-GALES, the GALES sub-model is used to estimate the stability of the forest stand in terms of critical wind speeds for uprooting and stem breakage at the stand edge or inside the stand (Gardiner et al. 2000). Spatial variables used as input to GALES are estimated using a geographical information system. Calculated critical wind speeds are linked to the geostrophic wind by taking into account effects of the terrain surrounding the stand using a rationale developed for the WAsP airflow model (Mortensen et al. 1993). Input data on speed-up coefficients due to the local topography, So, are calculated using the WAsP airflow model and are kept separately in a library. The effect of up-stream roughness changes, Sr, on the wind is estimated according to Kaimal and Finnigan (1994) and the average up-stream roughness length, z00, is estimated using a procedure by Troen & Petersen (1989). The critical wind, U0, of direction D0 and at height z above the zero plane displacement height, is cleaned of the effects of topography and surface roughness using

$$U(z) = \frac{U_0(z)}{(1 + S_o(D_0))(1 + S_r(D_0))}$$

where U(z) is the free stream wind speed. Assuming the logarithmic wind–profile for neutral stratification (Thom, 1971), the friction velocity, u*0, is calculated using

$$u_{*0}(D_0) = \frac{\kappa U(z)}{\ln\left(z/z_{00}(D_0)\right)}$$

where κ is the von Kármán constant, here assumed equal to 0.4. U(z) is linked to the geostrophic wind, G, aloft. This is done using Tennekes' derivation of the geostrophic drag law

$$G = \frac{u_{*0}}{\kappa}\sqrt{\left\{\ln\left(\frac{u_{*0}}{fz_{00}}\right) - A\right\}^2 + B^2}$$

where f=2*(the earth's rate of rotation in rad/s)*sin(latitude), and where A and B are dimensionless constants (Kristensen et al. 2000). The numerical values A=1.8 and B=4.5 were used, as recommended by Mortensen et al. (1993) and Troen & Petersen (1989). The annual probability of exceeding the critical geostrophic wind speed is calculated from a time series of geostrophic wind data using extreme value statistics by Gumbel (1958). The geostrophic wind data can be obtained by linking observed surface wind to the geostrophic wind in a similar way as above, or using output from a regional climate model. The latter option also provides opportunities to calculate the probability of wind damage based on climate change scenario data.

The following input is needed to run WINDA-GALES: an ArcInfo digital map (shape format) holding information on the forest cover and rooting conditions of the study area and its surroundings, a digital elevation model of 50 m resolution for the study area and its surroundings, and a time series of wind data.

3.2.2 Incorporation of adaptive management

Simulation of effects of wind damage risk-reducing forest management on different values

A forest management programme aiming at a reduced risk of wind damage has been defined that can be used in simulations of future states of the forest under climate change. The wind damage risk adapted management programme includes reduced length of the rotation period, reduction of the maximum age at which commercial thinning can be carried out, and use of deciduous tree species in regeneration at wind exposed locations. Adaptive feed-back is acquired through evaluation of consecutive forest states with respect to the probability of wind damage. If a specified probability of wind damage is exceeded, this invokes application of the risk-reducing management programme specified above. The effects of the management programme aiming at a reduced wind damage risk will be evaluated with respect to yield, risk of wind damage, and the provision of recreation and forest owner life-style values, and will be compared to the currently recommended forest management programme.

3.2.3 Tests and results under climate change

Testing is ongoing.

3.3 Atlantic Wales

The Atlantic Wales case study at Clocaenog Forest in North Wales covers an area of 5,662 ha across an altitudinal range 70-500 m. The main forest species is Sitka spruce (*Picea sitchensis)* comprising 53% of the forest. Other conifers represent 22%, broadleaves 7%, and the remainder being open space.

Clocaenog forest is part of the Welsh National Assembly Woodland estate and is managed by Forestry Commission Wales (FCW), and referred to in this document as the public forest estate (PFE). All Forestry Commission forests and woodlands in Britain (including the PFE in Wales) are certified as sustainably managed under the Forestry Stewardship Council (FSC) scheme. In Wales, the policy has been to reduce single species, single-aged stands of Sitka spruce and introduce a greater proportion of low impact silvicultural systems (LISS), including continuous cover forestry (CCF).

The main forestry issues relate to assessing the risk associated with transforming even-aged, single species stands in a windy climate, assessing the risks associated with species suitability on marginal sites in a changing climate, continuing to optimise sustainable management while meeting high production targets, improving forest access for recreation and relaxation, maintaining and enhancing forest biodiversity, and protecting woodland species and habitats from disturbance and damage while conducting forest operations.

Welsh forest policy has for some years promoted LISS (Anon, 2001), to reduce the over-reliance on clearfell-restock silviculture (CRS), promote better quality stands of trees and develop an increased mix of broadleaved species into the National Assembly Woodland estate. Although the target of 50% LISS management has been relaxed (FCW, 2009), the interest in species diversity and alternatives to CRS remain. This 2009 amendment to the 2001 forest policy towards increased LISS forms the main driver for the 'business-as-usual' (BAU) management trajectory for the Atlantic Wales case study.

Recent increases in outbreaks of biotic impacts have been linked to climate change (e.g. *Phytophthora ramorum* infection in larch http://www.forestry.gov.uk/forestry/INFD-85TDX6) possibly resulting from milder, wetter winters and warmer drier summers (Jenkins, Perry & Prior, 2007). Climate change impacts and adaptation information for Wales (Ray, 2008) suggests that forests managed using silviculture that perpetuates single species, single-age stands is at greater risk of abiotic and biotic damage from future climate change. So FCW has recently published policy guidance (Carrick, 2010) to support a change to more diverse forests and woodlands in Wales. This new 2010 policy guidance provides the policy driver for the 'forward looking adaptation' (FLA) manager for the Atlantic Wales case study.

The two forest management trajectories BAU and FLA can be simulated for the case study site using a suite of models and decision support tools, suitably modified to simulate the development of different forest design plans, and the resulting impacts on productivity and other forest ecosystem indicators. This plan focuses firstly on the wood-based production from successive forest design plans on different management trajectories into the projected future climate. This takes into account changes in site-yield potential, changes in wind risk through interactions between rotation length and silviculture. The models and decision support tools developed to support forest management in Britain over recent years have been adapted for use in Motive, and include:

Ecological Site Classification (ESC) – site species suitability and site yield potential (Pyatt, Ray & Fletcher, 2001; Ray, 2001)

ForestGALES – estimating current and future risk of wind damage to stands under management (Dunham et al., 2000; Quine, 2000)

Forest Yield – tools for accessing forest growth and yield information (Edwards & Christie, 1981; Matthews, 2008)

ASORT - Production assortment model (Rollinson & Gay, 1983)

BSORT – Stand diameter distribution model – tree and stand biomass (Matthews & Duckworth, 2005)

CARBINE (http://www.forestry.gov.uk/fr/INFD-633DXB) – Carbon allocation model (Matthews & Broadmeadow, 2009; Matthews & Heaton, 2001)

3.3.1 New features of the model components

Site yield potential

The 2 climate change critical climatic input factors required for ESC (accumulated temperature- AT, and moisture deficit – MD) have been evaluated as an empirical site-yield model for 3 species (Sitka spruce, Douglas fir and Scots pine) in a model called CDYsim (Climatic Dynamic Yield Simulator) . New model coefficients for the two climatic factors were calculated from a set of permanent sample plots in Britain using regression techniques. Results from this work show that reasonable RMSE values were obtained in models that do not use soil quality.

ESC has been extended to provide a site suitability assessment for 63 tree species. This knowledge-based exercise involved a review to assess the climate space of 35 additional species that may be useful on a range of site types in the future climate in Britain. Many of the additional species have been suggested for production forestry as alternatives to spruce (Carrick, 2010), to diversify the PFE.

The stand process-based model 3PGN has been parameterised for Sitka spruce (in prep) using Bayesian methods that incorporate the same Monte Carlo - Markov chain techniques used in the parameterisation of Scots pine (Xenakis, Ray & Mencuccini, 2008). Additionally, the parameterisation of 3PG by N C Coops for Douglas fir, provides another method to compare stand volume increments in future climates with the combined ESC or CDYsim and the ForestYield, ASORT, BSORT and CARBINE models.

Forest yield and product assortment

The models Forest Yield, ASORT, BSORT and CARBINE are being used as modules of the MOTIVE8 Wales simulation. All models work at a stand scale and provide the stand growth and wood production indicators from the case study forest through the century from the BAU and FLA management trajectories. CARBINE provides the models to measure the diameter distribution and volume from thinning a stand through a process of transformation to CCF. The methods provide a neat solution for calculating thinning volumes with changes in potential yield through climate change. The approach has been used to assess production and carbon sequestration (Matthews & Broadmeadow, 2009) in the future. However in MOTIVE8 Wales we have designed a simulation method to adjust the yield potential that would occur through increasing growing season temperature (AT).

ForestGALES

The wind risk model has been adapted to calculate the probability of wind damage occurring in stands following intervention. A recent analysis of future wind speed from Hadley RCMs, by the UK Met Office, showed no significant changes in the mean wind climate across Britain. However, there remains a great deal of uncertainty about changes in the extreme wind speed distribution over short time periods. So although the simulation will not have access to future wind projections (we will use the baseline wind climate for ForestGALES), we are looking at the sensitivity of stand damage to changes in the Weibull k and a parameters. This will provide an understanding of the uncertainty of the probability of wind damage in ForestGALES.

3.3.2 Incorporation of adaptive management in two FM simulation storylines

Forest database and forest design planning drivers

The sub-compartment database provides the spatial resolution for the modelling work. We must assume that all indicators measured at a stand spatial scale will be assessed at a sub-compartment scale. This is despite the fact that some of the spatial analyses require raster inputs (e.g. soil and climatic indices) and provide raster outputs (e.g. ESC species suitability, CDYsim yield or growth measures).

Forest design planning is described by coupe plans. Coupes are units in which a forest management activity is described, and in reality the coupe unit does not automatically have the same shared boundaries with sub-compartments. Typically in upland conifer plantation forestry (e.g. Clocaenog) the management coupes are larger than sub-compartments and may contain several sub-compartments. Coupe plans take advantage of the opportunity to amalgamate contiguous sub-compartments to deliver economies of scale, as well as deliver new forest landscape elements to improve forest structure and landscape aesthetics. Coupe plans provide the details of forest intervention, after which elements of the sub-compartment database are adjusted to take account of the change. In reality, the sub-compartment database boundaries would normally need to be modified to maintain the new structure of the forest. In our modelling plan we will continue to work with the same sub-compartment boundaries throughout the model simulation exercise.

A particular constraint to planning and the process of adaptive management is the logistical capacity of intervention. Planning of coupes to combine 1-2 felling sites per year delivering a maximum 15000 m3 of timber - by linking contiguous sub-compartments of similar size (identified as a function of age and yield potential). The harvesting capacity for the forest is set by the optimised forest management on the PFE. Since each FC District guarantees to deliver a volume of timber to the UK wood processing sector each year. The figure of 15000 m^3 per year from fellings and 15000 m^3 for thinnings in Clocaenog will be used for both management trajectory approaches. These assumptions require that felling coupes are planned each year in areas where endemic windthrow is beginning to occur (ForestGALES Index 6), and that coupe boundaries are chosen that have relatively windfirm green edges or are on sheltered sites. In addition, for both management trajectories there is a need to test and reduce the proportion of conifer over 300 m on acid sensitive lithologies in catchments which exceed 30% forest cover. This initiative is to reduce the acidity of stream water from forests in Wales.

The Atlantic Wales case study will test 2 management approaches to climate change on the public forest estate (PFE) in Clocaenog forest, Wales.

a) 'Business as usual (BAU)' assumes no anticipation of the effects of climate change or any subsequent need to adapt. Adaptation will only apply in a reactive sense (e.g. species becomes unsuitable, stand blows down). The model follows an approach of replacing like with like after the time of maximum mean annual increment. The most productive species are generally chosen. In addition, the areas currently flagged for LISS are transformed if the site is deemed suitable.

   A particular issue to consider for the BAU management trajectory:

   – Selecting the most productive species irrespective of site conditions, ie a presumption to plant either Sitka spruce, Norway spruce, Douglas fir, or one of the other main species used in Clocaenog. The rules to be applied will seek to maintain a species and FMA combination as shown in Figure 9.

b) The FLA approach is now recommended in policy guidance for management of the PFE in Wales. This simulation therefore tests the effectiveness of changing the forest structure for adaptation on a range of forest ecosystem goods and services. The storyline for this approach is that productive species are favoured but there is a new focus on species diversification according to the policy guidance note for Wales (Carrick, 2010). LISS, including continuous cover forestry (CCF) are favoured to develop multiple species, stand structures and age classes within and between stands. However there will be some forest land on the estate that is managed for single species, single aged stands. Here the approach would be to assess the previous forestry species and management system and adapt as climatic and edaphic constraints allow, guided by knowledge and anticipation of climate change predictions.

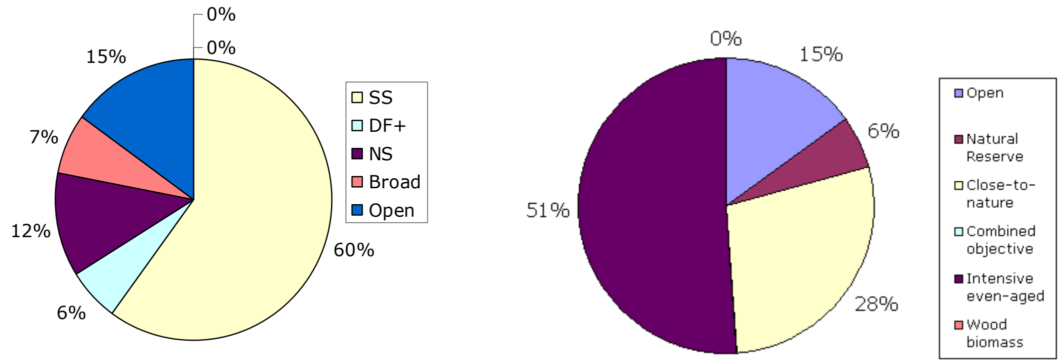


Figure 9. Aspiration for the species and FMA mix in the conservative business as usual management trajectory for Clocaenog forest (Note DF+ is other conifers). Specific species include SS for both LISS (FMA2/3 – close to nature/combined objective) and (FMA 4 – intensive even-aged), NS for red squirrel habitat, open space for black grouse, and broadleaved areas for riparian zones.

Particular issues to consider for the FLA management trajectory include:

- Amending the forest structure through targeting vulnerable stands to reduce the risk of loss (vulnerability could be from drought, winter waterlogging, pests and pathogens etc)
- Take every opportunity to use a greater range of species according to climate zone and soil type
- Take every opportunity to make use of LISS in forest management, and transform stands to CCF

It has been estimated that this approach could make significant changes to the species and FMA mix in Clocaenog forest, and this might approach or go beyond the distribution shown in Figure 10 by the end of the century.

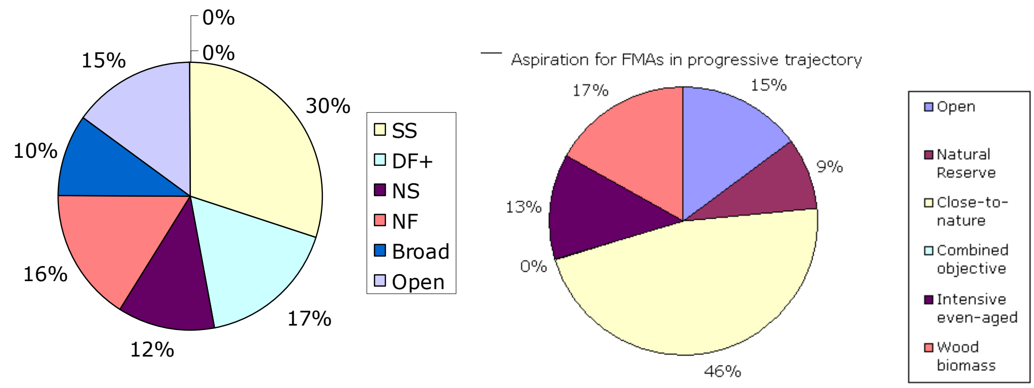


Figure 10. Aspiration for the species and FMA mix in the forward looking adaptation trajectory for Clocaenog forest (Note DF+ is other conifers). Specific species include SS for both LISS and fell-restock, NS for red squirrel habitat, open space for black grouse, and broadleaved areas for riparian zones. This approach seeks to reduce the reliance on SS, increase other conifer and broadleaved species, and introduce more woodfuel (FMA1) and increase FMA 2 (close-to-nature) from FMA3/4 (combined objective/intensive even-aged).

3.3.3 Tests and results under climate change

Work on the climate change extension of ESC has required reviewing the description of tree species climatic and edaphic envelopes from the literature and classifying this information in the dimensions and units of the site classification. Over 60 species have been reviewed and checked by internal peer review, and Figure 11 illustrates the approach for *Pinus sylvestris*. From the classification a set of response curves have been calculated to represent the changing suitability with the climate variable. Future climate projections from a Hadley Centre RCM were used to create downscaled digital grids of accumulated temperature and moisture deficit (as used in ESC) for future decades, taking account of latitude, longitude and elevation. The suitability and potential yield of the species was calculated by the combined response curves from ESC on a GIS. An example for the whole of Wales is shown in Figure 11.

In addition to the country scale maps of suitability the ESC model produces indicative suitability and site yield potential for smaller areas such as Forest Districts (Figure 12).

The empirical model CDYsim also predicts the yield potential from accumulated temperature (AT) and moisture deficit (MD) of a site. The model has been parameterised and tested on yield observations of Sitka spruce, Douglas fir and Scots pine permanent sample plots.

The root mean square error values are reasonable and comparable to results (Figure 13) for Douglas fir (3.04 m3/ha/yr) reported by Dunbar *et al* (2002) and work on Sitka spruce (2.31 m3/ha/yr) reported by Bateman and Lovett (1998), both of which developed models with multiple variables.

CDYsim has also been implemented in a GIS format and used to calculate the yield potential of Douglas fir in Wales (Figure 14).

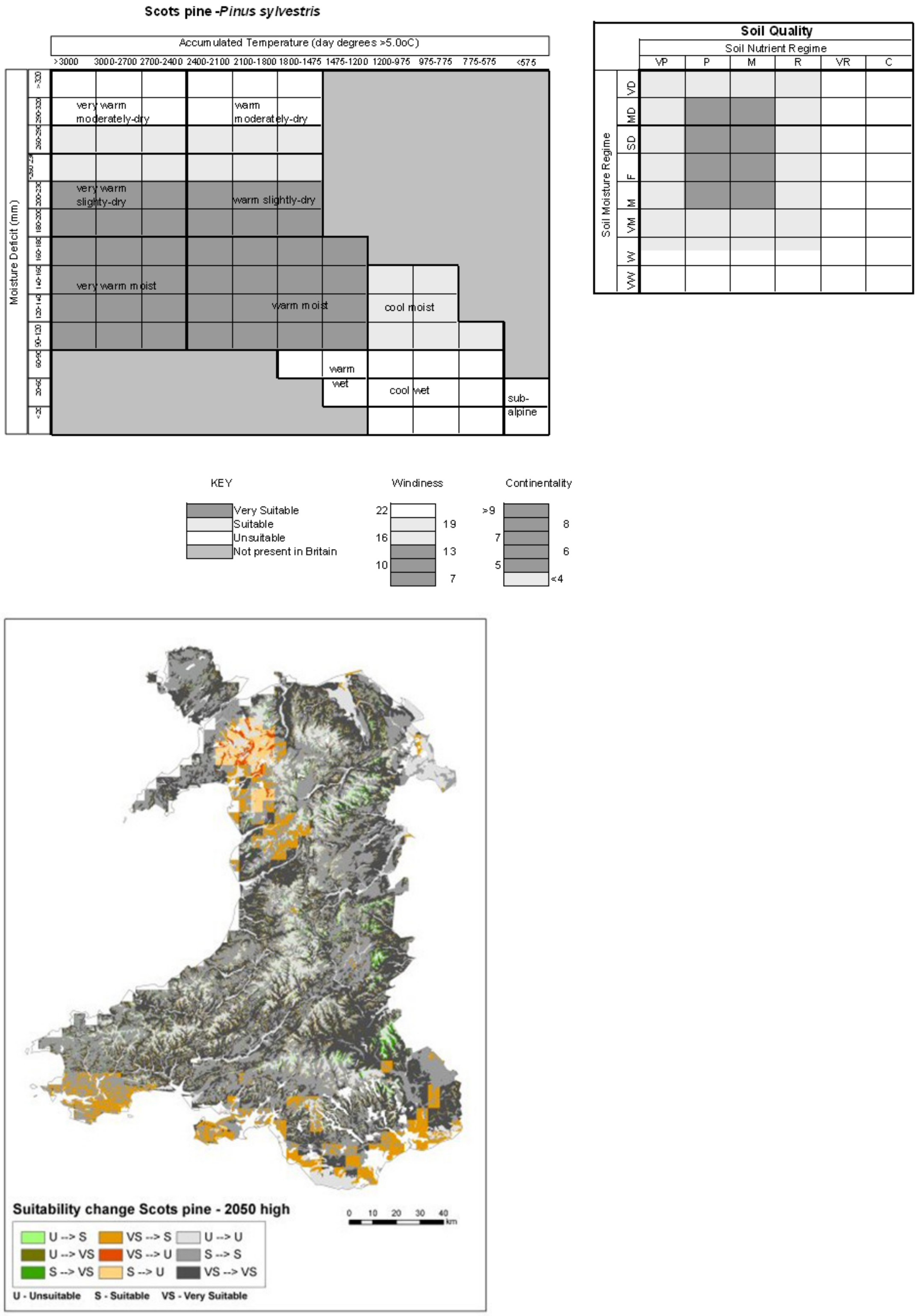


Figure 11. Above) Classification of Pinus sylvestris in the climatic and edaphic space used in Ecological Site Classification (ESC), Below) Change in the suitability class for Scots pine from the baseline climate 1961-1990 to 2031- 2060 for the A1FI climate projection produced by the Hadley RCM

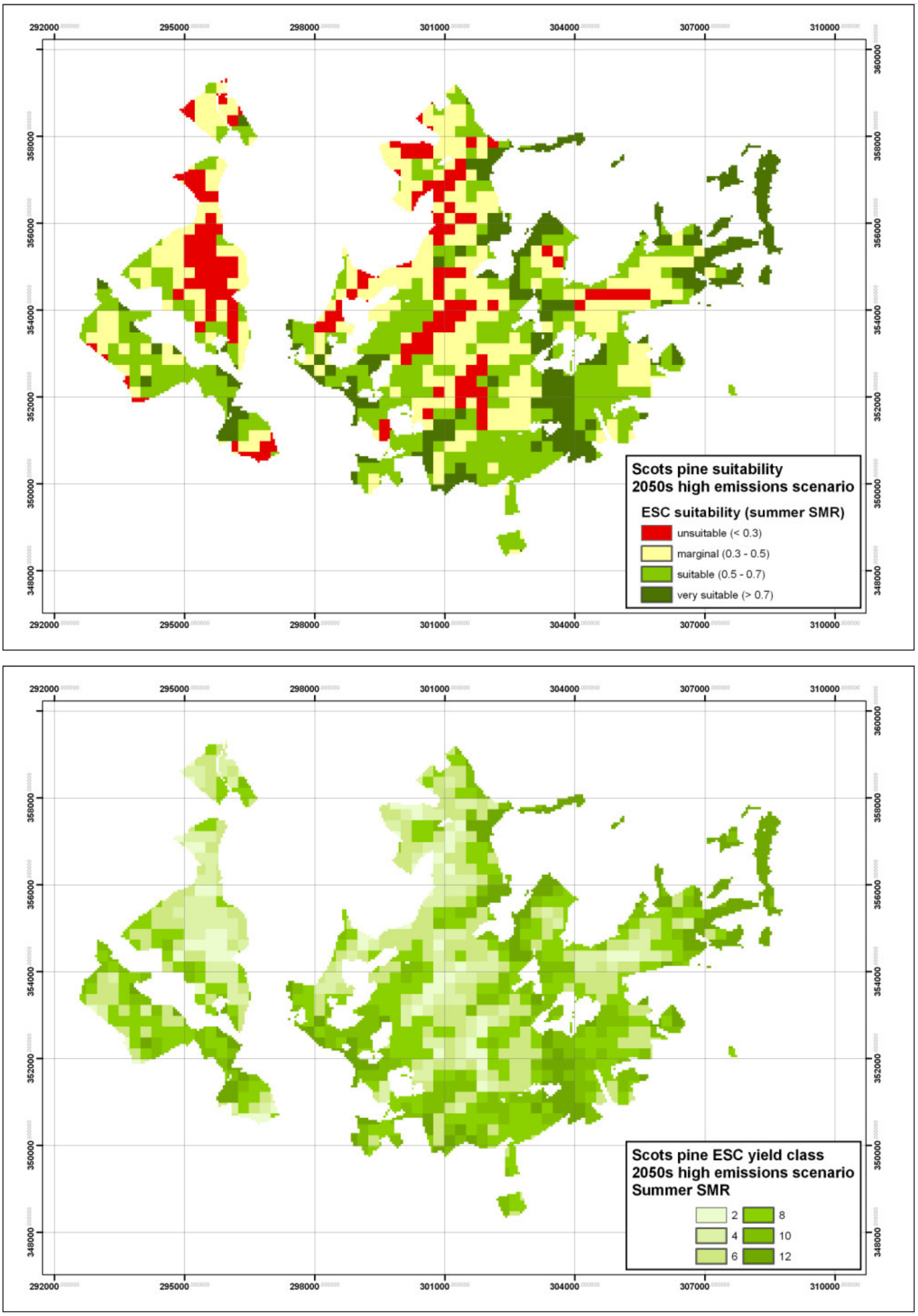


Figure 12. Calculation of Scots pine suitability (above) and yield potential (below) in Clocaenog Forest Wales using ESC for the projected climate A1FI from the Hadley RCM (2002).

Species	Model	Model	R^2	Ra^2	RMSE m3/ha/yr
DF	1	GYC=26.28540+0.00294*AT-0.03974*MD-0.06174*CONT-0.56152*DAMS	0.3077	0.3038	2.545
SP	1	GYC=-10.21964+0.00919*AT-0.03601*MD+0.66061*CONT+0.43123*DAMS	0.2460	0.2413	1.948
SS	1	GYC=9.16701+0.00499*AT+0.05080*MD-0.47710*CONT+0.04167*DAMS	0.3439	0.3425	2.681

GYC = General Yield Class (m3/ha/yr), AT=Accumulated Temperature (°C), MD=Moisture Deficit (mm), ELEV=Elevation (m), CONT=Continentality, DAMS=Windiness Score.

Figure 13. Results of the parameterisation of CDYsim for 3 species – Douglas fir, Scots pine, and Sitka spruce, showing RMSE values

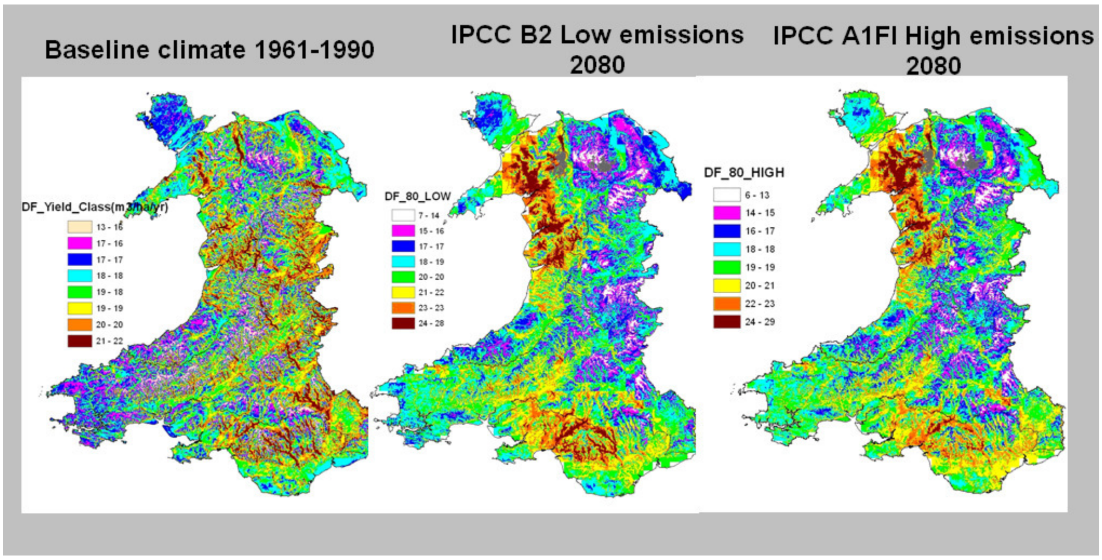


Figure 14. Preliminary results from CDYsim, showing the spatial distribution of Douglas fir in the baseline period and for 2 climate projections B2 and A1FI in 2080.

3.3.4 Simulating the forest design plan through the century

The challenge of the simulation is loosely coupling multiple model components in a framework that adequately emulates the rules, assumptions and methods of forest design planning, and at the same time produces outputs of forest ecosystem service indicators for work package 6.

To address this challenge we must work closely with forest planners in Wales, so that we properly understand the process that is to be simulated. Our work on this topic from 3 stimulating meetings with planners has resulted in a list of indicators that can be calculated, and a framework within which to operate the simulation of the 2 forest management trajectories. A high level view of the framework (Figure 15) shows the logical sequence of questions asked through the design plan period (10 years) (in green boxes).

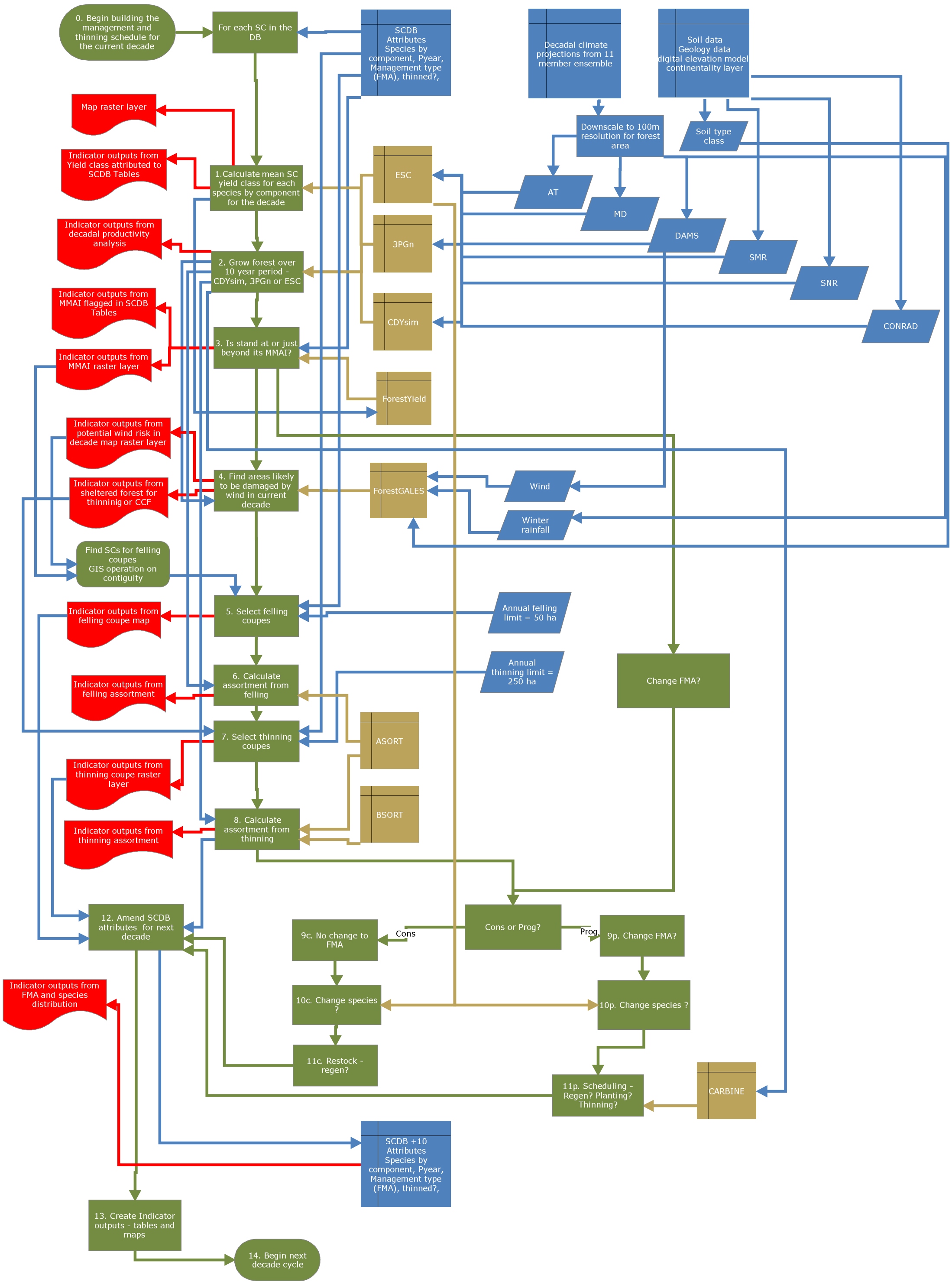


Figure 15. High level framework of the Motive8 simulation of forest design planning for the Atlantic Wales case study. Colour legend - Green = questions, gold = models, blue = data, red = outputs.

3.3.5 Next 6 months

In the next reporting period we will focus on testing the logic of the simulation process described in Figure 15. This will involve developing more detailed activity diagrams to describe the process, and testing the application of the models in the simulator. This activity will lead to the production of preliminary outputs agreed for work package 6.

3.4 Atlantic Veluwe

3.4.1 New features of the model

The initial tests with the original version of the selected model, Landclim (Schuhmacher et al. 2004), indicated several challenges to the application of the model to the case study. To account for the particular characteristics of the case study, several new model features were implemented:

- In Landclim a landscape is represented by a raster of smaller cells. Forest development is simulated at the scale of a cell and landscape processes such as disturbance or species dispersal are evaluated between cells. To simulate the case study at the full extent of ca. 8250 ha, the landscape was represented by a grid of 30 by 30 m cells. The majority of the landscape is extensively managed based on small group cuts or individual trees. In order to be able to represent this small-scale management approach, the original management module was improved in collaboration with the Forest Ecology group at ETH Zurich (C. Elkin, C. Temperli, H. Bugmann). The revised management module is capable to reproduce all current management practices in the case study in addition to a wide range of adaptive strategies.
- The soil nutrient status and the soil water holding capacity in the case study region are generally poor. Small local differences exist however that affect the growth conditions of trees. A nutrient growth factor was thus implemented in the model that allows simulating tree growth based on the nutrient, here nitrogen, requirement of a tree species in response to the soil nutrient status. This was implemented in a similar fashion as the growth limitation based on soil water holding capacity and the formulation was based on the Forclim model (Bugmann 1996). The new growth limitation based on tree species' nitrogen requirements improved the accuracy of the model in the simulation of the succession on the generally still developing sandy soils on the current heath lands.
- A significant effort was made to improve the accuracy of seed dispersal. This is an important aspect in the case study as particularly beech and oak are often restricted to historical lanes from which their dispersal is desired. This was achieved based on data from a research project on beech dispersal in the region, stakeholder feedback and expert opinion. Validation and stakeholder feedback indicate that beech performance is now satisfactory.
- One management concern is the effect of browsing by ungulates on tree regeneration and species composition. In the case study region several ungulate species occur that are not all accessing the same areas and that also differ in their effects on trees. In order to reproduce the diversity of effects, additional work was needed to parameterize species' drought-tolerances accurately. There is however no data on the long-term effects making a validation impossible. The verification of the results thus had to rely on studies from other regions. The results look very reasonable and realistic.
- Several tree species that occur in the case study were not part of the species that were originally parameterized for Landclim. The additional species were parameterized based on literature and expert opinion. A validation of the performance of the newly added species was possible to a limited extent only: species such as *Pseudotsuga menziesii* and *Quercus rubra* that were used for wood production in the past could partially be validated based on inventory data; new, invasive species that are of management concern such as *Prunus serotina* and *Robinia pseudoacacia* could

not be validated due to a lack of data. Current simulation results however indicate a realistic development of these species. However, stakeholders indicated in a recent meeting that the distribution of invasive species may be overestimated in the simulated conditions for 2100.

- During the verification of the Landclim model for application in the case study, the need was identified for revising parameters of species contained in the original model species set. This was necessary to adjust for adaptation of species to conditions in the case study region, e.g., increased resistance to drought by *Fagus sylvatica*. The revisions were made based on literature and validated using inventory data whenever possible. The stakeholder feedback to our results was positive.

3.4.2 Incorporation of adaptive management

The management approaches that are currently applied in the case study region range from no intervention to integrated management with a focus on wood production. Although the latter has a focus on wood production, the management is very extensive and aims to realise multiple purposes besides wood production such as recreation and biodiversity. Most current management approaches include efforts to diversify the current homogenous age structure and to increase the proportion of native deciduous tree species in favour of mainly non-native coniferous species. The current management approaches have proven quite successful in achieving their objectives under most climate change scenarios tested today, including the projections obtained from WP 2.

In order to investigate the effects from a gradient of management strategies, alternative strategies for most of the current management approaches were formulated. With the exception of the no-intervention approach, alternatives were developed concentrating more on the potentially beneficial effects of climate change on the one hand, and on the potentially adverse effects on the other hand:

- Beneficial effects may arise from the more moderate climate change scenarios that were tested, including the KNMI G scenario and the projections of the SMHI model provided by WP 2. The slight increase in temperature along with an increase in precipitation also during the growing season may be beneficial for tree growth and for the goal of increasing the proportion of deciduous species in favour of coniferous ones. The possible benefits are reflected in the alternative set of adaptive management strategies that will focus more on wood production.
- Potential adverse effects of climate change scenarios that project a stronger increase in temperature along with a decrease in precipitation during the growing season include generally poorer growth and increased drought stress also on desired tree species such as *Fagus sylvatica* and other native deciduous species. The alternative set of adaptive management strategies in this case increase the efforts of converting conifer stands to deciduous stands to reduce the risks of fire and storms. This may be achieved by increasing the distribution of drought-tolerant deciduous species such as *Castanea sativa* and *Tilia cordata* that currently occur localized only. The introduction of more drought-tolerant provenances of current desired species such as *Fagus sylvatica* is difficult to implement because of a lack of data that make any verification impossible.

The set of current management approaches, or the status quo and the two alternative management sets will be simulated in accordance with the suggestions of WP 5, i.e. starting with status quo management and 3 climate change scenarios in the year 2000 plus 2 decision points in the years 2025 and 2045 when the alternatives sets will be simulated in addition to the status quo. The type 3 ‘trend-adaptive manager’ will be simulated.

3.4.3 Tests and results under climate change

Status quo management has been simulated for the 3 climate change projections provided by WP 2 and, additionally, for 2 scenarios from the Dutch Meteorological Institute (KNMI), the moderate G and extreme W+ scenarios (KNMI 2006). The KNMI scenarios were used in the initial tests and they project a wider range of climate change effects than the projections provided by WP 2. The moderate KNMI G scenarios is quite similar to the projections of the SMHI model provided by WP 2. The MPI and Hadley Center model projections from WP 2 lie between the KNMI G and W+ scenarios (figures 16 and 17) in their impact on simulated forest development until 2100. The KNMI W+ scenario projects a stronger increase in temperature and a stronger reduction in precipitation, particularly during the growing season than the MPI and Hadley Center model projections from WP 2. To present the widest range of possible climate change effects, in the following, selected results are shown for simulations of the current forest conditions for status quo management in the case of no climate change and for the KNMI G and W+ scenarios.

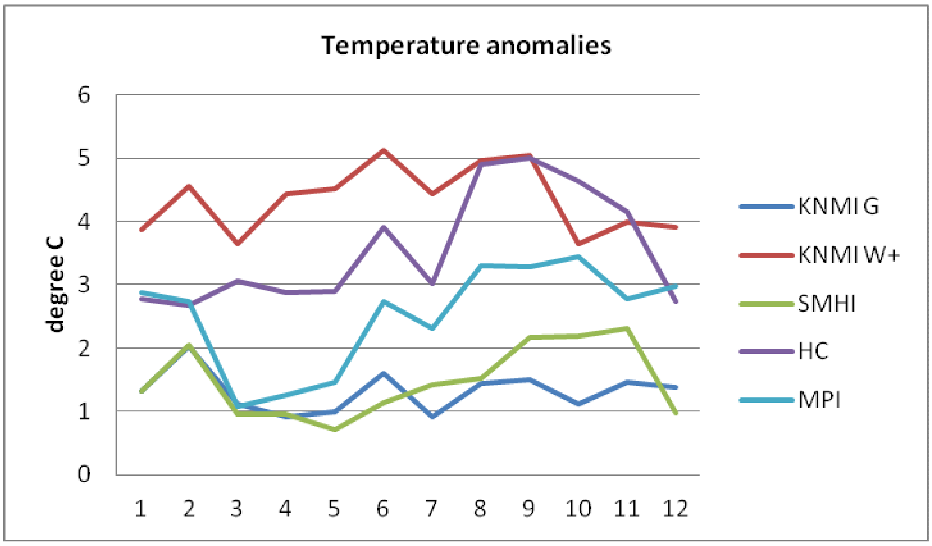


Figure 16. Monthly temperature anomalies [^{o}C] for five climate change scenarios based on monthly means from 1980 to 1999 and from 2080 to 2099.

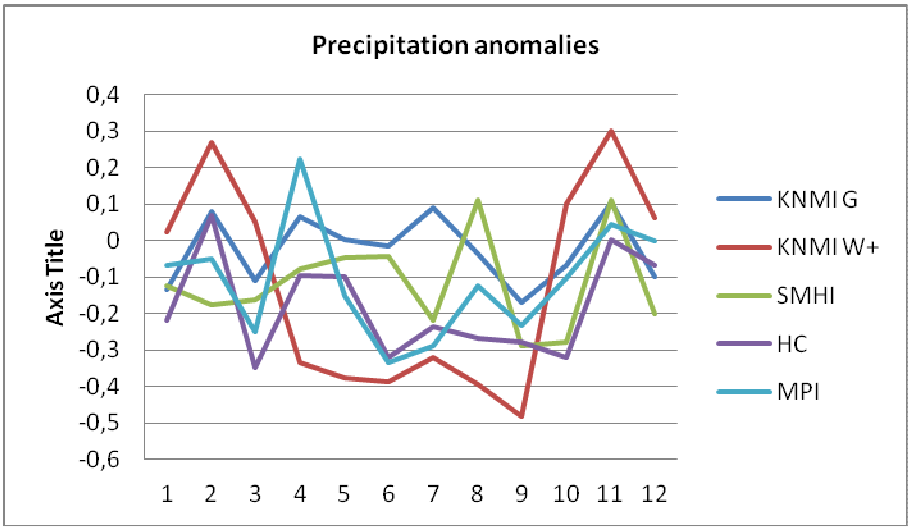


Figure 17. Monthly precipitation anomalies [%] for five climate change scenarios based on monthly means from 1980 to 1999 and from 2080 to 2099.

By 2100 only little change in the dominant species per 30 by 30 m plot can be expected between current climate and climate change based on the KNMI G scenario for status quo management (figures 18 and 19). This excludes the areas where current heath land is allowed to be colonised by trees in the center of the study area. A change in climate according to the more extreme KNMI W+ scenario may, for status quo management, result in an increased dominance of conifer species (figures 18 and 20). The two climate change scenarios result in different trajectories of succession on current heath land: under the KNMI G scenario deciduous species such as *Betula pendula* and some invasive broadleaves may be dominating by 2100 (center of the study area, figure 19). Under the KNMI W+ scenario *Pinus sylvestris* may be the dominant species, and some small area may remain heath land (center of the study area, figure 20).

The effects of climate change on biomass development from current conditions to 2100 is shown in figures 21 and 22 for 2 selected properties (out of 7). For the KNMI G scenario, biomass increases from current conditions to its maximum and remains more or less constant (figure 21). The species' fractions remain quite similar over time. Only in the case of the property 'Twickel – Hof the Dieren' there is a slight decrease in *Pinus sylvestris* in favour of *Larix*, *Pseudotsuga*, *Fagus* and *Quercus* (figure 21). Total biomass and species'fractions change quite dramatically in the case of the simulation results for the KNMI W+ scenario (figure 22). The initial increase in total biomass over the first 4 decades is followed by a decrease until 2100, particularly in the case of the property 'Twickel – Hof the Dieren'. On both properties the proportion of deciduous species, mainly *Fagus* and *Quercus*, declines in favour of particularly *Pinus* and *Pseudotsuga* (figure 22). This is an effect of increased drought conditions that favour drought-tolerant species that have low nutrient requirements.

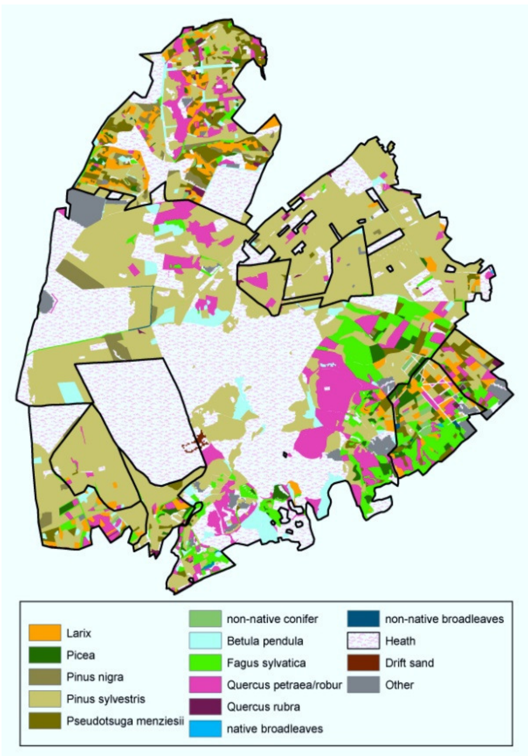


Figure 18. Dominant species per 30 by 30 m plot based on inventory data taken between 1997 and 2005. The case study extent and the different properties are outlined in black.

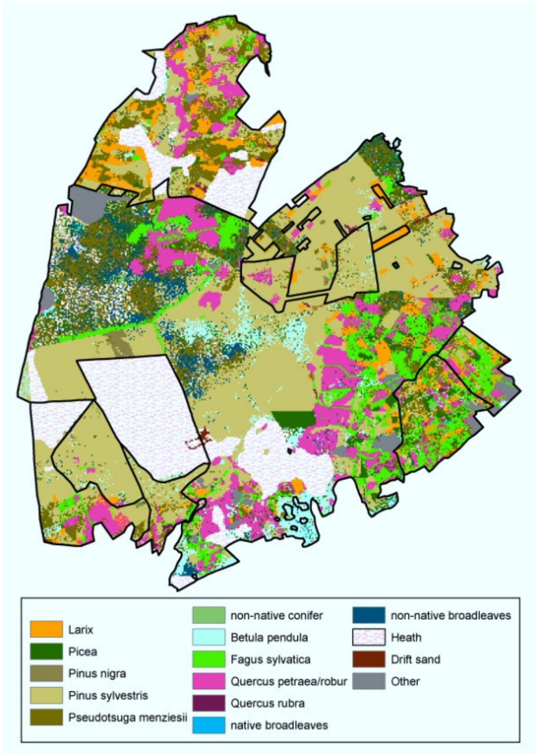


Figure 19. Dominant species per 30 by 30 m plot in 2100 based on simulated conditions for climate change based on the KNMI G scenario. The case study extent and the different properties are outlined in black.

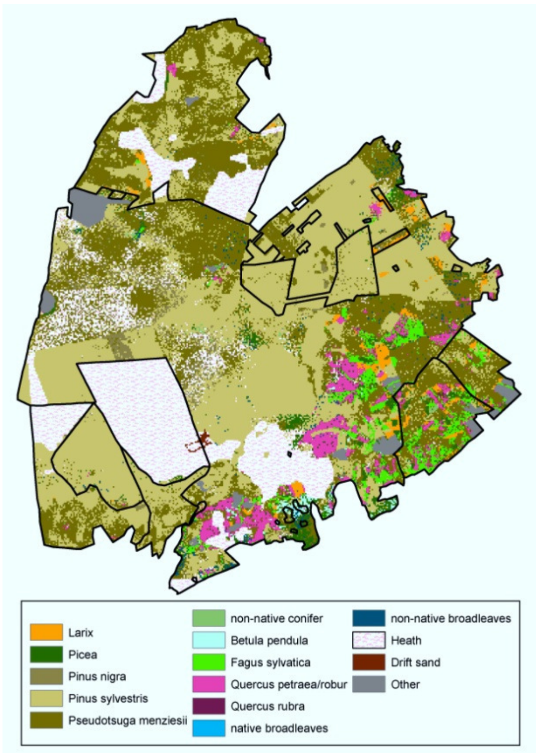


Figure 20. Dominant species per 30 by 30 m plot in 2100 based on simulated conditions for climate change based on the KNMI W+ scenario. The case study extent and the different properties are outlined in black.

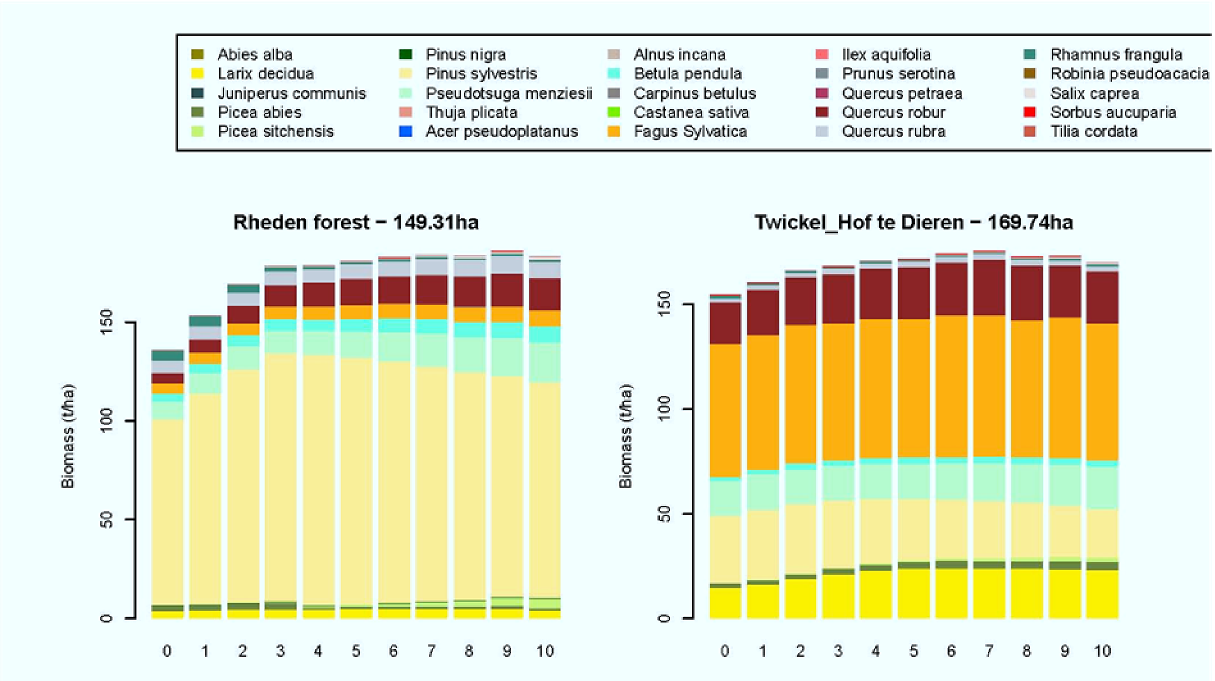


Figure 21. Temporal development of species biomass from current conditions to 2100 simulated for the KNMI G scenario and current management. Biomass values are aggregated over the area of an individual property. The results for 2 properties (out of 7) are shown as example: Rheden forest (south-central), Twickel – Hof te Dieren (south-east).

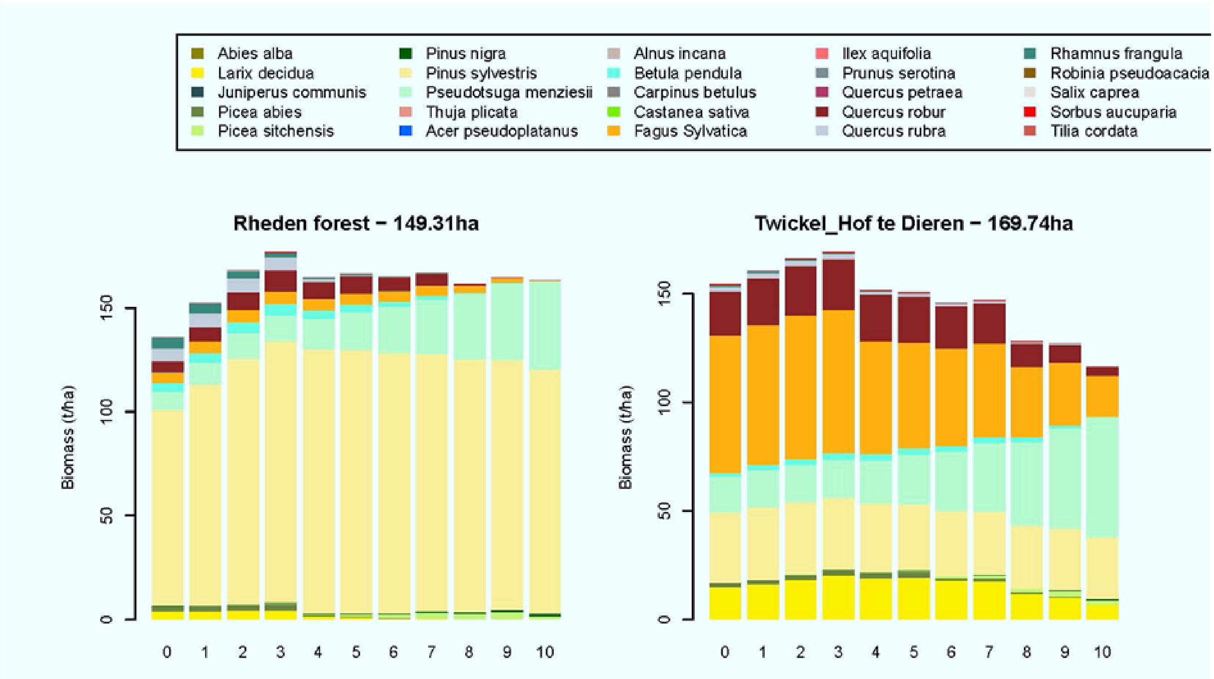


Figure 22. Temporal development of species biomass from current conditions to 2100 simulated for the KNMI W+ scenario and current management. Biomass values are aggregated over the area of an individual property. The results for 2 properties (out of 7) are shown as example: Rheden forest (south-central), Twickel – Hof te Dieren (south-east).

3.5 Central Black Forest (BWINPro)

In the Central Black Forest Model Region we have chosen to apply different models. In the following chapter 3.6 the developments according to the physiological process model LandClim are described. In contrast to that BWINPro is a classical single tree stand simulator. The model was developed at the NW-FVA and is freely available online, including handbooks with short descriptions of the mechanistic background of the model (http://www.nw-fva.de/). In a later step it is planned to compare the model outputs as well as incorporating climate effects from LandClim into BWINPro. Up to now it is of high interest, especially for the stakeholders, to use such single tree simulators for refined management prescriptions for the local environment under changing climate and risk of wind damages. Wind damages are one of the major threats to these forest. Therefore we have developed a framework, which enables to use the principle growth processes from BWINPRO and linked these with the empirical storm model, based on the observations of the 1999 gale "Lothar" (Schmidt et al. 2010). The problem with this type of approach is that the empirical storm model has included the regional effects of the storm based on Topex-values. This is a nonparametric regression approach with a sizeable amount of parameters and functions, technically only tractable under the statistical programming language R (R Development Core Team, 2010).

3.5.1 New features of the model

Both the empirical storm model and BWINPro are based on single trees. Therefore it is necessary to estimate single trees diameter distributions for all given stands in the model region. Precise stand information is not available, but the management plans in this region are providing information on age classes, standing volume, site-index, multi-layers, trees species and total volume on a geographically explicit polygon.

Based on this information a set of prediction models of single trees diameter distributions was developed. In the older versions of BWINPro a stand can only be generated based on quadratic mean diameter d_q and d_{max} (for each species in the stand). Both variables are not available in the geographically explicit management plans. Therefore in the new approach the diameter distributions were generated with a regression approach. As possible explanatory variables only the information from the management plans were used. As databases all forest planning-inventories on public ground were used to set up the regression analysis. This is a huge amount of information and we can view the process as way of regionalization; as one possibility to enhance the information needs for a given stand in a region, for which only the classical management plan information is available. Further this analysis allows for a more precise description of a typical stand in a given classification, e.g. "dominated spruce forest" in a "young development phase" and "mean site class".

The set of regression models is portioned on forest type and started with an estimation of mean stems/ha. In a second step the shape and scale parameters of the Weibull-distribution were estimated. In a third step the shares of trees species over diameter the diameter distributions were modelled.

This enables to produce reasonable single tree distributions for the ~1.000 stands in the model region (figure 23). Basically the same information was used in LandClim and enables comparative analyses in respect to the different model approaches.

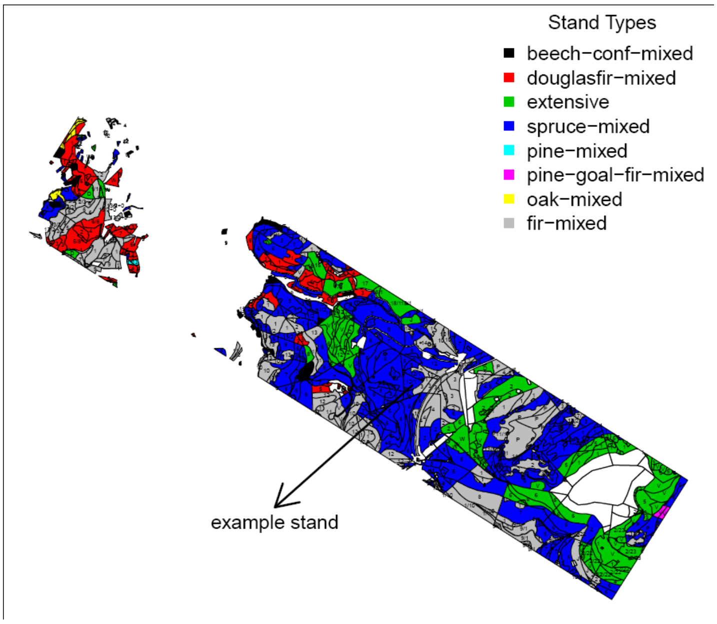


Figure 23. Overview of the current stand types in the model region.

With the above mentioned approach it is now possible to produce single tree information within these stands. As an example one stand is chosen and the management-plan contains information such as "spruce-mixed-type", dominant age class 120 years over 10-20 years regeneration, area shares of 75% spruce, 15% beech, 10% fir, with mean increments of 10, 6 and 10 m^3/ha/a and a total volume of 837 m^3/ha. The described procedure is delivering distributions of the following form, shown in figure 24.

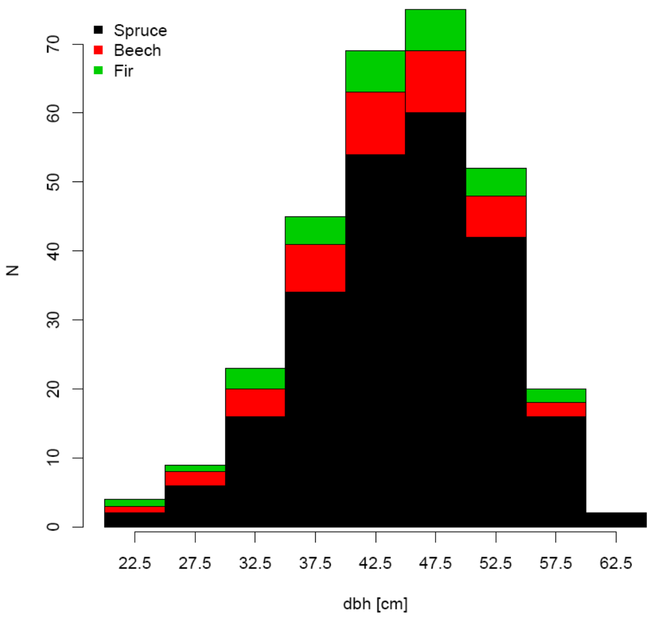


Figure 24. Estimated diameter distributions of the example stand.

Diameter distributions together with an adequate height-dbh model deliver the necessary input into the empirical storm model, enabling to predict storm throw probabilities for the single trees in a stand (at a given location in that region). Combined with the basic functionality of the growth simulator, the progress of vulnerability to storm events and its dependency from management activities can be explored.

For the example stand the storm throw probabilities are given in figure 25. Obviously these probabilities depend on dbh-height relations and are therefore sensitive to management alternatives.

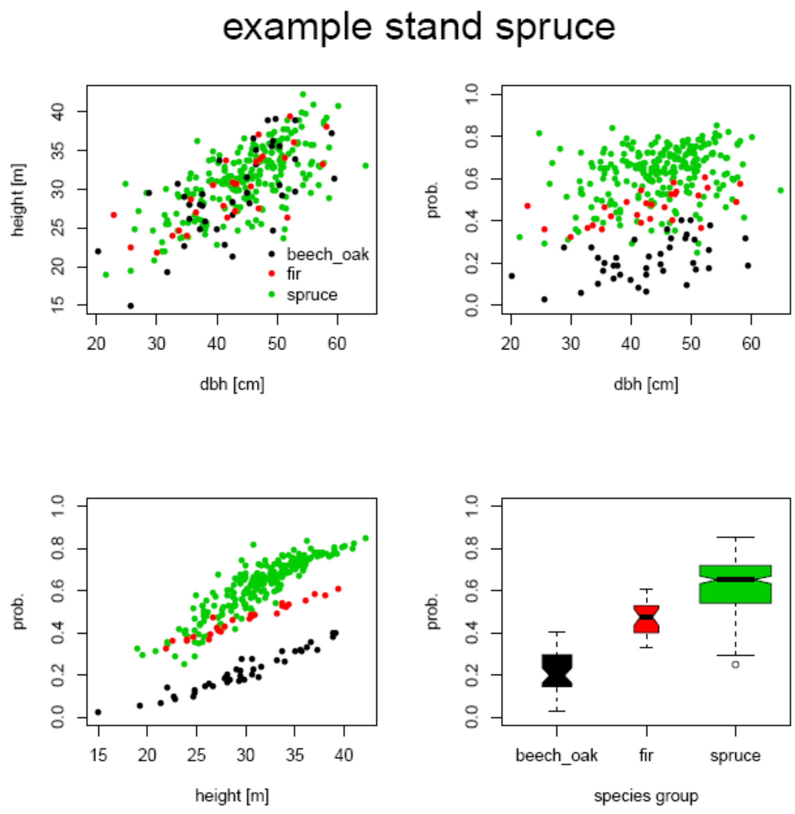


Figure 25. Storm throw probabilities of an example stand, for a given location in the model region.

3.5.2 Incorporation of adaptive management

Both the stand simulator and the empirical storm model rely on single tree information. Therefore it is straightforward to analyse different management alternatives, resulting in a change of storm-throw probabilities. Further each storm event can be seen as a type of unintended management, resulting in some interactions between effects from the storm and management. Thus the effects of management alternatives are stand-state dependent (one Management alternative can be recommend to an older stand, but is not relevant for a younger, on the same location and the same stand type).

We started with historic management as a type of Business as Usual. Further we used the same alternatives as described in the following Chapter on LandClim. They contain species changes, reduction of rotation length and different thinnings. This now allows us to assess quantitatively the efficiency of management alternatives influencing wind throw probabilities.

3.5.3 Tests and results under climate change

This modelling approach requires a frequency of heavy storm events. With the above shown flexibility in programming we are now able to investigate different frequencies. These tests are ongoing. In the future it is planned to incorporate the changes in growth, based on LandClim model into the single-tree simulator.

3.6 Central Black Forest (Landclim)

3.6.1 New features of the model

We have further developed an existing LandClim forest management module (Schumacher and Bugmann 2006) to broaden the range and increase the precision of forest management actions. In addition to other small adjustments we added more functionality in the definition of thinning and harvesting prescriptions. The amount of wood extracted within a thinning operation can now be defined by specifying an absolute target density, in addition to the already existing density percentage. Another major improvement was the implementation of a new planting routine. A description of the present functionality of this revised LandClim module is given below.

To implement forest management in LandClim a landscape is subdivided in multiple management areas for which the user defines management regimes with specific management objectives. In the Black forest case study we defined three separate management areas that differ in terms of site-characteristics and historic management. Each management area is further subdivided into stands, whereby stand boundaries were derived from the local forest management plan (Forstliche Versuchs- und Forschungsanstalt Baden-Württemberg (FVA), Abteilung Biometrie und Informatik). There are *ca*. 1000 stands ranging from <0.1 ha to an average of 1.5 ha and to a maximum of 41 ha in the whole study area.

A management regime is a combination of individual management prescriptions such as planting, thinning and harvesting. Both the timing and the share of a management area to be treated must be specified. The prescription is then executed stand by stand until the pre-set management area share is reached. Thereby, the user defines whether the stands with highest biomass, stands with highest tree density or random stands should be managed first. The execution of a management prescription in a stand can additionally be constrained by setting the minimum average tree size of the 100 dominant trees in a stand as an entry threshold. A thinning or harvesting prescription includes a tree species and size class specific instruction on the percentage of trees to be felled or on the density left on the stand.

Within a planting prescription the user defines the initial density and biomass of each species to be planted. The spatial and temporal allocation of the plantings can be linked to a harvesting prescription, i.e. re-plant stand after a clear cut, or planting can be defined independently. Therewith, we can now simulate a wide range of management systems including even-aged plantation forestry and un-even aged mixed species systems.

In order to represent projected bark beetle (*Ips typgraphus* L.) impacts on central European Norway spruce plantations under climate change, we extended LandClim with a bark beetle module. With this new module we aim to identify first the processes that drive bark beetle damages under climate change and altered disturbance regimes and second how these processes can be influenced by forest management in order mitigate bark beetle damages. We therefore developed an assessment of forest susceptibility to bark beetles with a climate driven phenology model following an approach previously applied by e.g. Shore and Safranyik (1992) and Seidel et al. (2007).

We determine forest susceptibility to bark beetle attacks by taking in account the following four factors: drought stress, the dominant age and the basal area share of Norway spruce trees and the amount of wind-thrown Norway spruce wood. The relationships between these factors and cell level forest susceptibility were derived from expert knowledge (Netherer and Nopp-Mayr 2005). Bark beetle pressure or virulence is modelled by using a temperature and day length driven phenology model (Baier et al. 2007) to calculate the number of potential bark beetle generations per year. Additionally, we use an index based on the beetle killed biomass in the previous time step in order to account for temporal population dynamics. We use a dispersal kernel and stochasticity to determine spatial distribution of bark beetle attacks based on the local forest susceptibility and bark beetle pressure assessment. A first version of this bark beetle module is now fully implemented in the framework of LandClim and is ready to use. We can now explicitly account for barks beetles when we design and test climate change adaptive management alternatives.

3.6.2 Incorporation of adaptive management

Following the guidelines from WP5 ("Modelling and simulating decision making in MOTIVE") we implemented both the historic management regimes and the adaptive management scenarios using the management module described above. As a basis for the quantification of the individual silvicultural operations we used descriptions of currently applied management regimes in the study area (Duncker et al. 2007) and guidelines of the local forestry authority (MLR 1999) as well as the scientific community (Spiecker et al. 2004).

Historically forests at higher elevations (500-1000 m a.s.l.) have predominantly been managed as *Even-aged Norway spruce* forest, whereby timber production was maximized by clear cutting stands when dominant trees reached a target diameter of 45 cm. Following clear cut the stands were replanted with Norway spruce and subsequently thinned to increase growth and maintain a Norway spruce monoculture.

At elevations between 300 and 500 m a.sl. an *Uneven-aged mixed Norway spruce* management regime was applied. In order to combine timber production with the promotion of biodiversity a structurally rich Norway spruce dominated perpetual forest was anticipated. Naturally regenerating deciduous tree species and silver fir contributed 20 to 40% to the species mixture.

We included these historic management regimes as business as usual scenarios representing the "no-change management type". Where forests have historically been managed as *Even-aged Norway spruce* forests we applied the *Uneven-aged mixed Norway spruce* management regime as an adaptive management scenario representing a "reactive management type".

We based the selection of future management scenarios on local forest management guidelines (MLR 1999) and recommendations of the research community (Spiecker et al. 2004). Both MLR (1999) and Spiecker et al. (2004) recommend the conversion of non-site adapted even-aged spruce monocultures to uneven-aged forests. A change in species mixture is recommended depending on a) how much the promotion of deciduous species in order to augment biodiversity and disturbance resilience is favored at the expense of coniferous timber production and b) whether or not the species mixture is actively adapted to warmer and dryer climatic conditions (figure 26). To represent that range of possible conversion options three adaptive management alternatives were selected.

1. The conversion to *Natural vegetation,* and thus the promotion of biodiversity and disturbance resilience, is accomplished by thinning Norway spruce at all development stages and otherwise ceasing forest management. No WP5 management type could be allocated to this management scenario.

2. By converting to an *Uneven-aged mixed Douglas/silver fir* forest using thinning and target diameter harvest the species mixture is adapted to a warming climate where at the same time valuable coniferous timber is produced. This is a “trend-adaptive” management alternative.
3. A second “trend-adaptive” management alternative is the conversion to an *Uneven-aged mixed oak* forest by means of shelterwood harvest, oak under planting and subsequent promotion of drought adapted species by thinning. Therewith the species mixture adapted to dryer climatic conditions and biodiversity as well as disturbance resilience is promoted.

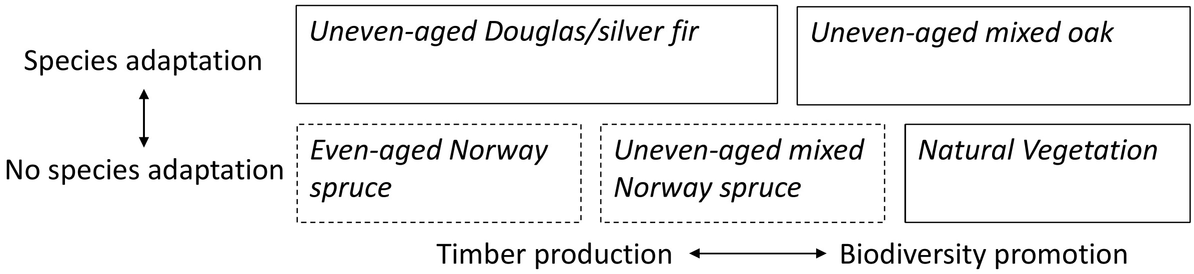


Figure 26. Selection of adaptive management regimes including the business as usual scenarios* Even-aged Norway spruce *and* Uneven-aged mixed Norway spruce *(dashed boxes). The selection represents a gradient from timber production to biodiversity promotion oriented management regimes (x-axis) and whether or not active adaptation of tree species to a warmer and dryer climate is taken in account (y-axis).

3.6.3 Tests and results under climate change

LandClim has been used to accurately simulate both current (Schumacher et al. 2006, Schumacher and Bugmann 2006) and historic (Colombaroli et al. 2010, Henne et al. 2011) forest dynamcis in the Swiss Alps and the Colorado Front range. The simulation of the potential natural vegetation (PNV) in the study area corresponds well to local PNV-maps and paleoecological records (Müller et al. 1992, Ludemann 2010).

We simulated the historic management regimes (see above) and qualitatively validated the resulting forest composition and structure with local inventory data (Forstliche Versuchs- und Forschungsanstalt Baden-Württemberg (FVA), Abteilung Biometrie und Informatik) on the stand as well as on the landscape scale. Although the simulated initialization data and the inventory data are in good agreement, we plan to initialize our scenario simulations directly with the inventory data. This requires the inventory data to be scaled to the LandClim inherent 25 by 25 m raster and further tests.

We simulated the management scenarios under the historic as well as under the three climate change scenarios provided by WP2; each scenario was replicated 15 times in order to account for LandClim inherent stochasticity. We found that forest states both in terms of species composition and stand structure simulated under the implemented management regimes match the management targets described in Duncker et al. (2007), MLR (1999) and Spiecker et al. (2004).

We tested the sensitivity of individual components of the bark beetle module to the range of climate change scenarios provided by WP2 in the Black forest case study area under *Even-aged Norway spruce* management. The tests revealed that the stand age and drought related susceptibility and the temperature driven bark beetle phenology were well represented. This now allows us to assess how efficiently management strategies such as a reduction in rotation length or the promotion of other tree species then Norway spruce mitigate bark beetle damages. We see potential for model improvement in the representation of the Norway spruce share-wind throw interaction and the consequential susceptibility. Further tests concerning the spatio-temporal dynamics of bark beetle infestation and damage might lead to a revision of the dispersal kernel and the model time step.

3.7 Central Alpine PICUS

3.7.1 New features of the model

Several new features have been implemented in PICUS. The features allowing the simulation and evaluation of adaptive management schemes will be presented in the following.

A major improvement of the current PICUS version 1.5 was to make the simulation of spatially explicit stands possible. Previous versions of PICUS had been limited to rectangular or squared simulation entities. Usually one hectare (100 x 100 m) was used as a simulation entity (e.g. Lexer and Seidl, 2009; Seidl et al., 2009), mainly because of hardware limitations. PICUS 1.5 uses the same 10 x 10 m horizontal patch resolution of previous versions, but is not bound to rectangular alignment of the patches any more. In practice stand polygons as available for example from forest inventories, as *.shp GIS-files, can be used. The shape file is converted into a raster file with 10 x 10 m grid cell size in a GIS environment. As value of the grid cells the stand ID is used. After converting the grid file in a PICUS readable format (e.g. *.txt) the forest initialization procedure can be started. In general no fundamental changes in the model structure had to be made.

The possibility to simulate spatially explicit forest stands also opens new possibilities with regard to management. Previous versions of PICUS have been already capable to deal with spatially explicit management on the rectangular simulation entity level. PICUS 1.5 is now able to handle spatially explicit management even beyond single simulation entities to account for interrelationships among neighbouring stands.

The approach is also used in management planning in the case study forest enterprise. There, management is mostly bound to skyline systems. Cable crane tracks crossing several stands and the shape of the slit cuts (gaps) are planned in a GIS environment as shape files. The shape file of management areas (i.e. the *.shp of the slit cuts) is converted into a grid file with a resolution of 2 x 2 m. The attributes of the grid cells are the years in which the management activities are applied. After exporting the grid file in a PICUS readable format (e.g. *.txt) the management needs to be defined in a PICUS management script. The management grid is read by PICUS.

Not only the spatially explicit simulation of stands and management has been improved, also the appraisal of forest goods and services has been enhanced. A major step in assessing forest ecosystem goods and services was the implementation of an assessment scheme for the protection against natural hazards in the PICUS environment. The assessment scheme developed by Frehner et al. (NaiS (Nachhaltigkeit im Schutzwald), 2005) covers the protection against (i) snow avalanche release, (ii) landslide, erosion and debris flow, (iii) rock fall, and (iv) flooding and torrential processes.

The indicators of the NaiS concept were taken and implemented in the PICUS ES assessment module. This module operates on a scale beyond single simulation entities based on the PICUS rockfall module (Rammer et al., 2010). For example slopes with several hundred hectares can be handled. The appraisal routine in the PICUS ES assessment module is based on single trees projected onto a digital elevation model (DEM). As each tree which is simulated by PICUS has coordinates, the trees of each simulation run can be transferred to the ES assessment module at any defined point in time during the simulation. As PICUS 1.5 is able to handle spatially explicit simulation entity shapes, not only the trees of a single entity, but also trees of several entities can be projected onto a DEM (figure 27).

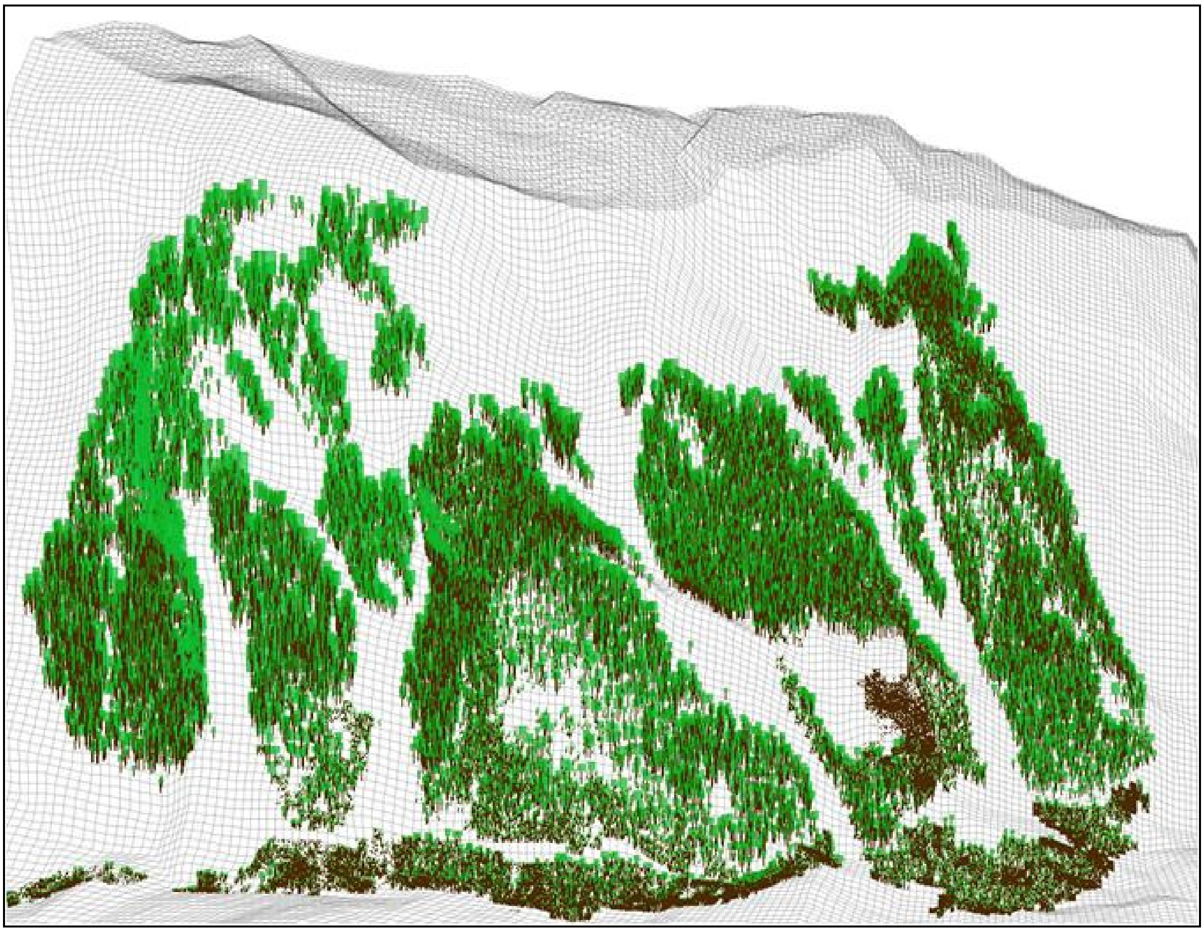


Figure 27. Trees from several simulation entities projected onto a DEM in the PICUS risk assessor module.

The indicators of NaiS are mostly referring to crown cover, gap size/length, and stem numbers above a certain diameter threshold. For each indicator thresholds are defined in NaiS. The possible results for each indicator are (i) ideal thresholds met, (ii) minimal thresholds met, and (iii) thresholds not met (Frehner et al., 2005). The crown cover and stem number indicators are calculated using a moving window of 50 x 50 m (5 x 5 pixels with a pixel size of 10 x 10 m). The calculated value is assigned to the centre pixel (figure 28).

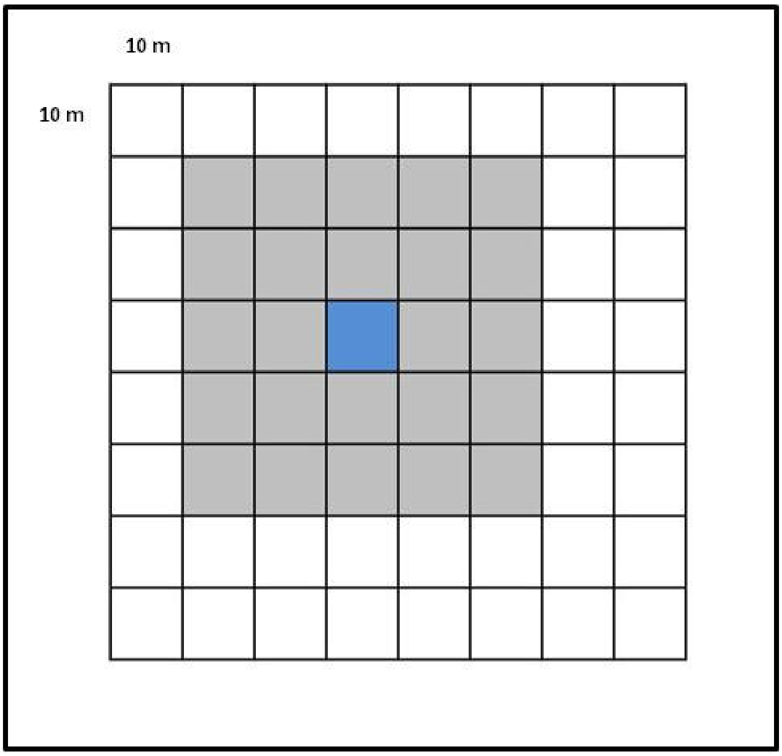


Figure 18. Schematic view of the calculation of stem number and crown cover indicators. The 50 x 50 m moving window, for which the indicators are calculated, is drawn in grey. The centre pixel, to which the indicator values are assigned, is drawn in blue.

For the indicators referring to gap size or length, moving windows with a certain width and length (dimensions according to maximum gap sizes as defined by NaiS) are moved all over the assessment area in a 2 m raster. The slope direction is accounted for where needed (protection against avalanche release and protection against rock fall). A tree/crown map with a resolution of 2 m is the basis for the appraisal of the gap indicators. For every position of the moving window, where no cells with tree/crown cover are underneath, the underlying 2 x 2 m pixels are considered to be part of a gap. The results of this assessment step are aggregated as a 10 x 10 m grid (figure 29).

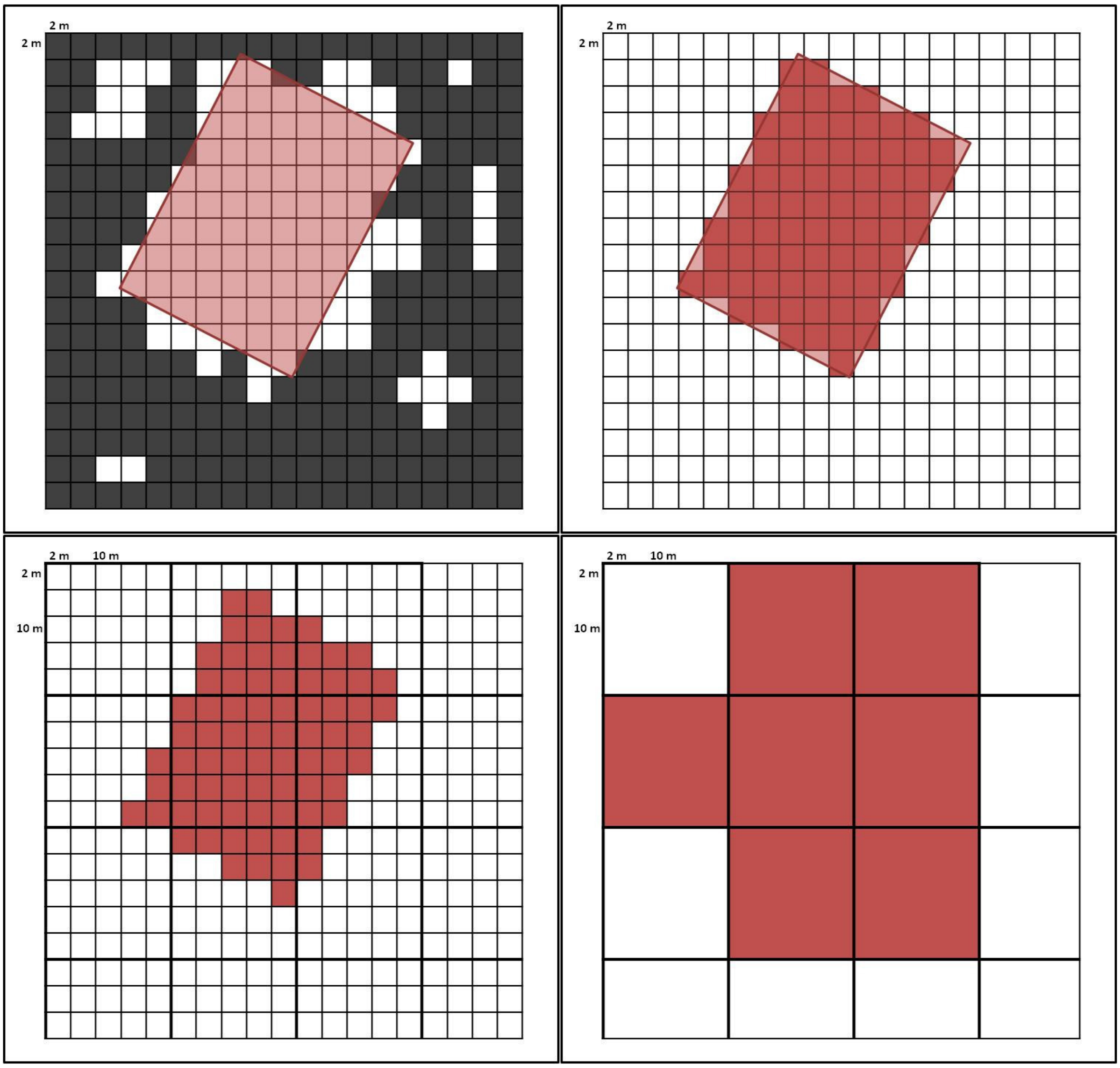


Figure 29. Schematic view of the gap detection procedure. Upper left: The black cells indicate crown cover, white cells no crown cover, and the red rectangle is the moving window. If the moving window fits into a zone with no crown cover, a gap with the extent of the moving window is detected (the centre points of the 2 x 2 m cells are decisive). Upper right: all cells underneath the moving window are considered as gap pixels (red). Lower left: for the aggregation a 10 x 10 m grid is used. Every 10 x 10 m grid cell which contains at least one 2 x 2 m gap pixel (red) is considered to be part of a gap. Lower right: Result of the aggregation process, the 10 x 10 m grid with gap cells in red.

The results for each protective function are made available as a 10 x 10 m grid. The results for the different protective functions are based on one or more indicators. The indicators are aggregated by AND, and the result is given in the same classes the indicators are judged (ideal thresholds met, minimal thresholds met, and thresholds not met; cf. Frehner et al., 2005).

The results can be displayed in the ES assessment module in a three dimensional view, or exported as grid file to a GIS. For easy communication the classes can be displayed in colours similar to traffic lights (green, yellow, red; figure 30).

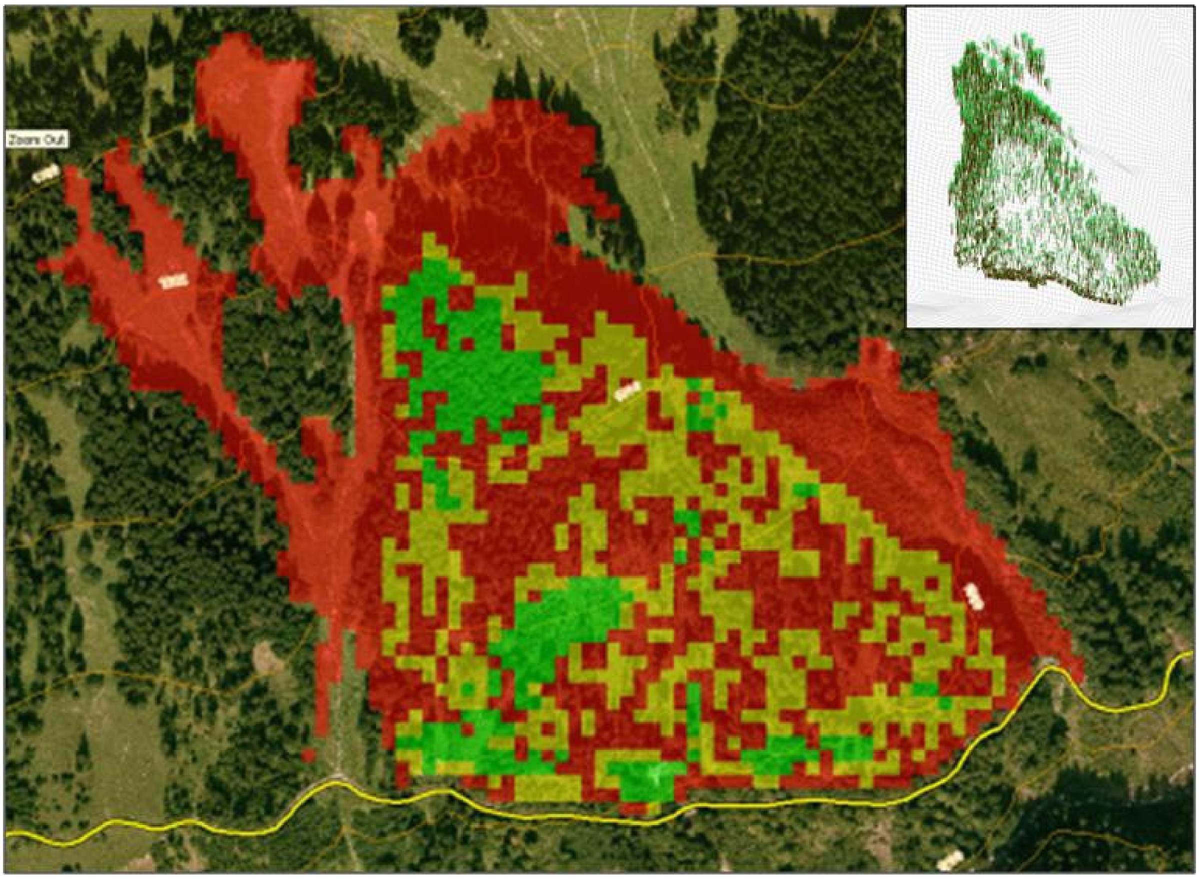


Figure 30. Assessment results for the initial state of the forest (insert) with regard to protection against rock fall in the transit zone (rock size: 0.2 – 5 m³) in a GIS environment. Green=ideal thresholds met, yellow=minimal thresholds met, and red=thresholds not met.

With this module, forest development, disturbance and climate change impacts, as well as management activities and their influence on the protection against natural hazards can be assessed. For example figure 31 shows the influence of a BAU management activity on the protection against rock fall in the transit zone (rock size: 0.2 – 5 m³).

3.7.1 Incorporation of adaptive management

The simulation of adaptive management (AM) is using the same approach as for the BAU management. The shape and size of canopy openings (i.e. slit cuts) can be adapted easily in the GIS environment. In the management script threshold diameters or species to be managed can be adjusted. The artificial introduction of tree species as an adaptive management strategy is using the same approach. The areas, where a certain species should be planted, are planned as shape file, and converted into a PICUS readable grid file with the year of planning as attribute. In the management script the management grids (e.g. slit cut and planting) and actions are defined. For each management grid the actions are determined in the script.

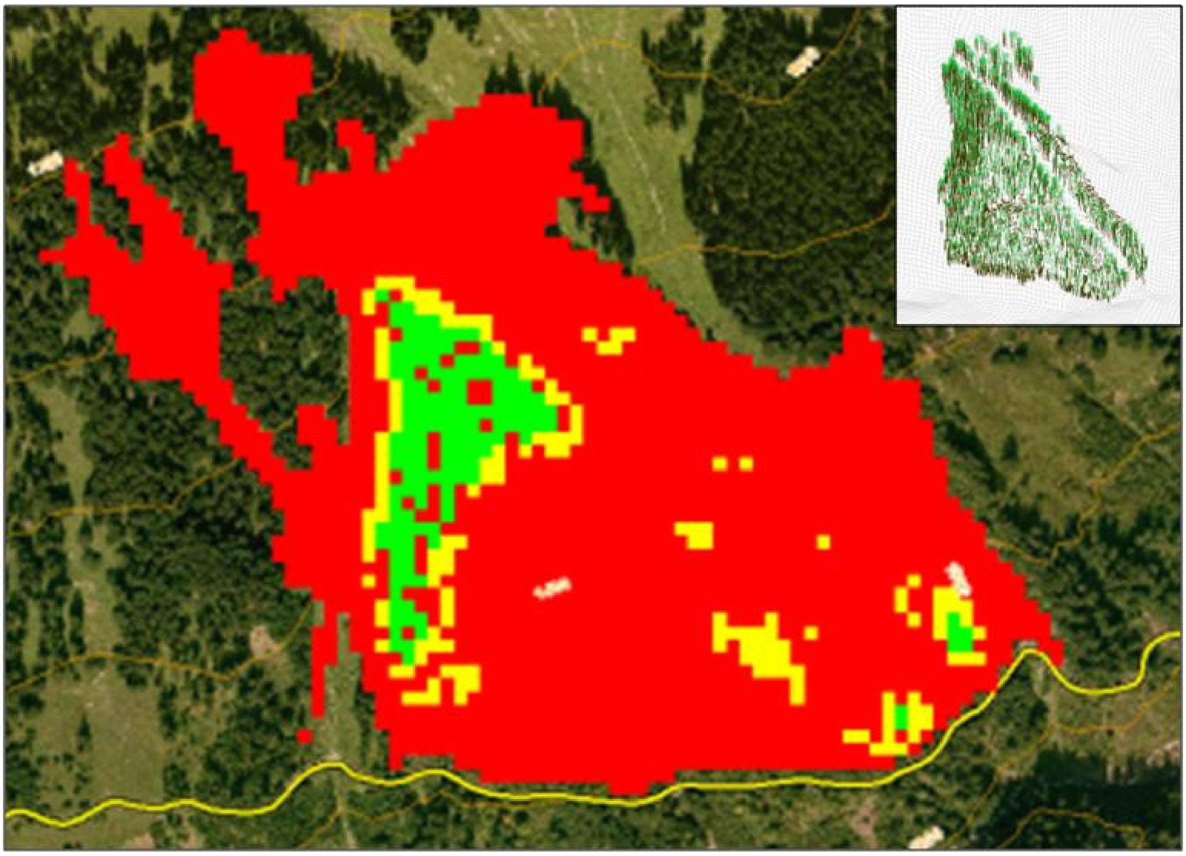


Figure 31. Assessment results after a simulation period of 25 years directly after a BAU management action (insert) with regard to protection against rock fall in the transit zone (rock size: 0.2 – 5 m³) in a GIS environment. Green=ideal thresholds met, yellow=minimal thresholds met, and red=thresholds not met.

3.7.2 Tests and results under climate change

Both BAU and AM have been tested under current climate and climate change conditions and show realistic behaviour and plausible results. In the current version the spatial abilities of PICUS have been improved with regard to management. However, the core of the management module has already shown its applicability in several climate change impact and vulnerability studies (e.g. Seidl et al., 2008; Lexer and Seidl, 2009; Seidl et al., 2009).

3.8 Central Alpine Landclim

3.8.1 New features of the model

LandClim was developed and rigorously tested in case study regions in the Swiss Alps that exhibit comparable environmental conditions as the Montafon case study region (Schumacher et al. 2006, Schumacher and Bugmann 2006, Colombaroli et al. 2010, Henne et al. 2011). Further development concerning the representation of forest succession in LandClim was therefore not necessary. We will simulate forest management in the Montafon case study using the management module as it is described in section **Fehler! Verweisquelle konnte nicht gefunden werden. Fehler! Verweisquelle konnte nicht gefunden werden.**.

3.8.2 Incorporation of adaptive management

In the framework of a Swiss national research program (Wald und Klimawandel, WSL/BAFU) LandClim is currently being applied in the central Alps (Valais and Davos) to assess the provision of forest ecosystem goods and services such as timber, biodiversity and protective functions under various climate change and adaptive management scenarios. The definition of likely silvicultural changes in the future, as for instance the promotion of forest heterogeneity, was based on interactions with forest practitioners. Concerning the definition and simulation of adaptive management scenarios specific to the Montafon case study region we are profiting from these experiences and continue to collaborate with the case study representatives (BOKU).

3.8.3 Tests and results under climate change

Tests including the final set of climate and adaptive management scenarios in the Montafon are at this point still outstanding. Nevertheless, from the successful application in the Swiss Alps it can be concluded that the representation of forest succession and also forest management in LandClim is at a stage where it can be readily adopted to the Montafon case study.

3.9 Mediterranean Prades

3.9.1 New features of the model

The process-based model ***Gotilwa+*** (Growth of Trees Is Limited by WAter), (Gracia *et al.*, 1999, www.creaf.uab.es/gotilwa+/), is used in the Mediterranean case study to simulate forest growth processes and to explore how these processes are influenced by climate, tree stand structure, management alternatives, soil properties and climate change. Gotilwa+ simulates carbon and water fluxes through forests under changing environmental and management conditions. However, up to now ***Gotilwa+*** did not provide explicit information regarding the risk of forest fires under different environmental and management conditions.

Therefore, in order to be able to simulate as well the impact of climate change and forest management in the risk of forest fires in the study area, ***Gotilwa+*** has been expanded with two new empirical models: (1) a fire occurrence model and (2) a fire damage models. Such models linked to ***Gotilwa+*** are able to provide information on how the risk of forest fires will change for different climatic conditions and alternative management schedules.

These models were based on simple variables representing forest stand structure and composition that are under the control of the manager (basal area, species composition, irregularity of the stand, mean diameter) as well as climate variables (aridity) which provide indirect information on the climatic conditions. Such models were developed for Catalonia (North-East Spain) using data from the Spanish national forest inventory and perimeters of fires that occurred in Catalonia during the last 15 years. Those models showed that both the occurrence of fires and the potential damage caused by fires are related to stand characteristics such as species composition, tree size, stand structure, and to climate variables (figures 32 and 33).

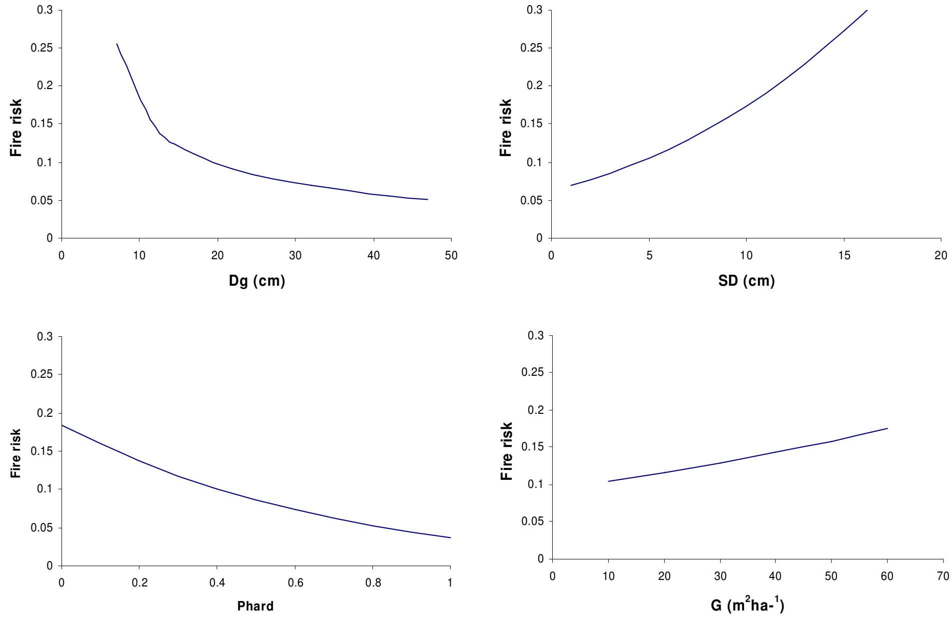


Figure 32. Effect of basal-area-weighted mean diameter (dg), total basal area (G), proportion of the number of trees of hardwood species (P_{hard}), and standard deviation of diameters at breast height (SD) on fire risk.

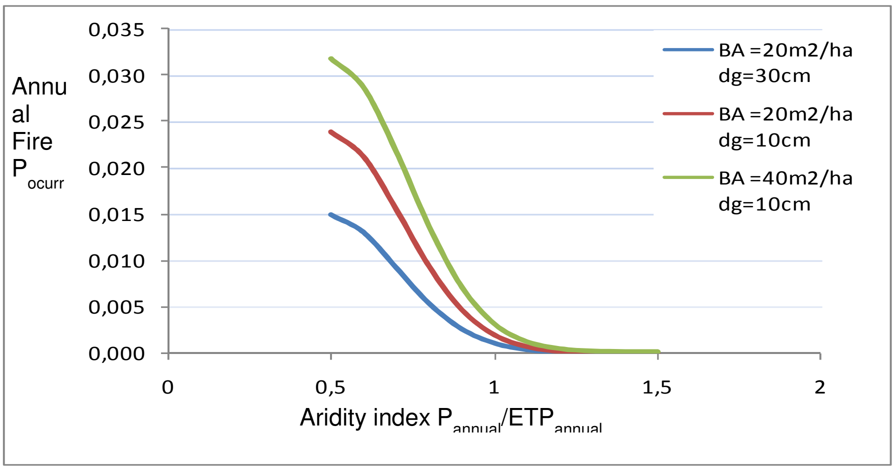


Figure 33. Effect of aridity index in the probability of fire occurrence in Catalonia.

After this new model was fitted, GOTILWA+ was expanded with the new climate sensitive fire occurrence model, in order to obtain information on fire risk under different management alternatives as well as climate scenarios. Fig. 34 shows a forest stand simulation made with ***Gotilwa+*** in the study area under the A1F1 climate scenario for two different management schedules as well as their impact in terms of fire occurrence and potential damage.

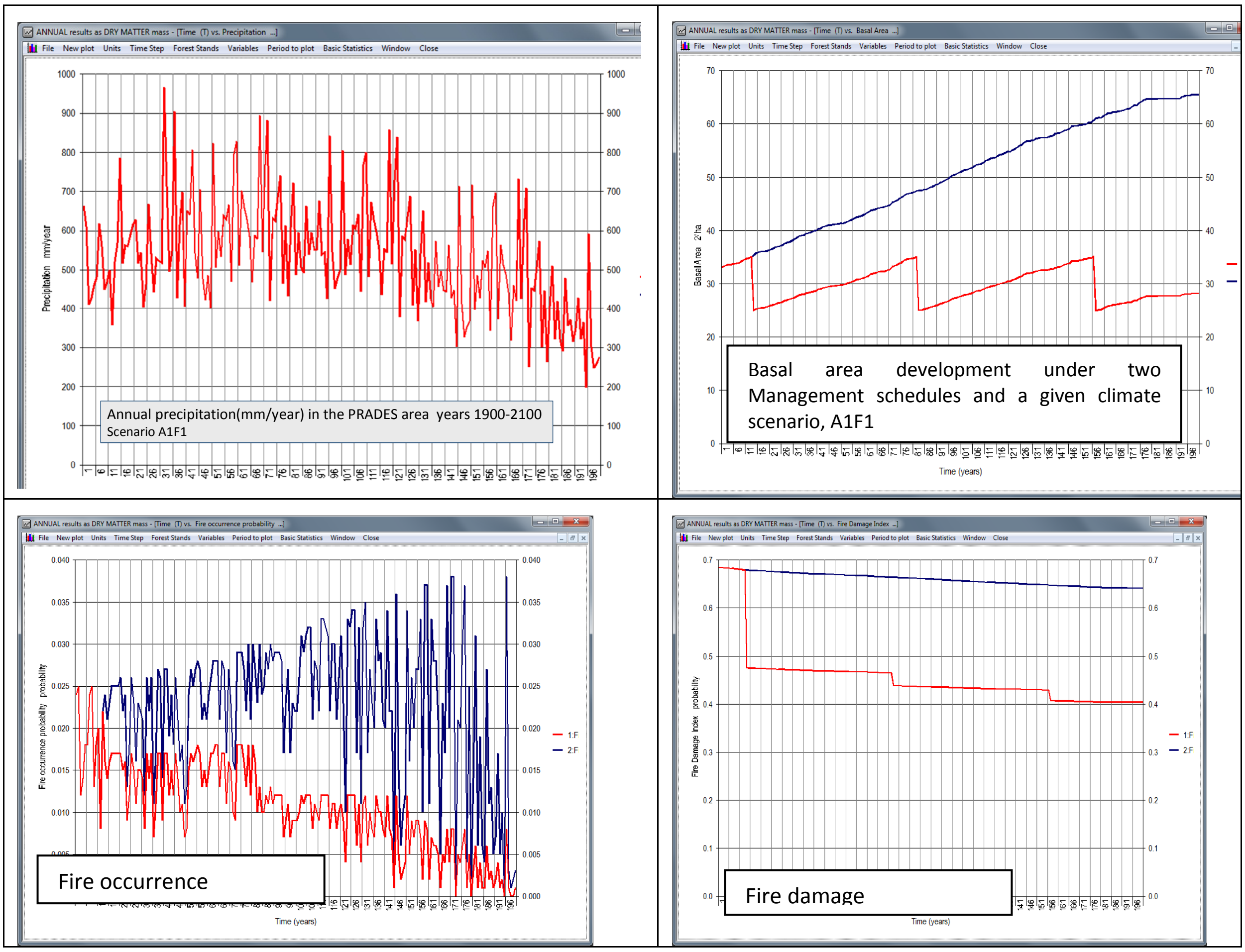


Figure 34. Simulation of two forest management schedules for a Pinus sylvestris stand in Prades under A1F1 scenario. Below, prediction of fire occurrence and damage under the A1F1 climate scenario and for the two management options.

3.9.2 Incorporation of adaptive management

In order to support the development of adaptive forest management in the Mediterranean case study a new forest management decision support tool that integrates (i) dynamic forest simulation models based on physiological processes controlled by climatic and edaphic factors, (ii) optimization techniques that can aid in finding the optimal combination of management variables (thinning intensity and periodicity, rotation length, etc) and (iii) user-friendly interfaces that facilitate the user the selection of climate scenarios, management objectives, site variables, economic parameters, etc., as well as provide visual and summarized information on the optimal forest management strategies have been developed based on the previous modeling tools.

Solving adaptive forest management problems requires, not only models able to predict forest development under different climate scenarios and management options but also tools that can aid in the search of the optimal combination of decision variables (the number, timing and intensity of thinning and the rotation length) to maximize a given management objective under a certain climate scenario. Such task is not an easy one due to the big amount of possible combinations (decision space) that need to be explored to find an optimal solution and requires the use of optimization algorithms.

Therefore, our study is one of the first attempts to optimize forest stand management in a Mediterranean context in the light of different changing climatic scenarios, considering different economic and ecological management objectives. To do so, GOTILWA+ (*Growth of trees is limited by water*) was expanded into a decision support system by linking it to a *Particle Swarm* optimization algorithm and a new interface that allows selecting among a set of management objectives, decision variables, climate scenarios and economic parameters in order to optimize the management of a given forest stand (species, density, site conditions, etc).

Our study starts with the management of *P. sylvestris* stands in north-east of Spain (Catalonia) under two different climate scenarios and four different management objectives; (1) timber profitability (soil expectation value), (2) biomass production, and (3) stand-level water use efficiency. Another study will be conducted to deal with the fire risk adjusted timber profitability. These objectives cover economic, ecological and fire risk-related goals and thus by comparing their optimal management regimes important insights to improve forest management policymaking and the adaptive management of Mediterranean forests in the face of rapidly changing climatic conditions will be gained.

3.9.3 Tests and results under climate change

In a first exercise, a stand of *Pinus sylvestris* from the case study area (Prades) was simulated. The growth of the stand has been simulated for the next 100 years under a “current” climate in two contrasting soils of 50 and 150 cm deep. The soil water holding capacity of both soils is, in average, 30 and 90 kg/m2. Figure 35 represents the mean diameter (cm) and dominant height (m) of the stand growing in both soils.

In a second set of simulations the managemet of the stands is simulated. The management of these plots has been optimized using the combination of the process based model Gotilwa+ and the swarm optimization algorithm (Eberhart and Kennedy ,1995.) to explore the optimal combination of the management regime variables (time and intensity of the successive thinning along a rotation length. Basically the optimization interface (see figure 8) explore the different combinations of those variables simulating for each of them the growth of the stand in the process-based model.

Figures 37 and 38 illustrate some outputs from the decision support tool.

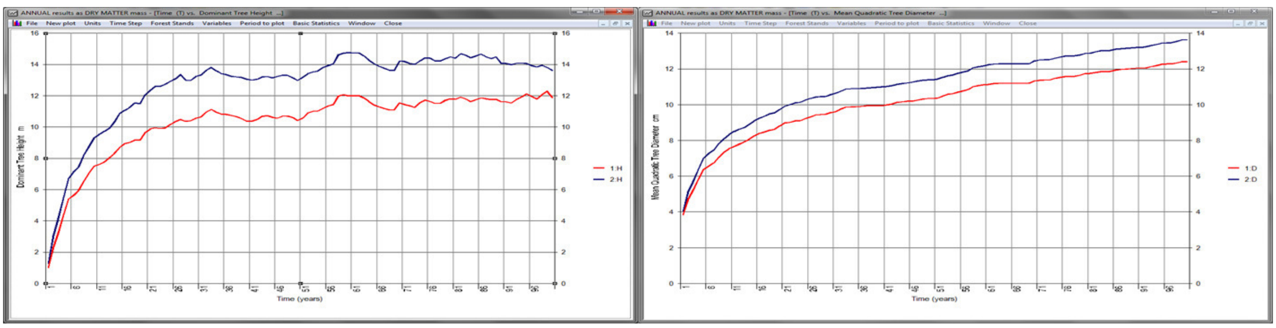


Fig 35. Dominant tree height (m) top, and mean DBH (cm) bottom) of a Pinus sylvestris stand. The growth of two stands on a soil of 50 cm (red plots) and on a soil of 150 cm deep (blue plots) during the next 100 years has been simulated with the Gotilwa+ process-based model using a “current “climate scenario

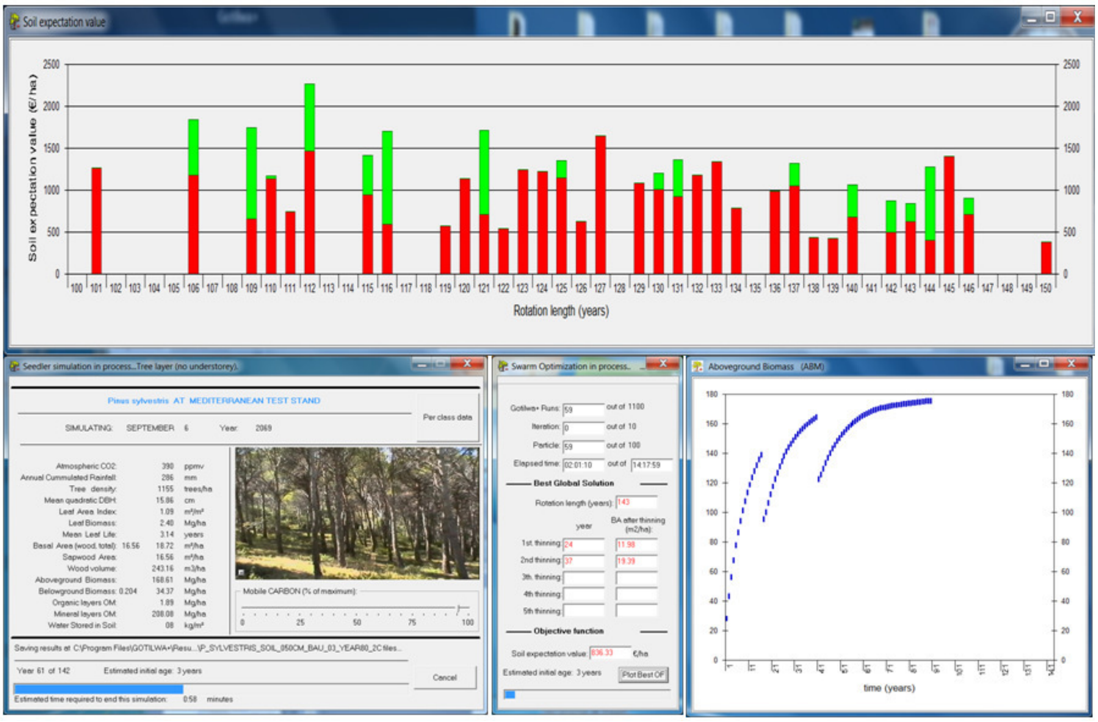


Figure 36. The interface of the Process-based decision support tool implemented in the Gotilwa+ model.

SOIL depth 50 cm			
	best	worst	
SEV €/ha	**2799**	1269	54%
ABMS m^3/ha·y	5.75	4.45	23%
WUE m^3/m^3	584	782	25%

SOIL depth 150 cm			
	best	worst	
SEV €/ha	**3370**	769	77%
ABMS m^3/ha·y	5.75	3.47	40%
WUE m^3/m^3	739	1263	42%

Figure 37. Soil expectation value (SEV, E/ha), wood mean production over the rotation length (ABMS, Tm/ha/y) and water footprint (WUE, m3 of water/m3 of wood) for Pinus sylvestris growing in two soils of 50 and 150 cm. The columns represent the best and worst values obtained for each objective function in both soils and the percentage of improvement between the worst and best, that can be obtained by selecting the optimal times and thinning intensities

SOIL depth 50 cm			
	BAU	CC	
SEV €/ha	2799	1644	**1155**
ABMS m^3/ha·y	5.75	4.62	**1.13**
WUE m^3/m^3	584	607	**23**

SOIL depth 150 cm			
	BAU	CC	
SEV €/ha	3370	1685	**1685**
ABMS m^3/ha·y	5.75	4.22	**1.53**
WUE m^3/m^3	739	734	**5**

Figure 38. Results obtained for the Pinus sylvestris stands (soil 50 and 150 cm) growing under a current climate scenario (BAU) and a A1FI scenario. Note in red the differences imposed by the climate change conditions. In the soil of 50 cm, the current SEV of 2799 E/ha will decrease to 1644 euros/ha, so the cost of climate change can be estimated as the difference, 1155 E/ha. In parallel to this economic cost, to produce 1 m3 of wood under the climate change scenario, 23 more m3 of water are required (from 584 to 607)

3.10 Mediterranean Chamusca

The Chamusca case study involves 3 main species, eucalyptus, maritime pine and cork oak (*Eucalyptus globulus*, *Pinus pinaster* and *Quercus suber*). Umbrella pine (*Pinus pinea*) is also becoming an important alternative to maritime pine that has strong problems with the pine nematode. The two first species are mainly managed as even-aged stands regenerated by clear-cut for wood production. They are fast-growing species, especially the eucalyptus, and therefore growth is strongly affected by weather and climate. The simulations will be made with the 3PG model (Landsberg and Waring, 1997; Sands and Landsberg 2002), complemented with additional output developed on the basis of available empirical data (e.g. Tomé et al.,2004). The 3PG has already been calibrated for the eucalyptus in Portugal (Fontes et al., 2006) and is being calibrated for maritime pine under the scope of MOTIVE. The objective is to include modules in 3PG in order for the model to provide the same output as the more detailed traditional empirical models (including information about individual trees). The model is designated by 3PG out^{+}.

Cork oak stands are sparse, spatially heterogeneous, often uneven-aged and it is usual to have cattle or sheep grazing underneath. Cork oak is a slow growing species managed as even or uneven-aged. The regeneration of existing even-aged stands is not expected to be based on clear-cut but else on promotion (protection of natural regeneration or planting) of regeneration (natural or by planting) following regeneration cuts close to rotation age. At present, simulations are based on an empirical model, the SUBER model (Tomé, 2004), but there is on-going research in order to calibrate a process-based model (3PG or YieldSafe, van der Werf et al., 2007) in order to take climate change effects into account. There is a recently developed empirical model for umbrella pine that might be implemented as well.

3.10.1 New features of the model

During the first two years of the MOTIVE project, the research developed at ISA for WP3 has focused two aspects: 1) the calibration/improvement of the forest models for each one of the three main species, eucalyptus, maritime pine and cork oaks; 2) implementation of the models into simulators adapted for different spatial scales and that provide the inputs needed for WP6. The results obtained in these two aspects are presented separately.

Calibration/improvement of forest models

The development of new models or improvement of existing models that took place or are on-going under MOTIVE (note that some of the models were developed in collaboration with WP 4):

- Quantification and modelling of carbon and nutrients stocks in even-aged maritime pine stands (Nunes et al., 2010)
- An individual tree growth model for maritime pine (Nunes et al., accepted)
- Several empirical sub-models for the cork oak model: prediction of cork caliber over time (Almeida et al., 2010); prediction of mature cork biomass over time (Paulo and Tomé, 2010); total tree height prediction (Paulo et al., 2011); prediction of site index for cork oak stands from environmental variables (Paulo et al., submitted)
- A system of equations to predict eucalyptus merchantable biomass per tree component (Fontes et al., submitted)
- Calibration of the 3PG model for maritime pine

– Comparison of the predictive ability of the 3PG and GLOBULUS (the empirical growth and yield model operational used in the country) for 1st and 2nd rotation eucalyptus stands

– Models for post-fire mortality modelling in maritime pine (García-Gonzalo et al., 2011) and eucalyptus (Marques et al., 2011)

The existing forest models were implemented in the simulators that are described in the next point. Due to the modular structure of the simulators, any improvements that will be achieved till the end of the project will be easily incorporated in the simulators.

Implementation of forest models into simulators

The forest growth models (3PG out^{+} and SUBER) were implemented into user-friend simulators that may work at different spatial scales: stand, landscape and regional. In any of the cases the simulation is based on the definition of one or more prescriptions for each stand. The prescription – set of silvicultural operations that will be applied during a planning horizon – is defined for each stand and is a combination of several forest management alternatives, allowing also for changes of the silvicultural system, species changes and, eventually, land use changes. A forest management alternative is based on a silvicultural system – e.g. even-aged with clear-cut, uneven-aged, dendro biomass, etc – and defines the sequence of silvicultural operations during the whole rotation of an even-aged stand or a cycle for uneven-aged silviculture. For instance, a prescription for a planning horizon of 100 years in a stand that is at present a maritime pine stand with 30 years of age may be (just a simple example, prescriptions can be more complex): 1) even-aged silviculture with thinning at 35 and 40 years of age, clear-cut at 45; 2) planting of cork oak with 600 trees per ha, for the next 85 years, first debark at 25 years of age, subsequent cork debarking every 9 years followed by thinning to maintain a 45% crown cover.

At present there are 4 types of simulators implemented (or at the last stages of implementation) for eucalyptus:

1. Stand simulator – simulates a stand for the planning horizon according to a pre-defined prescription; it can be used to simulate just one stand (single stand option) or a set of stands (multiple stands option), in this last case the same prescription will be used for all the stands.
2. Prescriptions simulator – simulates all the stands (polygons) within a landscape following a large set of alternative prescriptions for each stand, in order to provide input for optimization algorithms that are used to optimize management according to user-defined objectives (WP 6). It includes an automatic prescriptions writer that prepares a file with the list of prescriptions to be tested for each stand. As the Prescriptions simulator is mainly used to generate the input for WP 6, it does not take external drivers, such as wood demand or hazards (fire and pathogens), directly into account, although the risk of fire and/or pathogens is computed for each stand along the simulation horizon. Wood harvest depends directly on the prescriptions.
3. Landscape simulator driven by prescriptions – simulate all the stands (polygons) within a landscape following a prescription for each stand. Clear-cuts or other types of final cuts applied in even-aged forests are defined by the prescriptions. The primary unit of simulation is the stand but some of the spatial analyses require a data base on raster format as is the case for the simulation of hazards (at present, just wildfire occurrence). Hazards are simulated according to a scenario and the prescriptions are adapted after a fire occurs. This simulator was developed to simulate the evolution of the landscape using the prescriptions recommended by the optimization (WP 6)

4. Landscape simulator driven by consumption – simulate all the stands within a landscape following a forest management alternative for each stand but clear-cuts or other types of final cuts applied in even-aged forests are defined according to external drivers, namely wood and biomass demand or land use changes. The primary unit of simulation is the stand (that may be defined as polygons or artificially created pixels) but some of the spatial analyses require a data base on raster format as is the case for the simulation of hazards (at present, just wildfire occurrence). Hazards and harvests as well as change of forest management alternative and land-use changes (drivers of the simulator) are simulated according to scenarios. The simulation of a driver has slight differences between drivers. For instance fire simulation includes: 1) prediction of the probability of fire ignition for each stand; 2) prediction of a fire to start by Monte Carlo simulation using the previous probability; 3) in case of a fire to start, prediction of the size using historical fire size distributions; 4) simulation of the fire spread based on simple rules that use the prediction of the probability of a stand to burn according to its characteristics; 5) new fire ignitions are predicted until the burned area given by the scenario is achieved.

The stand simulator is implemented for the 3 main species and the adaptations to include maritime pine and cork oak in the prescriptions and landscape simulators are in course.

At present the simulators do not include the possibility to simulate mixed-species stands, however those stands have a residual area in the Chamusca country and there is no anticipation that their area will increase in the near future.

3.10.2 Incorporation of adaptive management

The simulators include an interactive construction of forest management alternatives that allow the user to select first a silvicultural system and then to define all the silvicultural operations that will be carried on along the simulation horizon, as well as the details associated to each one of the operations such as thinning type and intensity (defined in different ways), intensity of beating up, type of site preparation, etc.

Adaptive management is incorporated through the definition of prescriptions. The prescriptions may be defined in two ways:

1. By simulating a large number of alternative prescriptions generated with a prescription writer (see an example in figure 39) for each stand and selecting the "best" for each stand according to the scenarios (climate, for instance) and the objectives of the users (public administration, private stakeholders, society in general). Different prescriptions will be selected by optimization for different scenarios, depending on scale contex (figure 40).
2. By directly defining a series of prescription and associating one of them to each stand or stand type. Those prescriptions should be defined according to expert judgement of changes that should be introduced in the way forest are usually managed in order to cope with the expected changes, namely climate change.

It is also possible to find an intermediate solution by simulating several prescriptions for each stand but taking into account the adaptive management measures that might be thought to be appropriate.

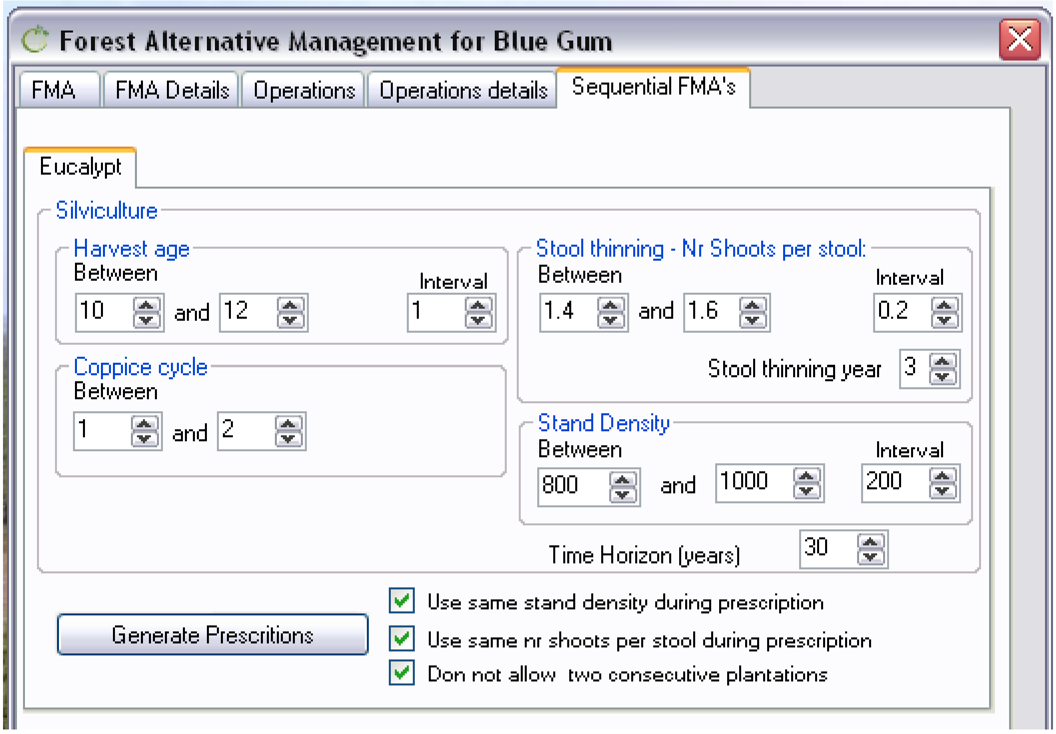


Figure 1: Prescription generator for Eucalyptus globulus

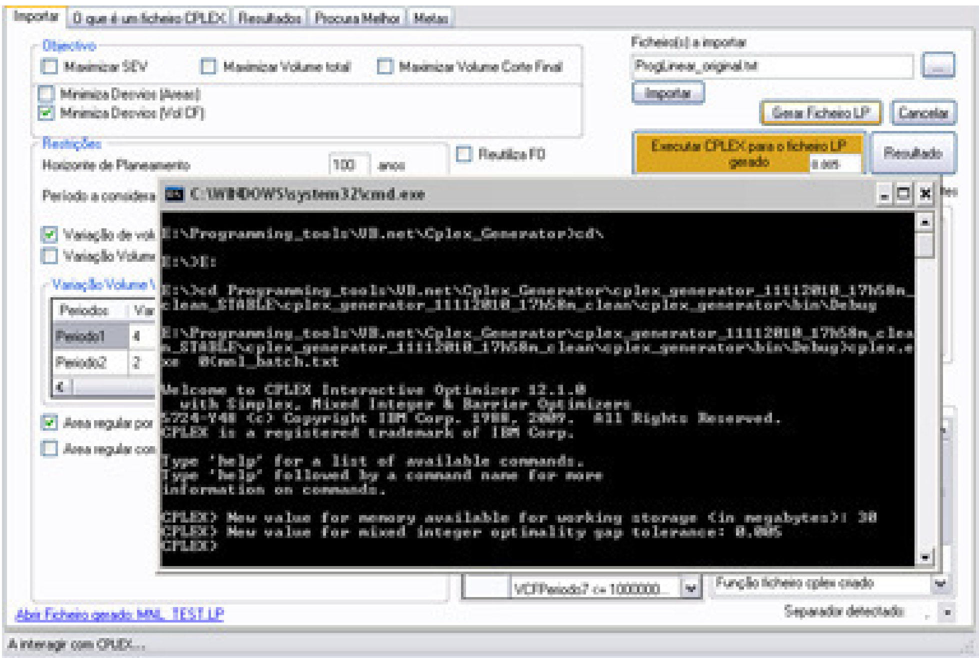


Figure 40. Interface for generating and finding best alternative (using CPLEX) with growth projections made on several prescriptions for each stand.

3.10.3 Tests and results under climate change

Tests are still on-going but it is possible to demonstrate already some results of the stand simulator.

Application of the stand simulator to eucalyptus

The stand simulator was used with the 3PG growth model ($3PGout^{+}$ variant) to simulate a eucalyptus stand for a planning horizon of 100 years. In order to assess the impact of rotation length, the single stand option was used and two alternative management prescriptions were compared under three climatic scenarios.

The eucalyptus stand is a planted stand with 4.1 years of age initially established with a stand density of 1103 trees ha^{-1} (no clonal material was used). The prescriptions are characterized by two rotations, one planted stand followed by a coppice stand, after which the stand is harvested and replanted with a starting density of 1400 trees ha^{-1}. The two rotations cycle is repeated throughout the simulation period. A shoots selection operation is performed at the age of 3 leaving 1.6 sprouts per stool. The only difference between both prescriptions is the rotation length which was considered 10 years for the first prescription and 12 for the second. Stand growth was simulated with $3PGout^{+}$ model for both prescriptions under three climatic scenarios: base line (BL), A1B (A1B) and B1 (B1) and the results were plotted in figures 41 and 42.

Note that the climate scenarios, provided by WP2, are not definitive as they were found not to be plausible and work to improve them is still on-going.

Application of the stand simulator to cork oak

The two simulations presented were made using the SUBER v5.0 model for a period of 100 years since the year 2011 to 2111.

The data used regards 6 plots with 2000 m^2 area each, installed in a cork oak plantation from 1994. The initial plantation was established with a 4x2 m spacing, in Arenosoils, with an average soil depth of 100 cm.

The measurement was made in 2011, when the trees were 17 years of age. The estimated site index for this plantation is 16.1 m for a base age of 80 years.

The simulations were made assuming the following management options:

- The first debarking in the stand occurs when the quadratic mean diameter, measured over cork, is equal to or greater than 17 cm (70 cm of perimeter). This happened in the year 2026 (tree age equal to 32 years)
- Trees are first debarked when the perimeter at breast height is equal or greater than 70 cm.
- Formation pruning is made 5 and 15 years after the first debarking, in order to clear the main stem of branches until a height of 3 m.
- Debarking coefficients are used according to maximum values allowed by the national legislation.
- Cork debarking rotation periods equal to 10 years.
- Mechanical control of the understory vegetation with mounted knifes or chains at a 3 year interval (the first year coincides with the year of the first debarking)
- Sanitary thinning operations are made annually, despite the age of the stand, to remove dead trees.
- The first thinning occurs in the year of the first debarking of the stand, in order to achieve a stand crown cover equal to 50%.

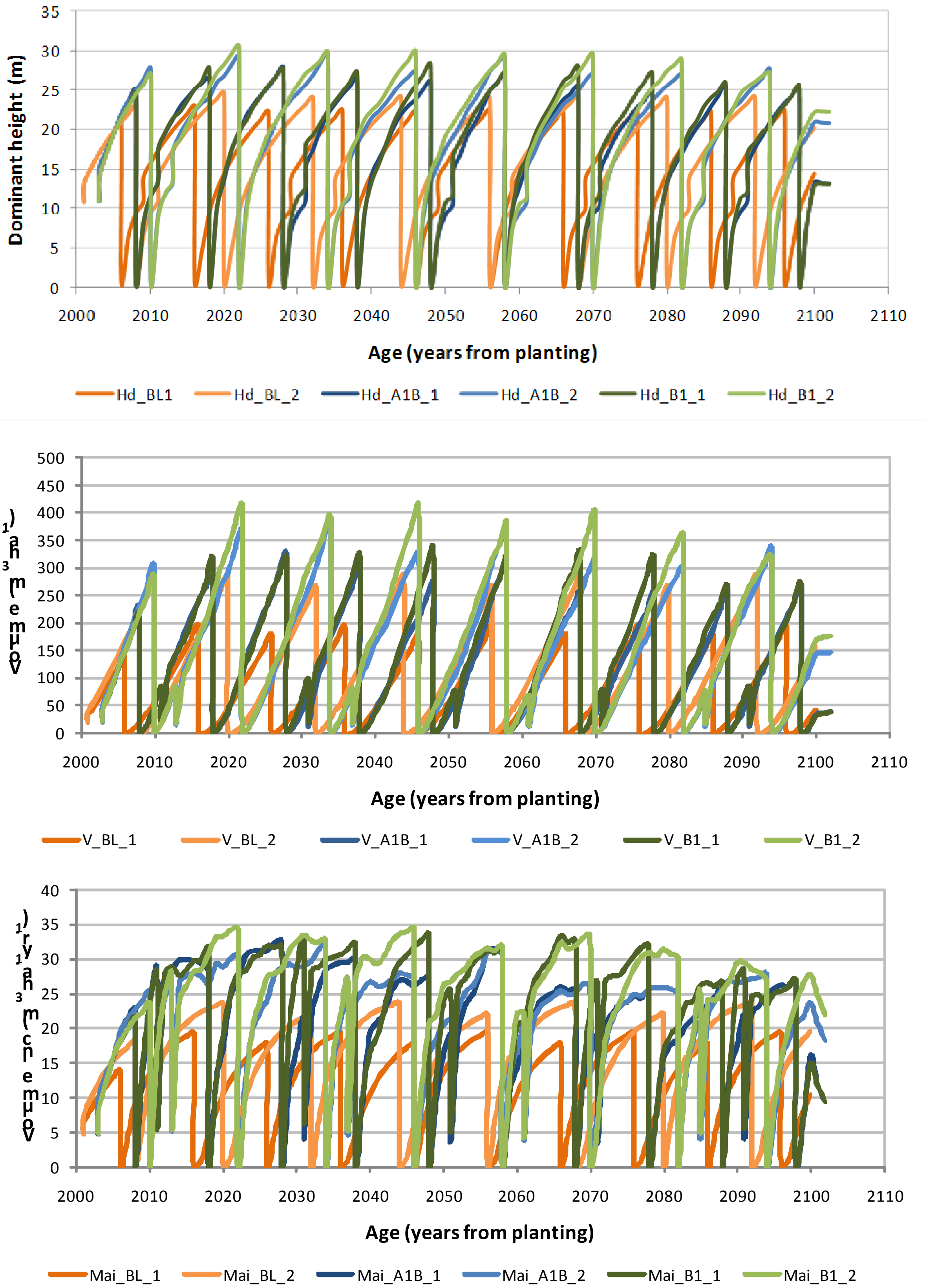


Figure 41. Evolution of dominant height, standing volume (Volume) and mean annual increment (Mai) for prescriptions 1 and 2 under each climatic scenario.

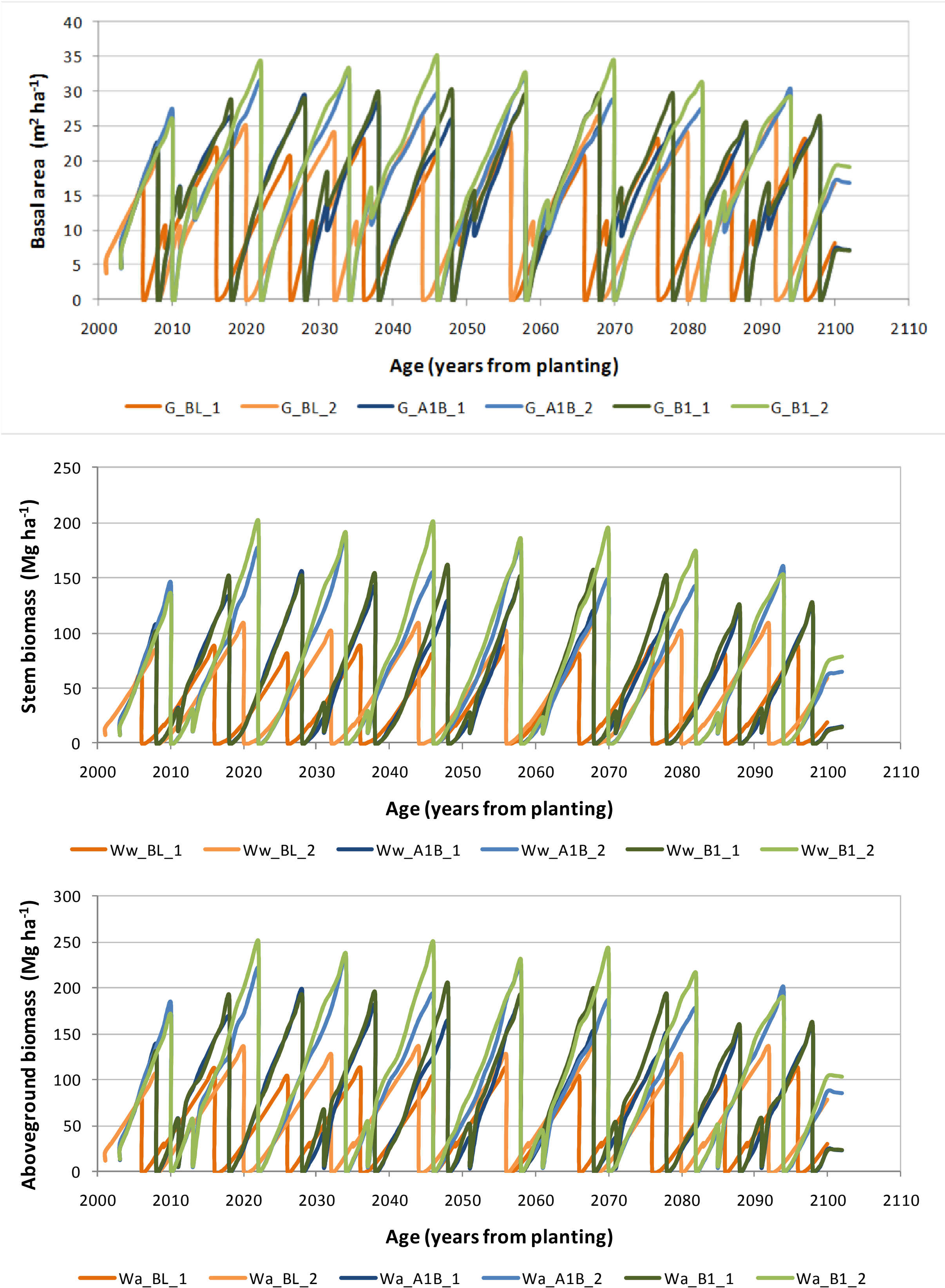


Figure 42. Evolution of basal area stem biomass (Ww) and aboveground biomass (Wa) for prescriptions 1 and 2 under each climatic scenario.

– Thinning operations are made at the time of the debarking (after debarking takes place), until the stand is over 100 of age. The thinning operations reduce the stand density for a value that corresponds to a crown cover of 50%.

– For the first simulation no regeneration plantation was assumed along the 100 years of the simulation. For the second simulation, 200 trees ha^{-1} were considered for regeneration of the stand in the year corresponding to an age of 70 and 100 years old of the initial stand.

The information used for cork quality and cork growth index distributions is presented in Table 3.

Table 3. Cork quality and cork growth index distributions (in proportion) used in the simulations

Cork quality classes							cork growth index classes				
1	2	3	4	5	6	refuse	< 18	18-23	23-27	27-41	>41
0.08	0.08	0.08	0.35	0.21	0.12	0.08	0	0	0.08	0.7	0.22

Cork prices from 2009 (Table 4) were considered for characterizing the cork market.

Table 4. Cork prices (€/@) for the year of 2009. 1@ = 15 kg

<table>
<tr><td rowspan="2">Cork thickness class (mm)</td><td colspan="7">Quality class</td></tr>
<tr><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td></tr>
<tr><td>< 18</td><td colspan="3" rowspan="3">11.75</td><td colspan="4">0.70</td></tr>
<tr><td>18 – 23</td><td rowspan="2">11.65</td><td colspan="2" rowspan="4">6.50</td><td rowspan="4"></td></tr>
<tr><td>23 – 27</td></tr>
<tr><td>27 – 41</td><td colspan="3" rowspan="2">88.25</td><td rowspan="2">51.50</td></tr>
<tr><td>> 41</td></tr>
</table>

Figures 43 and 44 show some of the outputs of the two simulations. The regeneration at ages 70 and 100 years is visible in figure 44 that corresponds to the prescription in which regeneration took place at these two ages. The impact of this operation is clear in the stand stocking and also on the wood that can be obtained from thinnings in the last period of the simulation. C stock is also highly influenced by the protection and/or planting of new trees close to the end of rotation.

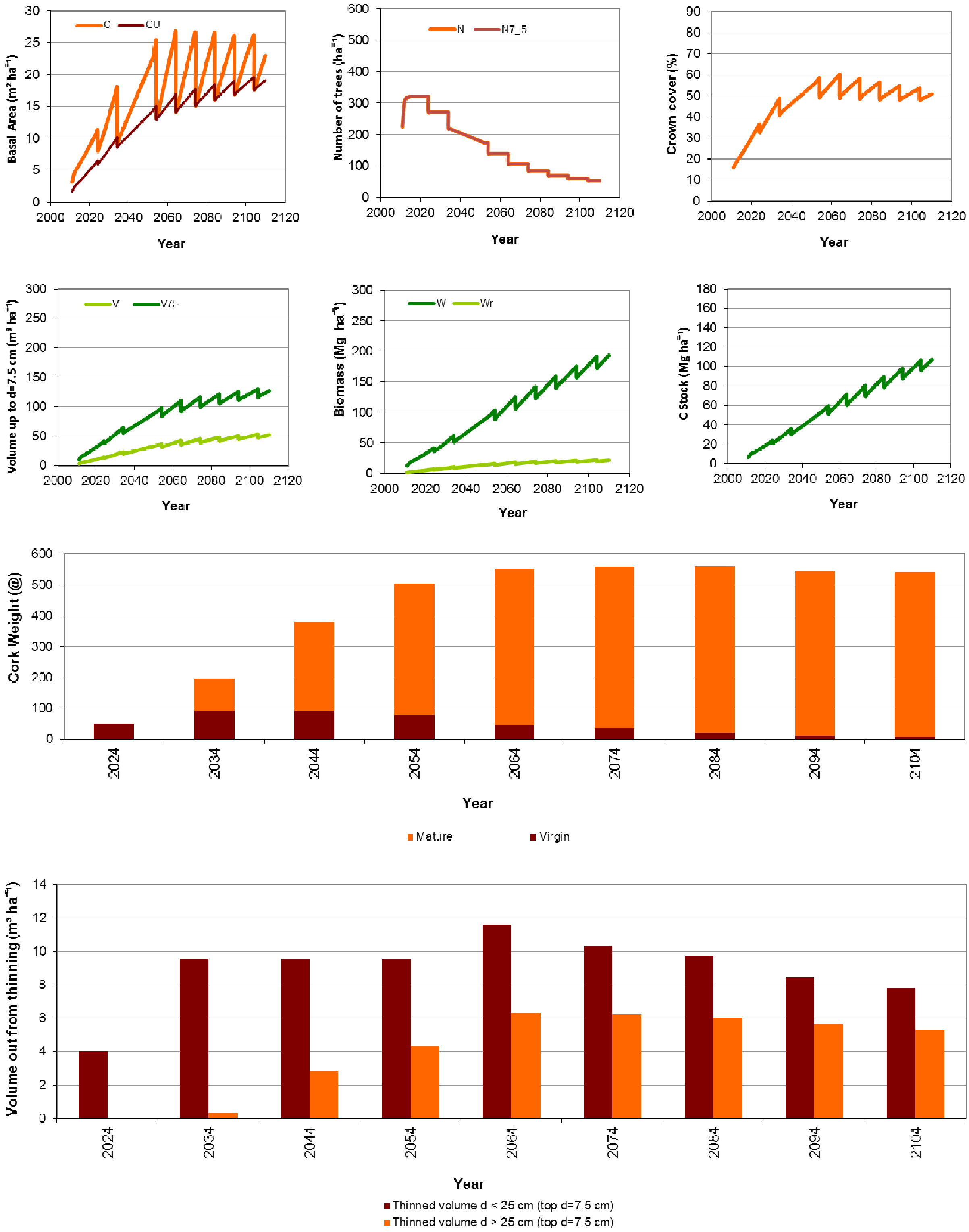


Figure 43. Simulation of a cork oak stand during a 100 years long planning horizon: no regeneration close to the end of the simulation period.

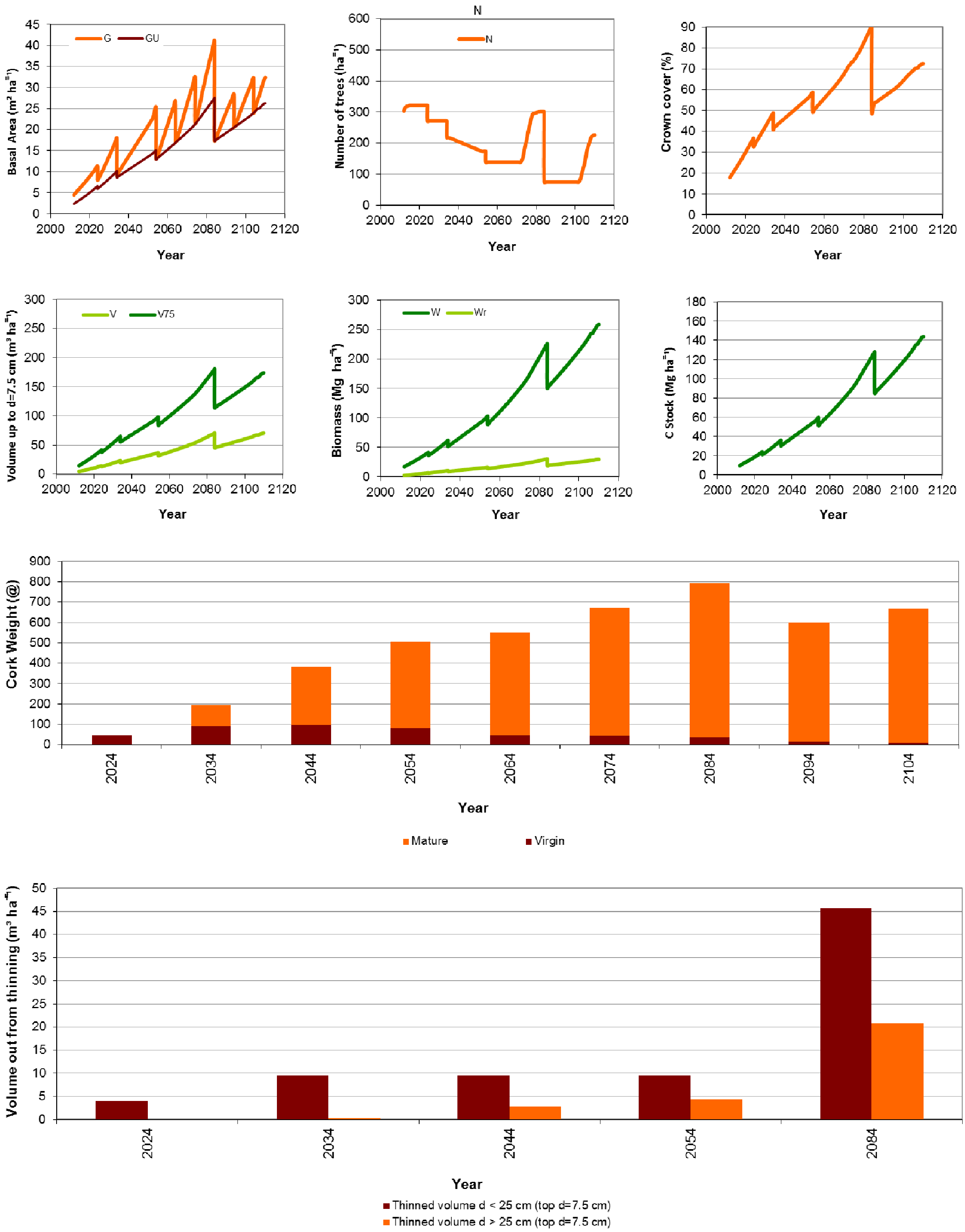


Figure 44. Simulation of a cork oak stand during a 100 years long planning horizon: regeneration was simulated at ages 70 and 100, with visible influence on the stocking of the stands as well as in other stand variables.

3.11 Bulgaria

3.11.1 New features of the model

The tree species of importance for the Bulgarian case-study were parameterized, for Bulgarian conditions, in the forest ecosystem model PICUS 1.5. With regard to coniferous species the parameterized species are *Pinus sylvestris* and *P. nigra*. Regarding deciduous tree species four oaks were parameterized: *Quercus robur*, *Q. petrea*, *Q. frainetto* and *Q. cerris*. For the parameterization Bulgarian yield tables and dendrological literature (e.g. Schütt et al., 2006), as well as stem and allometric analyses, conducted in the case study area, were used. Differences with regard to coppice and high forest have been considered. Sample plot data from the case study were used to check the parameterization results. Based on field inventory data on sprouting after coppice cuts the regeneration module was enhanced. PICUS is able to simulate generative and vegetative reproduction of oak species. Therefore high forest and coppice, as well as mixed stands can be simulated.

3.11.2 Incorporation of adaptive management

In the case study adaptive management relates to the transfer from (i) coppice to high forests or pine plantations, (ii) from plantations to mixed coppice and high forests, or to (iii) stay within the coppice system. The enhanced regeneration module of PICUS 1.5 allows for the simulation of those adaptive management approaches. The management module did not need to be modified.

3.11.3 Tests and results under climate change

Tests under climate change conditions have not yet been accomplished

3.12 Romania

3.12.1 New features of the model

The model selected for the case study (LandClim, Schumacher et al. 2004) takes into account the most important driving variables, which were identified by the field questionnaire: drought, windthrows. It is not foreseen to develop it further. Instead, its main parameters are being tested on a study site where forest growth has not been influenced by human activities for centuries: the forest reserve laying at about 30 km from the case study location offers the possibility to test the main modules (regeneration, growth) without interaction with the management module or the windthrow module.

The study site is large and resulted in a supersized matrix of unit cells which would have required an outrageous computation time, without guaranties that the computers could actually go to the end of the runs. The basic cells size formerly used in LandClim simulations - 25 or 30 m - was extended to 100 m. This feature matches with the size of the management units, which are mostly over 3 ha.

The description of the management in the model is rather different from the one used so far in this model. Forest management in Romania is largely based on a target age that defines the end of a production cycle, instead of having a prescribed diameter threshold that would trigger a harvest and stand replacement. A conversion between tree age and size or stand state can be found and is provided by the inventories, but this is a rather indirect.

Therefore, the Romanian case study does not require developing new features of the model, but rather to test its performance outside of its calibration zone before in order to apply it at large scale and test management options.

3.12.2 Incorporation of adaptive management

The range of management types that need to be represented in the case study is very large. But the incorporation of the adaptive management is possible in LandClim by the description of the management intervention through a detailed definition of the input parameters set.

The management changes were described after discussions with the management authorities. They consist mainly in responding to observed trends (a very prolific beech regeneration and a tendency to occupy stands formerly dominated by coniferous species), to climate change (more drought or early droughts).

The main adaptive management actions deal with an intensification of the thinnings, which could also be more frequent, and a shortening of the rotation cycle. Species composition could also be changed, that is, Norway spruce or beech could be favoured in some places. The different adaptation options were structured into management approaches. Each approach translates into specific sets of parameters characterising the different management types and their variants. Two decision points should be used. For each decision point, at least one management alternative will be used apart from the status quo and in combination with different climate change scenarios.

3.12.3 Tests and results under climate change

Testing is on-going. There are no results available yet at the scale of the case study. The Romanian case study is in mountainous zone. The climate changes, which are likely to be a winter and summer temperature increase with more frequent droughts, could lead to changes in forest composition with an increase of the broadleaves species contribution to volume. At decision points, changes in the management could be introduced, such as favouring a given species.

4 Overview

This deliverable describes the models that are available in each case study as well as the way they can take adaptive forest management into account. Some of the models were already available before the project but all of them had to be improved in order to become useful for MOTIVE. For that they had to fulfil the following goals

- Be sensitive to climate change
- Be able to simulate hazards risks and/or hazards occurrence and impact
- Be very flexible in the simulation of different silvicultural systems and forest management alternatives, providing a large set of sustainability indicators that can be used to assess the impact of different prescriptions
- Be implemented in a simulator at some spatial scale (stand, management area and/or region)

Different case studies have used different models and different ways to achieve the goals listed above. The most important methods that were used are described below.

4.1 How do models simulate the impact of climate change

The simulation of the impacts of climate change requires the use of detailed process-based models. However, those models are usually developed as a scientific tool to better understand plant growth processes and are not usually used for management purposes. One of the main drawbacks of such models is the amount of parameters they require as well as the detail that is needed for the characterisation of the site as an initialization of the model.

Different ways have been used in order to obtain models that can be applied in forest management and still be able to simulate the impact of climate change. The most commonly used methods are the development of “correction factors” for empirical models and the use of simple (parameter sparse) process based models that are often combined with empirical functions in order to produce the required detail of the output. In the first method the “correction factors” are applied to traditional empirical growth and yield models in order to make them climate sensitive. The correction factors are obtained by running a detailed process based model under different climate scenarios and examining the behaviour of the forest in comparison to the simulations of a traditional growth model.

The correction factors’ method is being used under MOTIVE in both Boreal case studies. In the Northern Boreal case study, the correction factors were developed by the individual tree increments in diameter and height by running the FinnFor model (Kellomäki et al., 1997) for different site types and different climatic scenarios. In the South Boreal case study, factors to modify site index as a function of climate change (Blennow et al., 2010a) will be used.

The 3PG model (Landsberg and Waring, 1997; Sands and Landsberg 2002), and modifications /improvements of it, a simple process based model developed to bridge the gap between detailed process-based models and operational forest management will be used by the Atlantic Wales and Mediterranean Chamusca. In the Atlantic Wales case study, 3PG is combined with several other model, namely with an ecological site classification that determines the suitability of a habitat for a certain species. The Central Alpine case study uses the PICUS model, a process-based model for mixed stands that was developed from the 3PG ideas. The PICUS model is also being used in the case study Bulgaria.

The Mediterranean Prades site is the only one using the Goliwa^{+} model, a model that was specifically developed to simulate the growth of trees in sites with serious water limitations.

Large scale landscape models incorporate processes, such as regeneration and succession, at larger scales and for simulations of long periods, and are therefore very useful to simulate forest dynamics at landscape level. This type of models operates on the basis of a raster system combined with a shape of management areas. The model LANDCLIM (Schumacher et al., 2004) has been developed in order to improve the tree growth module of a large scale landscape model, making it, to a certain extent, climate sensate. This model is being used by the following case studies: Atlantic Veluwe, Central Black Forest, Central Alpine and Romania.

4.2 Simulation of hazards risks and hazards occurrence and impact

All the models include modules for the prediction/simulation of hazards risk and/or hazards occurrence and the subsequent impact. Northern case studies focus mainly wind storms while the Southern case studies focus wild fires.

There is a large variety in the way the risk of hazards is predicted from more empirical models based on logistic regression (fires in the Mediterranean case studies) to more mechanistic models for the prediction of Wind blow risk. The prediction of fire risk can be computed on a stand basis but the occurrence and impact only make sense when applied at a larger scale. The same is true for the Wind blow model.

4.3 Simulation of different silvicultural systems and forest management alternatives providing several sustainability indicators as output

All the models described for the 8 case studies are able to simulate different silvicultural systems and different forest management alternatives.

They do it in different ways, from the simple control of thinnings implemented by the Northern boreal case study to other models that allow the forest management regime to be completely defined by the users in an iterative way (such as for instance the Mediterranean case studies or the ones based on LAND CLIM). The Northen Boreal case study establishes maximum and minimum thresholds for basal area that depend on stand age. Each time the upper threshold is attained, the stand is thinned to a basal area equal to the lower threshold. This is a simple method but very useful as it automatically adapts the forest management alternative to the stand growth rate affected, on its turn, by climate change.

An analysis of the different case studies shows that all of them allow for some flexibility on the way silvicultural systems and forest management alternatives can be defined. Some case studies show the possibility to automatically simulate several alternatives for each stand that will then be used by some type of optimization to select the “best” alternative for each stand, under each scenario (for instance, Northern Boreal and the Mediterranean case studies).

Sustainability indicators are part of WP 4.4 (Ecosystem goods and services under different management options) and therefore are not included in this deliverable.

4.4 Implementation of models into simulators operating at different spatial scales

Models are collections of sub-models – equations and/or procedures – that must be interconnect by some logic through a computer program, the forest simulator. The use of forest growth models imply that they are implemented in some type of simulator. This is the case for the models that are being used in the MOTIVE case studies, all are implemented in some type of simulator.

Depending on the objective for which they are being used, simulators may operate at stand, management area/landscape or a larger region (eventually a country). In MOTIVE there are simulators at different spatial scales. All case studies that use the LANDCLIM model operate at landscape level as the model has been conceived specifically for this level. Most of the other model were conceived using stands or trees as the primary unit of simulation but can operate at different spatial levels. This is the case for the model from the Northern Boreal, Atlantic Wales and Meditteranean Chamusca cases whose models work at tree/stand level but that were implemented in stand level and management area/landscape levels. The Mediterranean Prades case mode is, at the moment, implemented just at stand level.

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