



**Deliverable D5.3: Maps and report of population extinction risks under different management scenarios.
H2020 GenTree project**

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GenTree

Optimizing the management and sustainable use of forest genetic resources in Europe

Deliverable D5.3

Maps and report of population extinction risks under different management scenarios

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1 Summary

- **General context:** Since the early 1990s, many European countries have established coordinated strategies for the management of Forest Genetic Resources (FGR), relying notably on dynamic *in-situ* FGR conservation networks. Ongoing and predicted climate change (CC) however, questions the sustainability and long-term objectives of these existing networks, with 33–65 % of conservation units predicted to be at the limit or outside species' bioclimatic niche by 2100. Meanwhile, FGR are also one of the available tools for adapting forests to CC, through assisted migration or evolution-oriented forestry practices.
- **Objective:** The main goals of the Task 5.2 in GenTree is to investigate the vulnerability of conservation units across the European network of major tree species, to understand the ecological processes underlying vulnerability of major tree species to CC, and to evaluate how genetic diversity and management practices can mitigate vulnerability.
- **Methods:** These issues were addressed in GenTree's task 5.2 by combining genetics, ecophysiology and population dynamics in a predictive ecology framework. Simulation were done using a process-based model (CASTANEA) to assess a combined vulnerability index taking into account late frost risk, carbon starvation risk and hydraulic failure risk. We compared the vulnerability of five major European species (*Fagus sylvatica*, *Quercus petraea*, *Pinus sylvestris*, *Pinus pinaster* and *Picea abies*) under current and future climate with or without mitigation measures through forest thinning or assisted migration.
- **Results:** The model reproduces the current niche of the species. Results show that *Fagus sylvatica* GCUs have a higher vulnerability than other species under current climate. Our simulations show that the two deciduous species are less vulnerable than pines under climate change. Finally, thinning and assisted migration have significant but low positive effect in mitigating vulnerability.

2 Introduction

Ongoing global and climate changes are expected to have major impacts on forest ecosystems and their ecosystem services (ES), with for instance an expected increase in tree mortality due to drought and heat (Hauck, Winkler, & Priess, 2015), and 21-50% of economic value loss projected for European forests by 2071-2100 (Hanewinkel, Cullmann, Schelhaas, Nabuurs, & Zimmermann, 2013). There is thus an urgent need to forecast the future of European forests and the resilience of their ES, in order to implement well-informed public policies.

2.1 Physiological drivers of forest vulnerability to climate change

The numerous drivers expected to affect ecosystem functioning and increase tree mortality include shifts in rainfall patterns, global warming, increase in frequency of “extreme” climatic events (i.e. drought, storm, flood, snow, late frost) and changes in biotic interactions (i.e. pest, invasive species, competitions at the community level) (McDowell et al., 2011). Moreover, these factors can interact: for instance, drought can increase tree vulnerability to pest (McDowell et al., 2011) or of forest stands to fire (Turco et al., 2017). Most declines of European forest tree populations are expected at rear-edge margins of species distribution and are expected to be primarily driven by severe droughts resulting from the raising average temperatures and decreasing precipitations predicted by most climate models. Increasing risks of late frosts are also expected to increase the vulnerability of deciduous tree species particularly.

Two major inter-related physiological mechanisms are usually considered to explain mortality in response to drought: hydraulic failure and carbon starvation. Catastrophic failure of the plant hydraulic system can result from xylem embolism (cavitation), which progressively reduces the conductance of xylem. To avoid hydraulic failure, trees can close their stomata, which mechanically reduces transpiration, but at the same time also reduces photosynthetic activity, which can lead to carbon starvation particularly during long drought periods. Hydraulic failure is largely acknowledged as the principal mechanism involved in extensive crown death and tree mortality observed during drought, but the multi-dimensional response of trees to desiccation is complex (Choat et al., 2018). Moreover, drought-induced responses such as hydraulic failure and carbon starvation do not necessarily lead to mortality, but they weaken the tree that subsequently becomes more vulnerable to other stressors, such as pests or diseases.

Besides increasing mortality driven by drought and high temperature, higher risk of late frosts is also expected due to the advance of leaf unfolding dates in response to climate change, which have been documented for many tree, shrub and perennial plant species. The relative shifts in the timing of leaf unfolding vs. the timing and intensity of frost events determine whether frost risk changes under climate warming. Although relatively large safety margins were found regarding frost risk during leaf unfolding across many European temperate tree and shrub species, these safety margins tend to shrink with climate change (Bigler & Bugmann, 2018). Moreover, nonlinear changes in the timing and intensity of frost events are expected in the future due to the intrusion of cold arctic air masses that are affected by changes in the polar vortex. Frost damage is expected to increase for deciduous trees in particular, but evergreen species also show a non-negligible vulnerability to late frost at specific stages of leaf unfolding.

2.2 Adaptive potential of forest tree population under climate change

Because of their large and diverse gene pools, native genetic resources of natural forest tree populations represent a central component of numerous options for adaptation of forests

under CC. Local adaptation is widespread in tree populations throughout their distribution ranges (Alberto et al., 2013). In deciduous trees, strong genetic differentiation in patterns of budburst dates are observed across latitudinal or altitudinal gradients. They are usually interpreted as the result of natural selection in order to avoid late frost on one side and to maximize the duration of the vegetation period on the other side (Kramer et al., 2017). The scientific knowledge on genetic differentiation of physiological traits involved in response to drought is far less extensive. However, populations originating from drier regions are expected to have evolved traits conferring an increased resistance to water stress (e.g., reduced risk of hydraulic failure) while populations originating from wetter regions are expected to have evolved traits conferring a better ability to exploit favorable conditions for growth (e.g., higher water conductance).

However, the speed of ongoing CC is likely to exceed the natural adaptive response potential of most species and populations (Kuparinen et al. 2010). Options to enhance forest adaptation to CC through the management of their gene pool can be classified along a gradient spanning from “hard” to “soft” options, depending on the intensity of human impact. On the hard option side, a full-control strategy (called assisted migration) consists in replacing the local population by a presumably better-fit population. This is achieved through plantation of so-called Forest Reproductive Material (FRM), which comes either from a breeding program or from a selected seed stand. This strategy allows for drastic stepwise evolutions, but the resources presumably better fit in the long term may be less fit in the short term, thus raising trade-off issues between short-term and long-term risks. Furthermore, this strategy requires minimizing uncertainties about the ecological integration of the alien resource in the new site under future climates. On the soft option side, evolution-oriented forestry consists in guiding, i.e. supporting and accelerating, natural evolutionary processes using the local genetic resource, ecologically integrated within its current environment. This is achieved through natural regeneration. This strategy produces progressive changes only, limited by the evolutionary potential of the local resource, but it is flexible and relaxes the ecological uncertainty related to introduction of alien material (Lefèvre et al., 2013). The “hard” strategy based on large scale movement of genetic material and the “soft” strategy based on the exploitation of local adaptive potential, which are not mutually exclusive, have their respective advantages and constraints that still need to be more precisely quantified.

The knowledge, management and conservation of FGR thus play a crucial role for the adaptation of forests to CC. Indeed, FRM needed for assisted migration could be found in part in GCUs, as conservation networks were often designed to encompass marginal ecological conditions. Additionally, under current legislation, only evolution-oriented forestry can be used to adapt GCUs themselves to CC (as introduction of FRM from long-distant gene pools is prohibited). However, the genetic resources of most GCUs are poorly characterized in most species. Moreover, bioclimatic niche projections under future climate recently brought evidences of the generally high vulnerability of individual GCUs and the whole conservation networks to CC (Schueler et al. 2014). Indeed, target species in 33–65 % of conservation units, mostly located in southern Europe, are predicted to be at the limit or outside species’ projected bioclimatic niche by 2100. The highest average decrease in favorability¹ throughout the network can be expected for coniferous trees (although they are mainly occurring within units

¹ In this work, the favorability of a specific conservation unit for a species has been calculated as a function of both the species probability of presence and the actual prevalence of the species.

in mountainous landscapes, where velocities² were the lowest). There is thus an urgent need to better understand the ecological processes underlying the vulnerability of forests to CC in general and in conservation networks in particular, and to investigate how genetic diversity and genetic adaptation can contribute to the adaptive response of forests to CC. Here we use the concept of vulnerability in the broad sense as the product of the set of risks that forests face and not in the strict sense used in the literature as a single component (e.g. vulnerability to water stress) of a given risk (e.g. the occurrence of water stress).

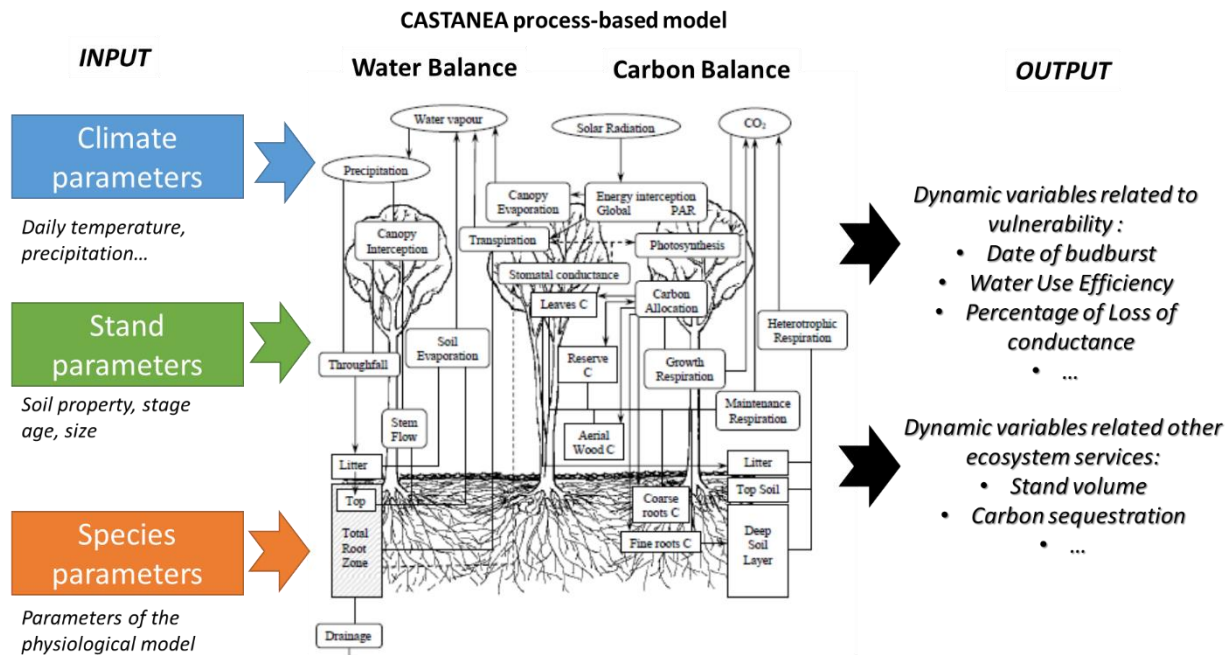
2.3 Towards scenarios for forests management of and the provisioning of ecosystem services.

Scenario construction and comparison is now widely acknowledged as the best approach to predict extinction risks and the future provision of ES (Hauck et al., 2015). Based on the same initial state (description of land cover and land use), the scenarios typically combine quantitative changes in ecosystem functioning (predicted by dynamic forest simulation models taking as input variations in temperatures, rainfall, and logging schedules) with plausible futures of ES based on qualitative narratives (evolution of management policies, innovative management strategies).

The first step toward ES assessment thus requires documenting land use and their expected changes, before evaluating the combined effects of climate and land use change on ES provisioning. Ideally, this should be done at a local scale and at fine spatial grain, which allows accounting for the heterogeneity in ecological system, ownership and management (Tuffery et al., in prep). However, approaches at a broader scale can also yield useful predictions, despite the expected loss of precision due to upscaling, such as the effect of large-scale policy changes.

² The velocity of climate change is an index of the speed of temperature change (km yr^{-1}), derived from spatial gradients ($^{\circ}\text{C km}^{-1}$) and multimodel ensemble forecasts of rates of temperature increase ($^{\circ}\text{C yr}^{-1}$) over a given period; introduced by Loarie et al. (2009)

Figure 1: Conceptual scheme of the CASTANEA process-based model. CASTANEA simulates the different biophysical and physiological processes (photosynthesis, respiration, phenology...) related to water- and carbon balance at stand level. The model takes as input >120 parameters and allows simulating variables related to stand vulnerability and other ecosystem services.



2.4 Objectives of GenTree task 5.2

We have divided the work performed in GenTree task 5.2 into four steps each associated to specific objectives. Detailed material and methods for objective 1 are available Petit-Cailleux et al. (submitted). Detailed material and methods for objective 2 to 4 are available in Appendix 5.2 of this document.

Objective 1: Determine the physiological thresholds triggering mortality at the rear-edge of the species distribution, using beech as a model. This preliminary step was based on the combination of (1) an exceptional yearly individual monitoring of 4327 European beech trees in a peripheral warm and dry population, with (2) simulations of the carbon reserves, hydraulic conductance and late frosts using the process-based ecophysiological and biophysical model (CASTANEA, Figure 1). This first step allowed us to introduce new knowledge on the processes related to vulnerability of beech and also to finely calibrate CASTANEA for this species.

Objective 2: Understand the ecological drivers of the vulnerability of major tree species and of their GCUs network across Europe. For this second step, we used CASTANEA simulations to predict the vulnerability of five European forest species (Table 1) under CC across their distribution ranges. Simulations were run considering the heterogeneity in climatic and soil conditions across Europe, and assuming that forests were unmanaged. Focusing on the risks associated to late frosts, carbon starvation and hydraulic failure, we produced vulnerability maps of GCU networks under historical and future climates. This step also allowed us to derive a vulnerability status for GCUs of each species at different time scales.

Objective 3: Incorporate scenarios for forest management and ecosystem services. In this step, we used CASTANEA at European scale to predict combined impacts of CC and management scenarios on vulnerability, carbon sequestration and wood production for the five species listed in Table 1. Simplified management scenarios over Europe were described based

on existing knowledge and their share were derived from existing databases. Simulations were run considering the heterogeneity in climatic and soil conditions as well as of silvicultural practices across Europe, but assuming complete homogeneity of other CASTANEA parameters within and among populations of each species. This step allowed us to test how management options contributed to vulnerability (here, the risks associated to late frosts, carbon starvation and hydraulic failure), and to predict the changes in provisioning of various ecosystem services expected under CC.

Objective 4: Investigate how management practices based on FGR can mitigate the vulnerability of major European tree species and of their GCU network. For this step, we considered that three major adaptive traits related to vulnerability to CC (risks associated to late frosts, carbon starvation and hydraulic failure) were (genetically) variable within species (both within and among populations). These focal traits are (1) the date of budburst (TBB), related to vulnerability to late frosts, (2) water use efficiency (WUE), related to vulnerability to carbon starvation, and (3) the percentage of loss of conductance (PLC), related to vulnerability to cavitation. At this stage, we considered only *Fagus sylvatica* and the four other species will be treated in the manuscript resulting from this deliverable. Simulations of vulnerability, carbon sequestration and wood production were first run considering simultaneously the heterogeneity in climatic and soil conditions, silvicultural practices, and key adaptive traits across Europe. Secondly, we simulated assisted migration scenarios where genetic diversity is taken into account (i.e. populations do not display the same adaptive values for the traits considered). This step allowed to test for the first time how intra-specific variability is likely to mitigate the impact of CC on the vulnerability and associated ecosystem services of a major tree species.

Table 1: Broadleaf and conifer species studied in GenTree Task 5.2 and their genetic resources in Europe

Tree species	Distribution	Major threats to FGR	Nb <i>in-situ</i> DCUs	Castanea
<u><i>Fagus sylvatica</i></u>	Atl, Alp, Con, Med	Climate change	469	cal.
<i>Picea abies</i>	Alp, Bor, Con	Climate change, pests	471	cal.
<i>Pinus pinaster</i>	Atl, Med	Forest fire, pests	42	cal.
<i>Pinus sylvestris</i>	Alp, Bor, Con, Med	Climate change	313	cal.
<u><i>Quercus petraea</i></u>	Atl, Con	Pests, hybridization	250	cal.

Tree species: Broadleaf species are underlined. *Distribution*: Alpine (Alp), Atlantic (Atl), Boreal (Bor), Continental (Con), Mediterranean (Med). *Nb in-situ GCU*s: Number of GCUs in Europe (EUFGIS data, <http://portal.eufgis.org/>). *Castanea*: species for which the biophysical model CASTANEA is calibrated

Figure 2: Summary of the objective of this deliverable.

Step	Species	Approach	Outcomes
1- Physiological thresholds triggering beech mortality at rear edge	Beech	Combining CASTANEA simulations at stand- and individual- level with experimental survey of mortality	<ul style="list-style-type: none"> New knowledge on mortality Physiological thresholds to mortality
2- Ecological drivers of the vulnerability of major tree species and of their GCUs' network across Europe	5 species	CASTANEA simulations for 3174 stands across Europe, accounting for heterogeneity of climate + soil	<ul style="list-style-type: none"> Vulnerability maps of GCU networks under historical and future climates
3- Incorporation of scenarios for forest management and ecosystem services	5 species	As above + heterogeneity of silvicultural practises	<ul style="list-style-type: none"> Impact of current management options on forest vulnerability and other ecosystem services
4- Impact of FGR-based management practices on the vulnerability of major tree species and of their GCUs' network across Europe	Beech	As above + intra-specific variability of key adaptive traits within and among populations	<ul style="list-style-type: none"> Impact of innovative management options (assisted migration) on forest vulnerability

Figure 1: CASTANEA model

3 Results

3.1 *Combining statistical and mechanistic models to unravel the drivers of mortality within a rear-edge beech population*

As several studies report increasing dieback of trees over temperate forests, a major issue in ecology is to identify the physiological drivers of mortality. In this study, we investigated the drivers of mortality in a major European tree species, *Fagus sylvatica*, at the rear-edge margin of its distribution.

Based on an exceptional dataset of yearly individual monitoring of 4327 European beech trees, we first used empirico-statistical models to quantify the effects of climate, competition, tree size and health on mortality. Secondly, we used the process-based model CASTANEA to simulate the variations in carbon storage, loss of conductance and late frosts and to disentangle the mechanisms driving temporal and inter-individual variations in mortality.

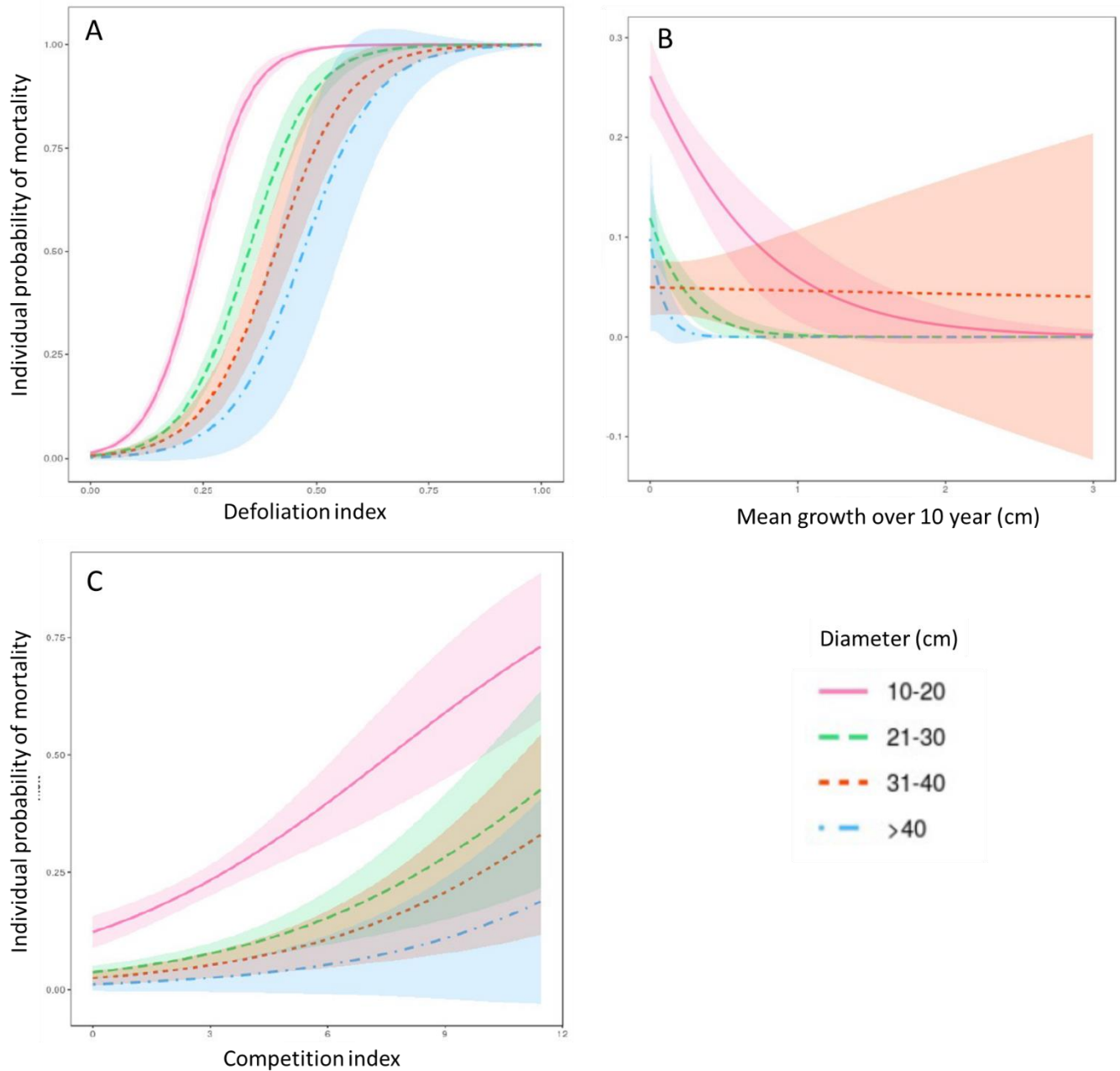
The empirico-statistical models first showed that the rate of mortality at population level was associated to drought indices. Secondly, the individual probability of mortality decreased with mean growth, and increased with crown defoliation, bud-burst earliness, and intra-specific competition. Moreover, interaction effects between tree size and most of these factors were detected, such that small trees always had a higher probability of mortality (Figure 3).

CASTANEA simulations allowed the rate of mortality at population level to be explained by a combination of physiological responses to climatic stress, including the loss of conductance, the decrease of carbon reserve and the impact of late frost. Moreover, we showed that trees with early bud-burst suffer a higher loss of conductance and a higher number of late frosts, despite their ability to accumulate more carbon reserve. Crown defoliation was found to limit the impact of hydraulic stress by allowing more carbon reserve to accumulate.

This study allows to disentangle the processes underlying mortality, show why it is necessary to account for individual variability in vulnerability. It also allowed us to define physiological thresholds for mortality in beech, a major step for the other objective of this task. A first manuscript was produced, currently under review:

Petit-Cailleux, C., Davi, H., Lefevre, F., Garrigue, J., Magdalou, J.-A., Hurson, C., ... Oddou-Muratorio, S. (2019). Combining statistical and mechanistic models to unravel the drivers of mortality within a rear-edge beech population. *PCIEcology*.

Figure 3: Effect of ecological factors (A: Defoliation, B: growth; C: competition) on the individual probability of mortality for trees of different diameter classes. These results were based on statistical analyses of 4327 trees monitored since 2003.



3.2 Ecological drivers of species and GCU network vulnerability at European scale

Simulations were run across Europe, using a grid of 3174 cells, each measuring 45km x 45 km. In each cell, species and stand variation was considered fixed. We accounted for the heterogeneity in climatic and soil conditions across Europe, assuming that forests were unmanaged.

Simulation were first run from 1959 to 2015 for the historical climate. Then, one climate change scenario was considered: RCP 8.5, i.e. a pessimistic scenario. The RCP 8.5 was estimated using the Model for Energy Supply Strategy Alternatives and their General

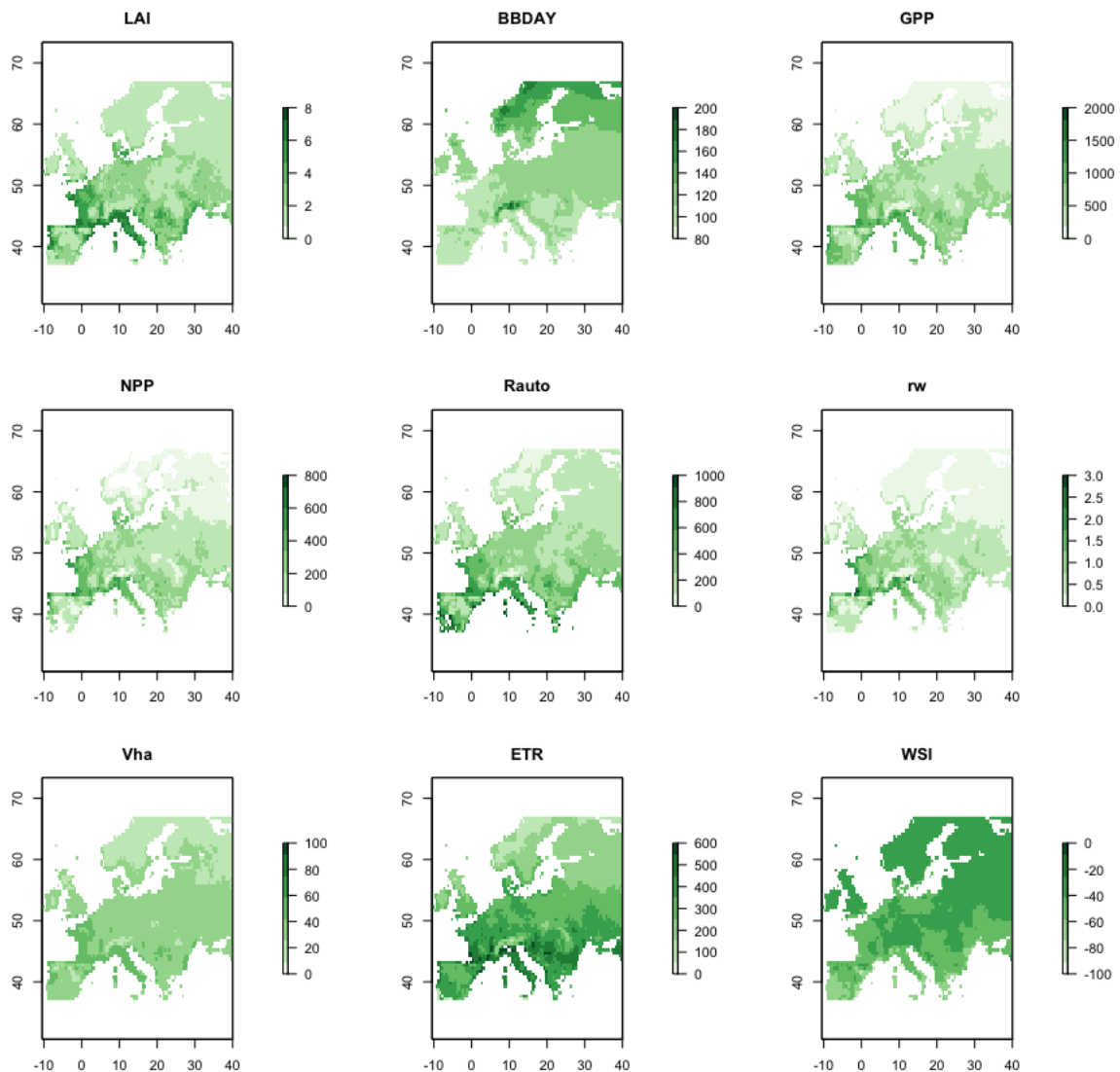
Environmental Impact (Moss et al., 2010) predicting a rise of up to 1370 CO₂-eq in 2100. Simulations were run from 2015 to 2100.

The vulnerability of the stands is assessed first through three indicators obtained by the previous study (objective 1): percentage of loss of conductance (PLC), level of non-structural carbohydrate (NSC), and Number of frost days (Frost). Then we computed a combined Vulnerability Index (CVI) for each pixel i as follows:

$$CVI_i = \frac{frost_i / nyears}{maxFrost} + \frac{PLC_i}{maxPLC} - \frac{NSC_i}{maxNSC}$$

To compare all the CVI over all the simulations we set maxFrost to 0.17 frost per year, maxPLC to 30% of cavitation and maxNSC to 200 gC.m⁻²

Figure 4. Simulated forest ecosystem variables of *Fagus sylvatica* across Europe from 1979 to 2008 without silviculture: Leaf Area Index (LAI in $\text{m}^2 \text{ leaves} \cdot \text{m}^{-2} \text{ soil}$), date of leaf unfolding (BBDAY in Julian day), Gross Primary Production (GPP in $\text{gC} \cdot \text{m}^{-2} \text{ soil}$), Net Primary Production (NPP in $\text{gC} \cdot \text{m}^{-2} \text{ soil}$), Autotrophic respiration (Rauto in $\text{gC} \cdot \text{m}^{-2} \text{ soil}$), yearly ring width increment (rw in $\text{mm} \cdot \text{year}^{-1}$), stand volume (Vha. m^3), Evapotranspiration (ETR in $\text{mm} \cdot \text{year}^{-1}$) and soil water stress index (WSI in $\text{Mpa} \cdot \text{year}^{-1}$)



Using *Fagus sylvatica*, a species for which we have the most information on tree physiology and forest functioning, we evaluated the model's ability to reproduce many of the variables of ecosystem functioning (Figure 4). Leaf Area Index (LAI) ranged from 2 to 8, date of leaf unfolding (BBDAY) from 80 to 200, Gross Primary Production from 500 to 1500 $\text{gC} \cdot \text{m}^{-2} \cdot \text{year}^{-1}$, Net Primary Production (NPP) from 200 to 600 $\text{gC} \cdot \text{m}^{-2} \cdot \text{year}^{-1}$, Evapotranspiration (ETR) from 300 to 600 $\text{mm} \cdot \text{year}^{-1}$, Water Stress Index summing the predawn water potential (WSI) from 0 to -100 $\text{MPa} \cdot \text{year}^{-1}$. In this base simulation without thinning, ring width ranged from 0 to 2mm and stand volume (Vha) was low under 100 $\text{m}^3 \cdot \text{ha}^{-1}$. Across Europe, Net Ecosystem Exchange (NEE) was positive (*Fagus* acted as a carbon sink) for 52% of the total Area.

We used the simulated Non-Structural Carbone biomass (NSC) as an indicator of habitat suitability for a given species. It is itself quite well correlated with simulated Net Primary Production or simulated radial growth, which are two other proxies generally used to estimate habitat suitability for a species in process-based global models.

The current distribution of *Fagus sylvatica* was well reproduced using simulated NSC except in southwestern France, where beech is probably not present for reasons other than climatic ones. Beech is vulnerable (high CVI) in southeastern Europe to higher PLC (higher cavitation risk), southwestern Europe due to both higher PLC and higher late Frost risk, and in northeastern Europe due to higher late frost risk.

Figure 5. Risk associated to cavitation, late frost and carbon starvation of *Fagus sylvatica* across Europe for the period 1979 to 2008 without silviculture. Top left: species distribution area and Genetic Conservation Units. Top: percentage of loss of conductance (PLC), Number of frost days (Frost), Bottom: biomass of non-structural carbohydrate (NSC in $g \cdot m^{-2}$ soil) and combined Vulnerability Index (CVI, see text)

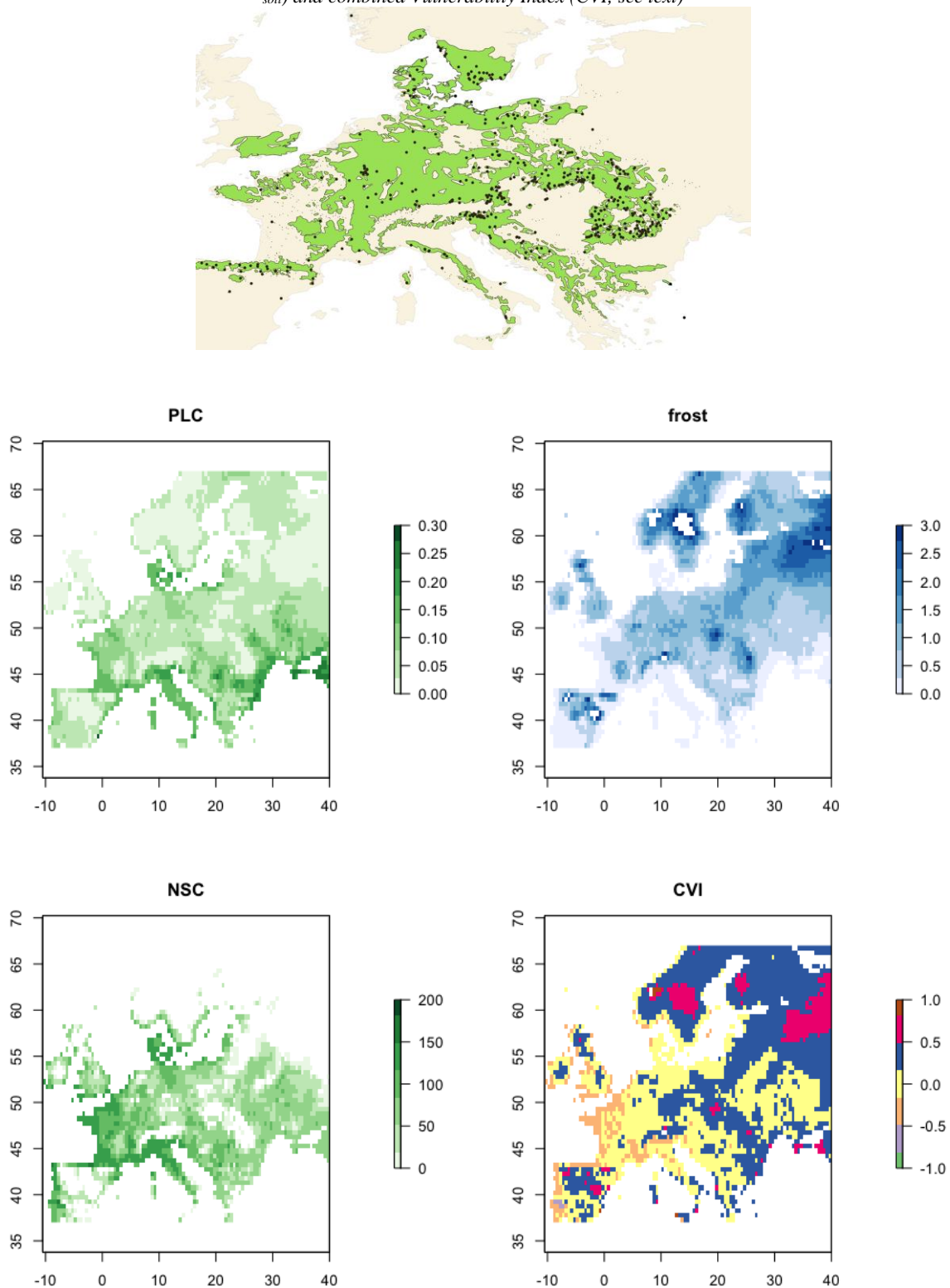
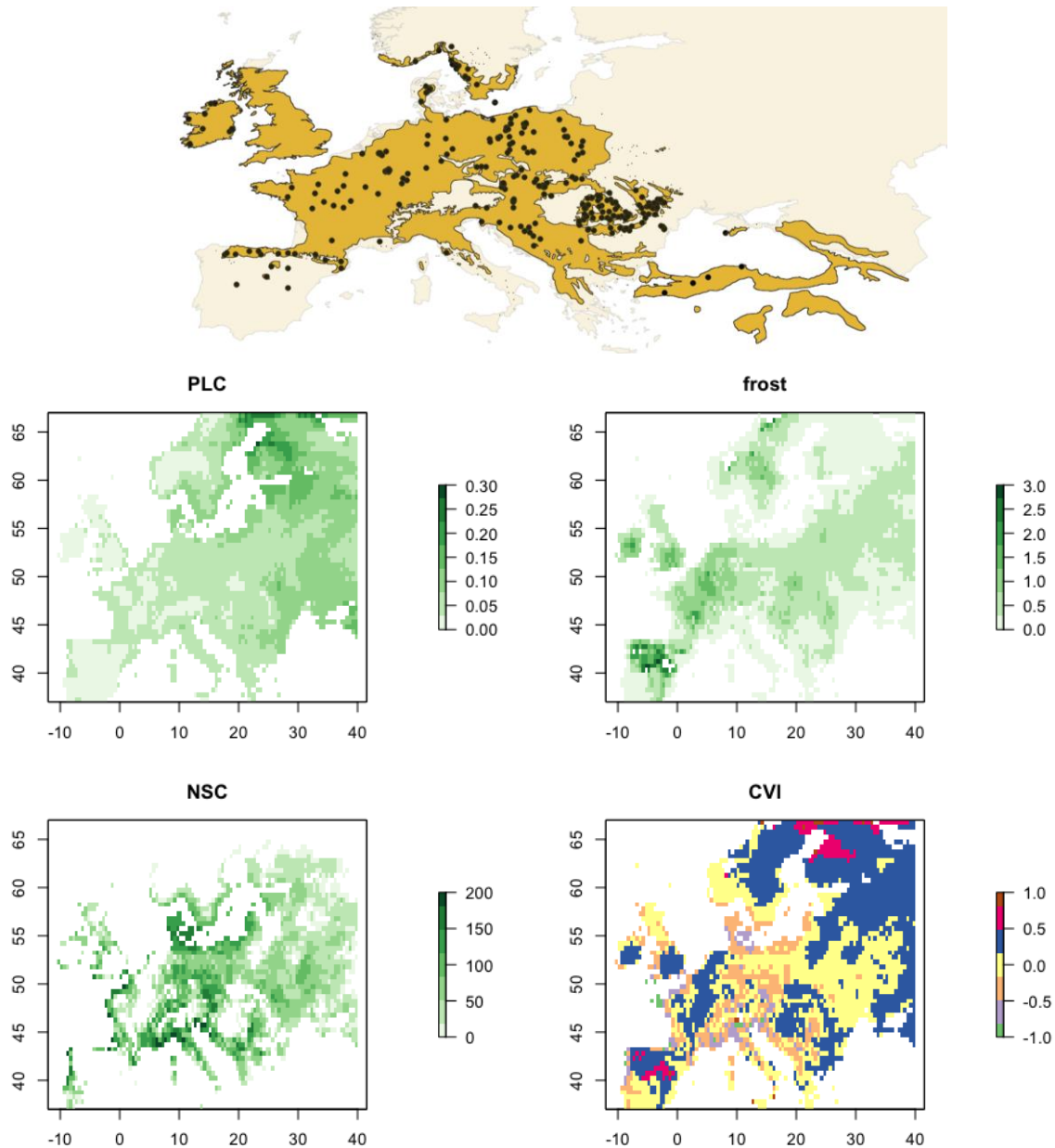


Figure 6. Risk associated to cavitation, late frost and carbon starvation of *Quercus petraea* across Europe for the period 1979 to 2008 Top left: species distribution area. Top: percentage of loss of conductance (PLC), Number of frost days (Frost), biomass of non-structural carbohydrate (NSC), Bottom: level of non-structural carbohydrate (NSC in $g\cdot m^{-2}_{soil}$) and combined Vulnerability Index (CVI, see text)

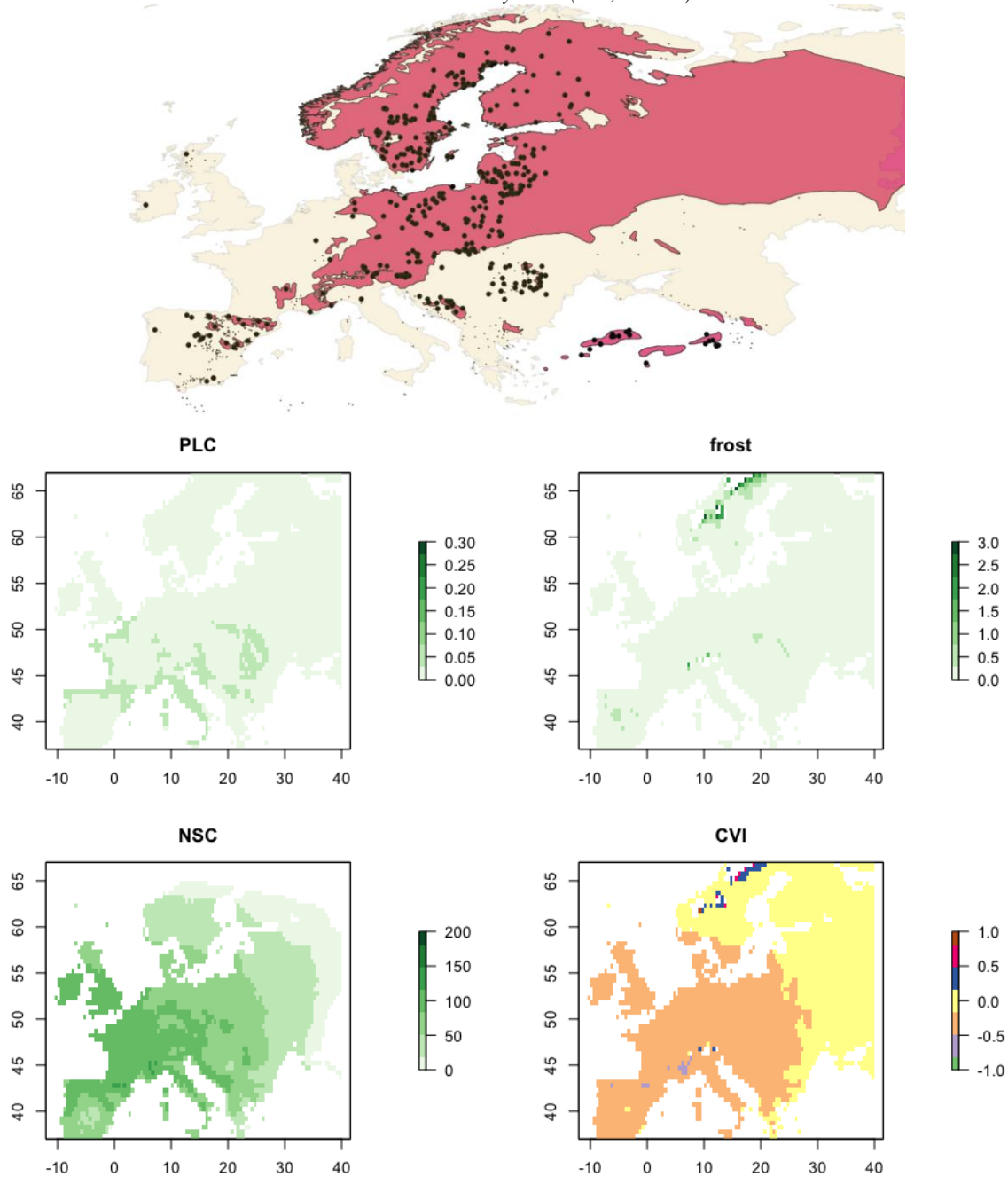


The model failed to simulate well the potential distribution of *Quercus petraea* (Figure 6) using the Non-Structural Carbon Content (NSC) due to frost effects in western Europe, maybe overestimated with the threshold value of zero degree used.

The model indicates potential habitat suitability for Scots pine (Figure 7) outside its current niche, particularly in Italy, in western France or in the Carpathians. These predictions are not unrealistic because locally we often find *Pinus sylvestris* in these areas.

The model clearly simulates a wider suitability of *Pinus pinaster* across Europe than its current distribution, but captures well the area where it is planted in southwestern France and northern Spain. This bias is probably due to the lack of winter frost effects in the model.

Figure 7. Risk associated to cavitation, late frost and carbon starvation of *Pinus sylvestris* across Europe for the period 1979 to 2008 Top left: species distribution area. Top: percentage of loss of conductance (PLC), Number of frost days (Frost), biomass of non-structural carbohydrate (NSC), Bottom: level of non-structural carbohydrate (NSC in $g \cdot m^{-2}_{soil}$) and combined Vulnerability Index (CVI, see text)



The model assess correctly the habitat suitability of *Picea abies* across Europe using NSC (Figure 9), except in western Europe maybe because we underestimate the drought effect. Its niche is limited by carbon starvation in the south and cavitation in eastern Europe.

Figure 8. Risk associated to cavitation, late frost and carbon starvation of *Pinus pinaster* across Europe for the period 1979 to 2008 Top left: species distribution area. Top: percentage of loss of conductance (PLC), Number of frost days (Frost), biomass of non-structural carbohydrate (NSC), Bottom: level of non-structural carbohydrate (NSC in $g \cdot m^{-2}_{soil}$) and combined Vulnerability Index (CVI, see text)

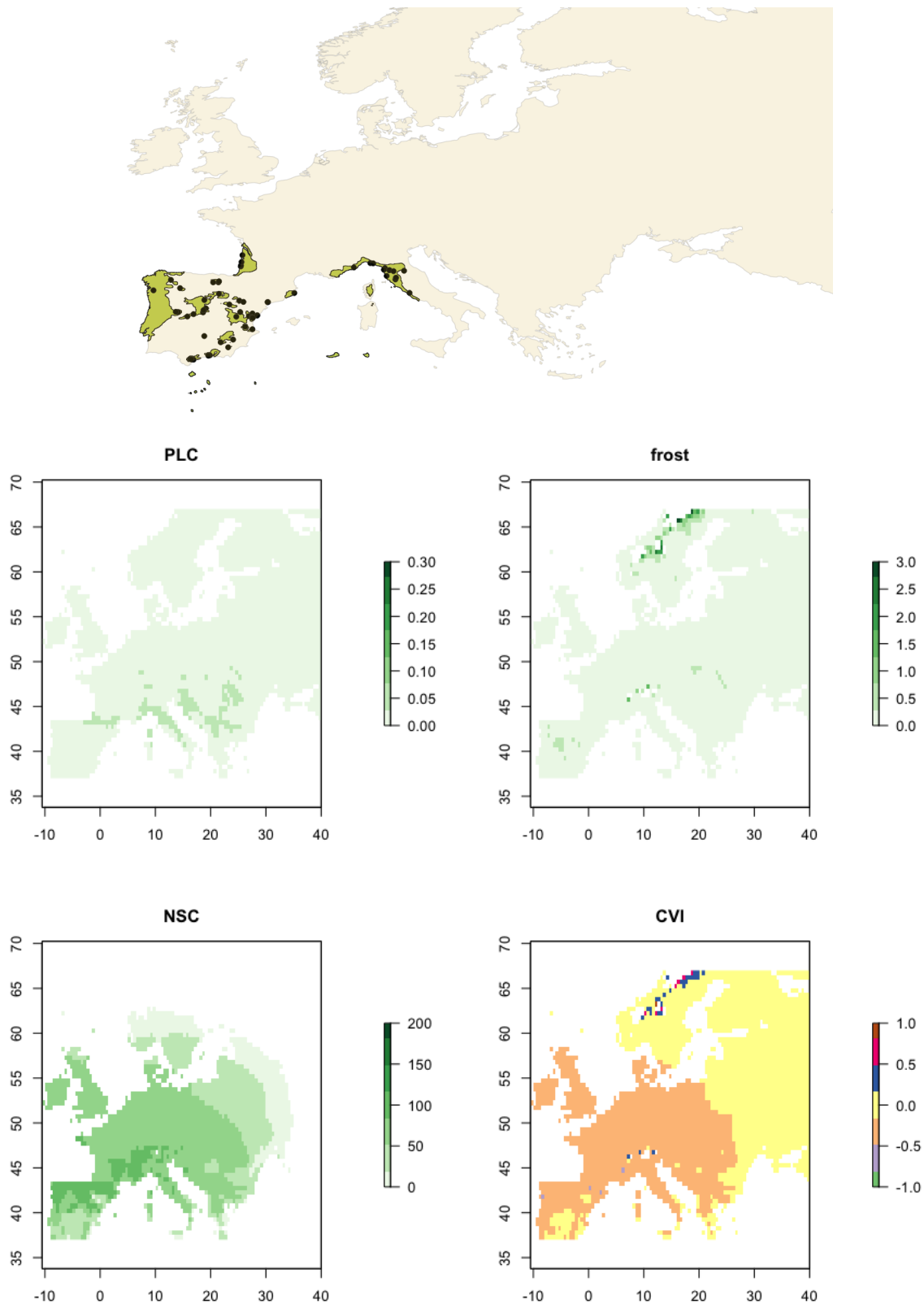
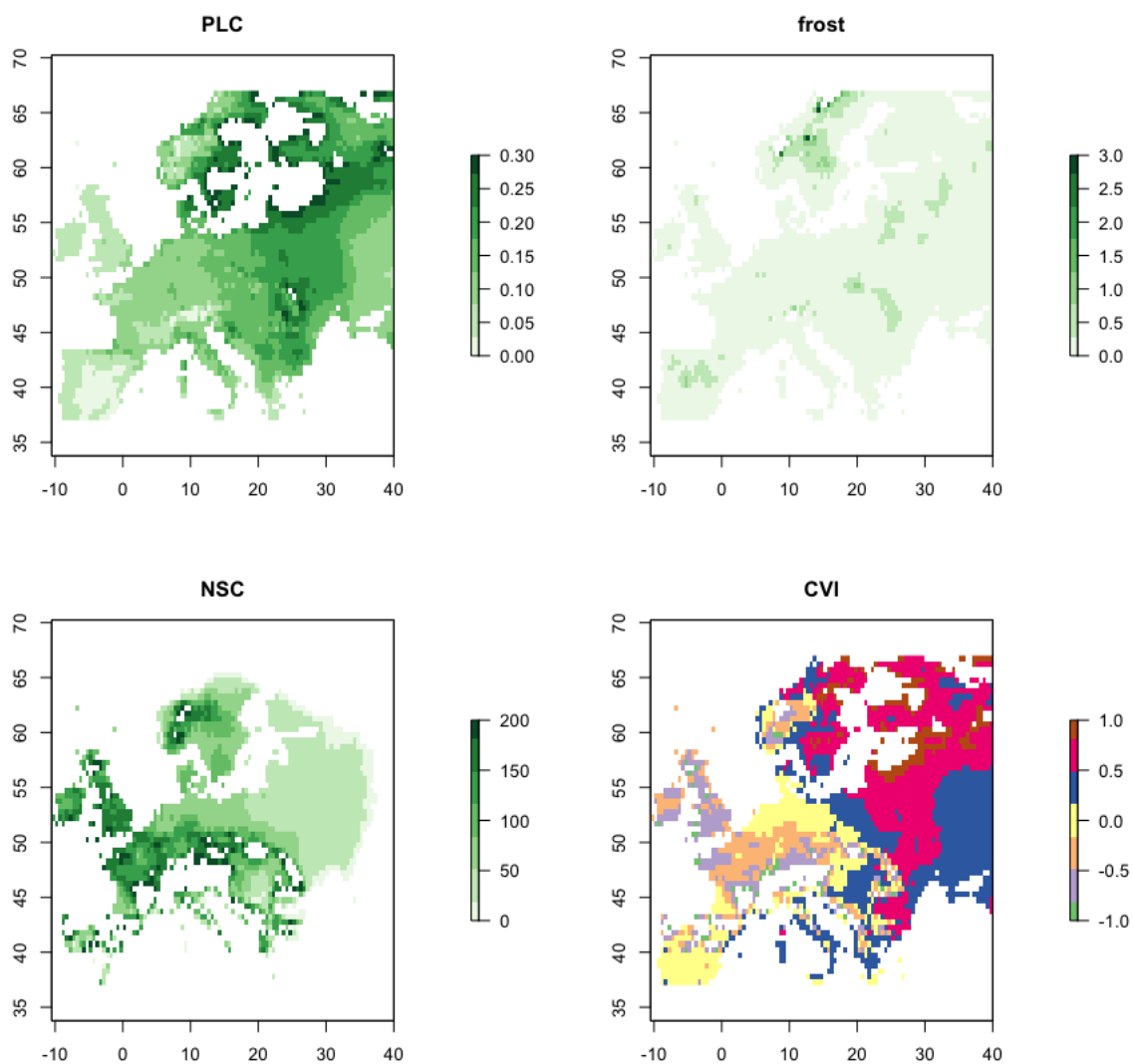
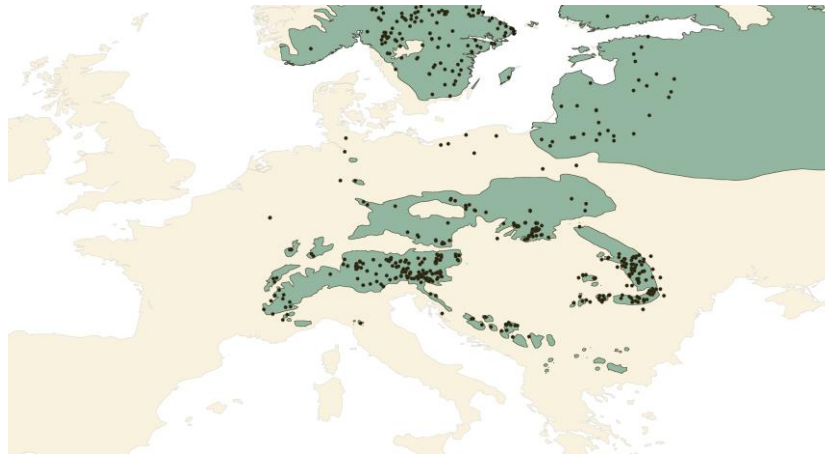


Figure 9. Risk associated to cavitation, late frost and carbon starvation of *Picea Abies* across Europe for the period 1979 to 2008 Top left: species distribution area. Top: percentage of loss of conductance (PLC), Number of frost days (Frost), biomass of non-structural carbohydrate (NSC), Bottom: level of non-structural carbohydrate (NSC in g.c. .m⁻² soil) and combined Vulnerability Index (CVI, see text)



According to the CVI index, on average since 1978 for all GCUs, *Fagus sylvatica* is currently the species most vulnerable in terms of cavitation, late frost and carbon starvation risks, followed by *Pinus sylvestris*, *Pinus Pinaster*, *Picea abies*

In beech and oak GCUs, the model predicts a lower vulnerability (lower CVI, i.e. lower risks of cavitation, late frost and carbon starvation) in scenario 8.5 (Table 2), due to a strong increase

in reserves (CO₂ fertilization effect and increasing vegetation length) and a decrease in the number of late frosts (data not shown). By contrast, the vulnerability will slightly increase in pine GCUs and remain very low in Spruce GCUs (Table 2).

Table 2: Combined Vulnerability Index on Genetic Conservation Units (GCU) for past or future scenarios (rcp=8.5) without (WS) or with silviculture (S)

Species	Past CVI (WS)	8_5 CVI (WS)
Fagus sylvatica	0.10	-0.19
Quercus petraea	-0.03	-0.55
Pinus sylvestris	-0.18	-0.06
Pinus pinaster	-0.27	-0.08
Picea abies	-0.56	-0.61

3.3 Incorporating forest management and ecosystem services into vulnerability scenarios

Including forest management in vulnerability scenarios had relatively small effects on the outcomes. In the case of *Pinus sylvestris*, for example, management reduced the leaf area index (LAI) from 5.63 to 4.56. This reduced the risk of cavitation (Figure 10), but it was already low without silviculture. Silviculture also improved the level of reserves in the southern part of the distribution range but decreased it in the northern part.

The overall vulnerability of GCUs measured by the CVI changed very little, from -0.0676 without silviculture to -0.0679 with silviculture on average across all GCUs. For beech, the beneficial effects of silviculture were even lower with almost no change in CVI (Figure 11). This lack of effects of management masks temporal dynamics that are different for the different species (Figure 12). Between 2006 and 2098, beech exhibited sharp declines in reserves (NSCs) punctually buffered by silviculture, while pine reserves declined steadily and silviculture, by increasing standing stocks, increased vulnerability.

Figure 10. Effect of silviculture on vulnerability and biomass production of *Pinus sylvestris* across Europe from 2006 to 2098 under rcp 8.5 using the Hadgem climate model Top: percentage of loss of conductance (PLC), Medium: biomass of non-structural carbohydrate (NSC in $g\cdot m^{-2}\text{ soil}$), Bottom: Combined Vulnerability Index. Left: without silviculture (WS) and right: with silviculture (S)

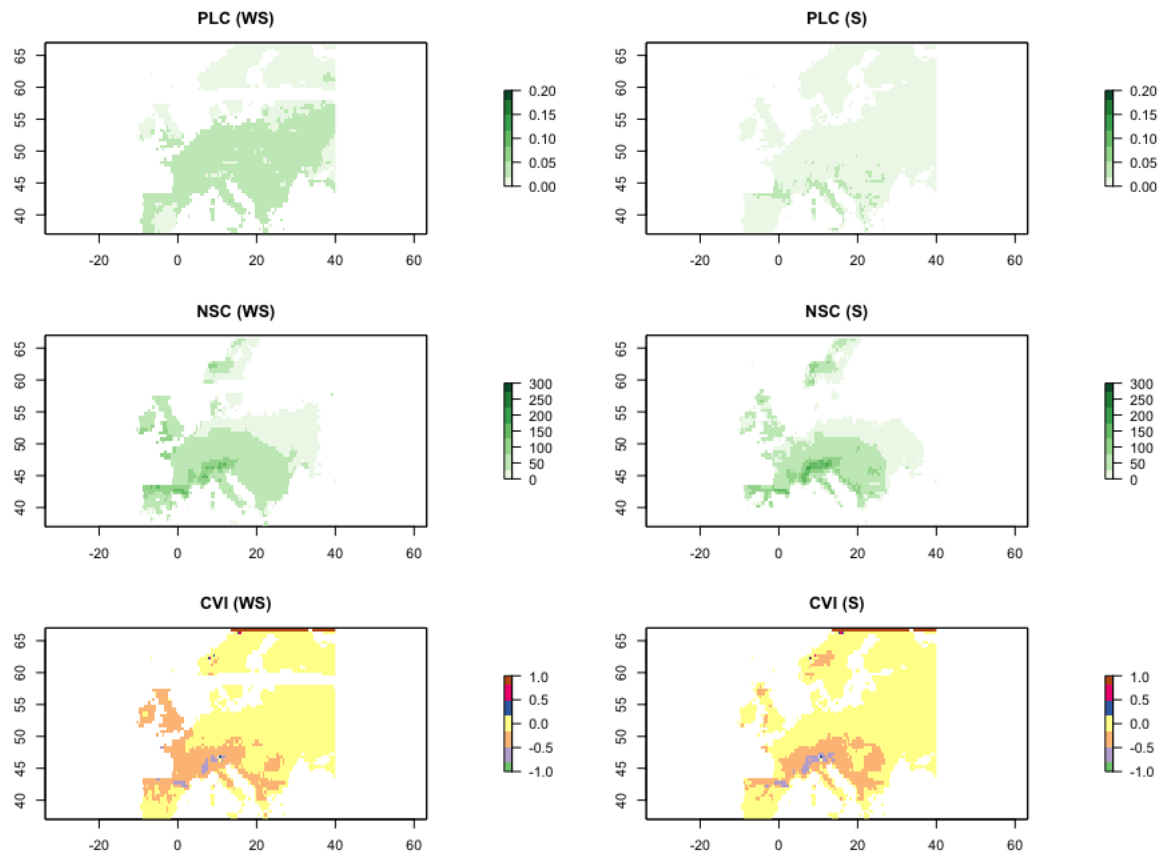


Figure 11. Effect of silviculture on vulnerability and biomass production of *Fagus sylvatica* across Europe from 2006 to 2098 under rcp 8.5 using the Hadgem climate model Top: percentage of loss of conductance (PLC), Medium: biomass of non-structural carbohydrate (NSC in $g\cdot c\cdot m^{-2}\cdot soil$), Bottom: Combined Vulnerability Index. Left: without silviculture (WS) and right: with silviculture (S)

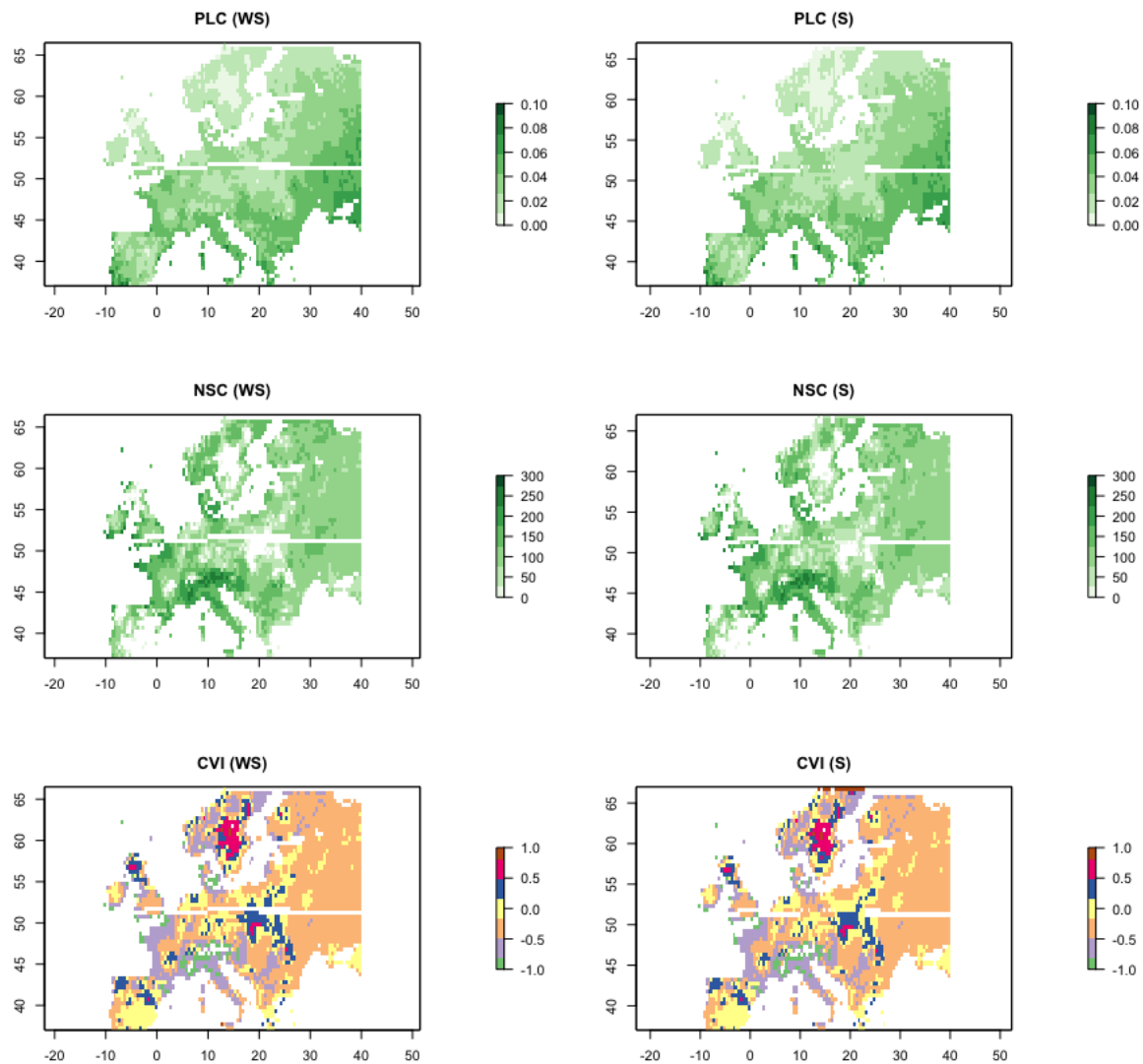
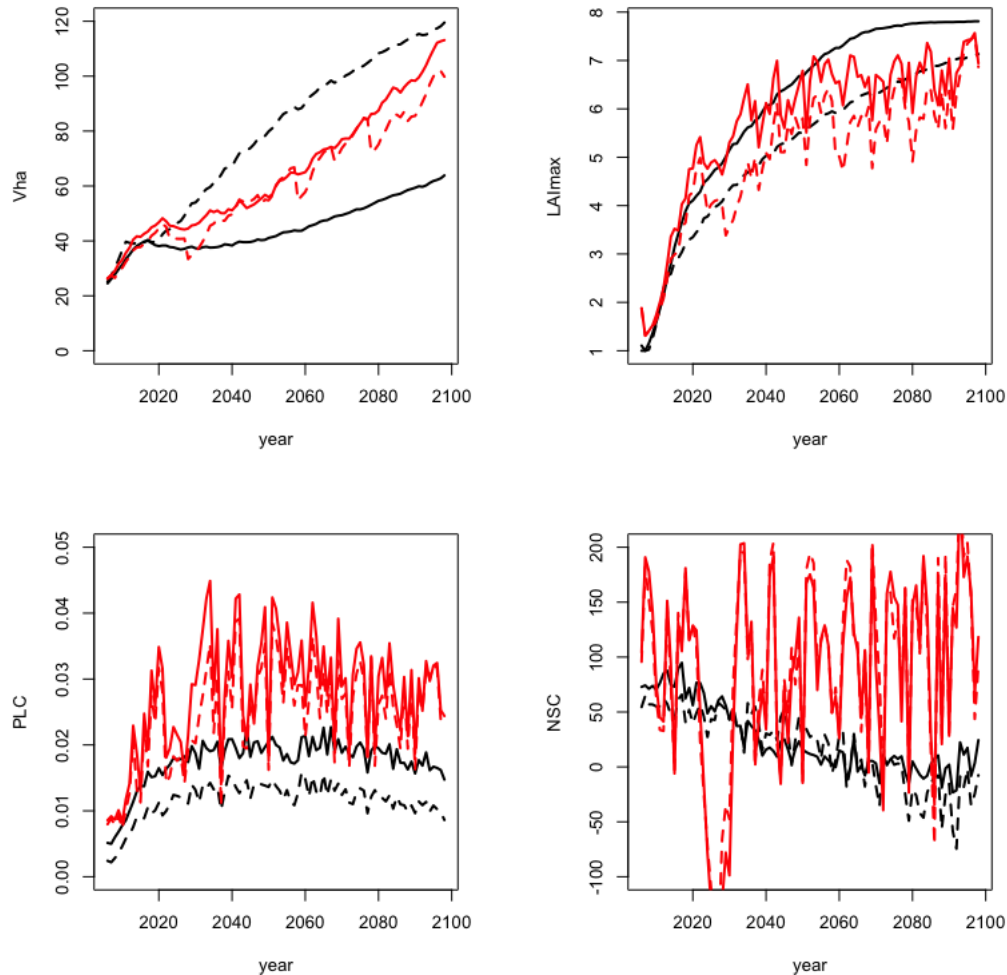


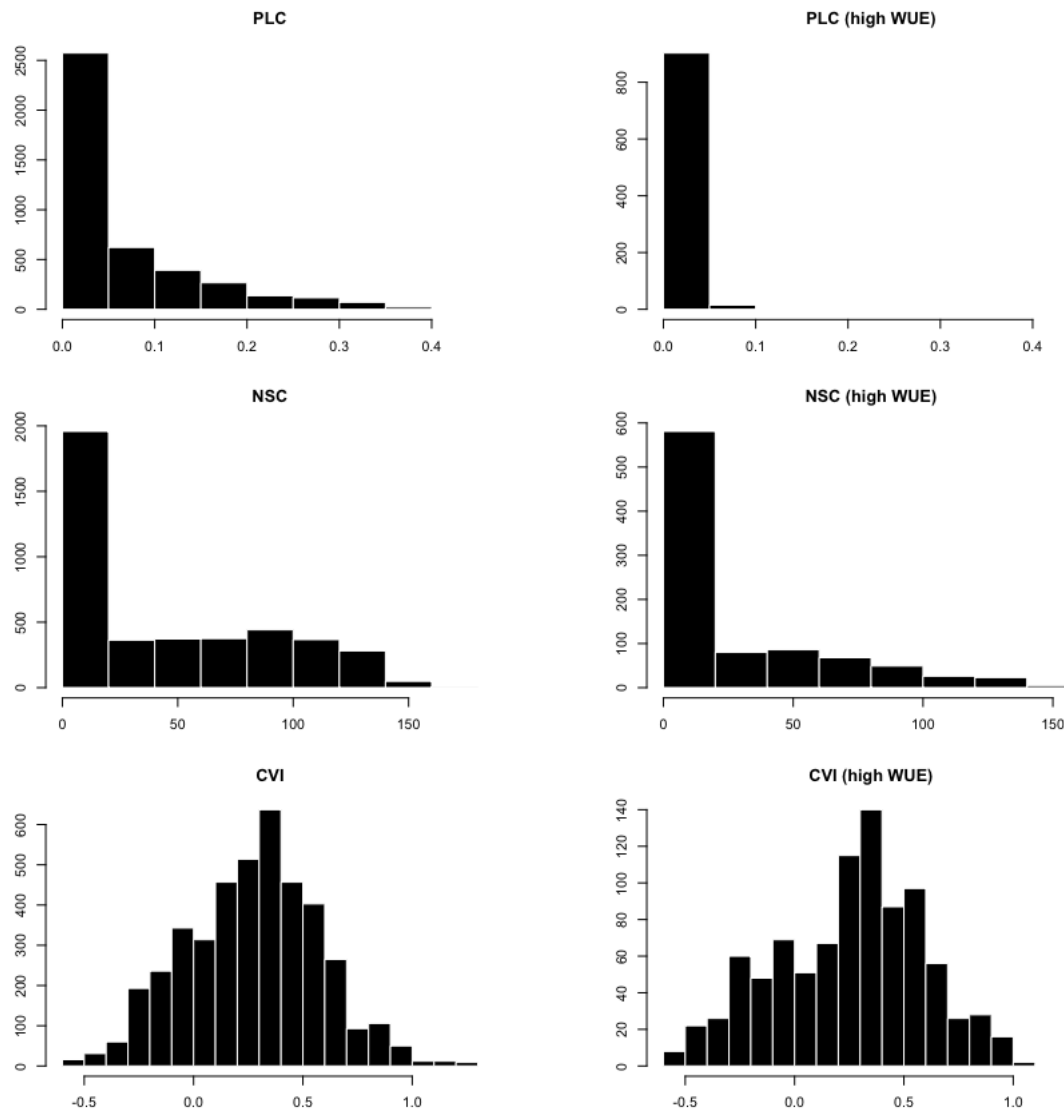
Figure 12. Average temporal dynamics of stand volume (V_{ha} $m^3 \cdot ha^{-1}$), Leaf Area Index (LAI_{max} $m^2 \text{leaves} \cdot m^{-2} \text{soil}$), percentage of loss of conductance (PLC) and biomass of non-structural (NSC in $g \cdot m^{-2} \text{soil}$) across Europe from 2006 to 2098 under rep 8.5 using the Hadgem climate model without silviculture (continuous line) and with silviculture (dashed line) for *Pinus sylvestris* (black) and *Fagus sylvatica* (red)



3.4 Investigating how management practices based on FGR can mitigate the vulnerability of major European tree species and their GCU networks

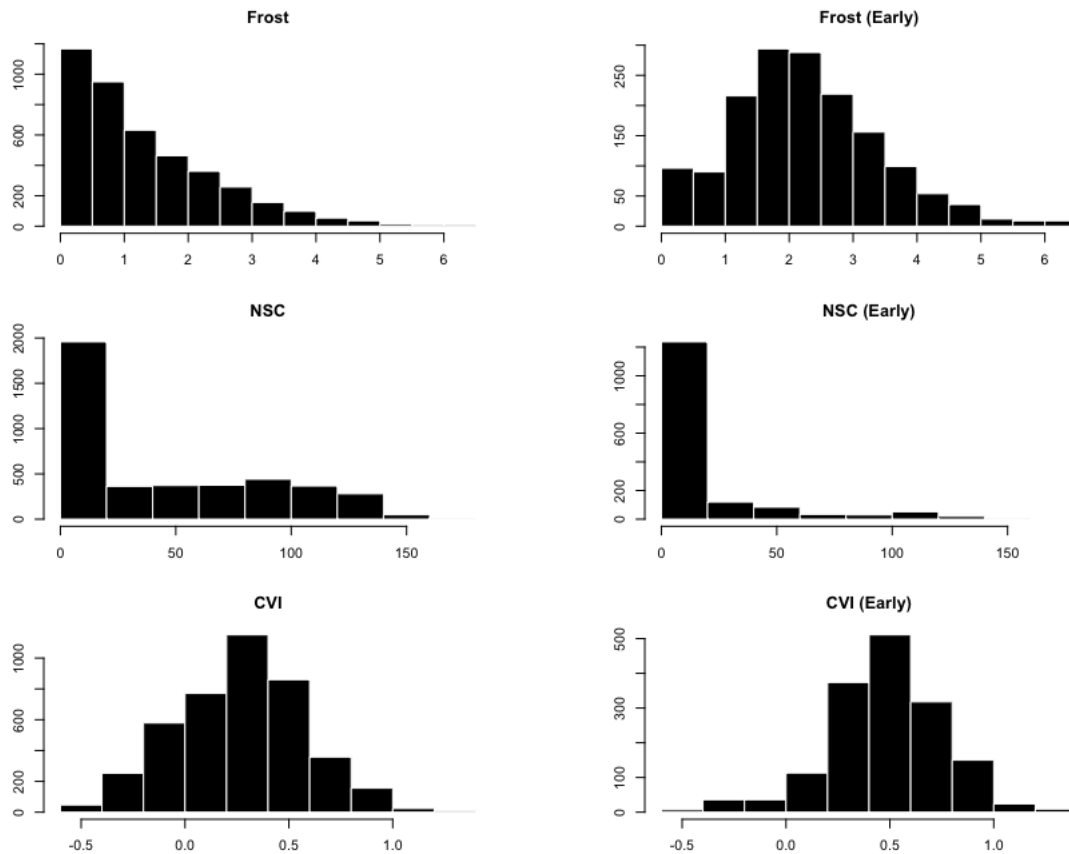
In this part, we have tried to test if using genotypes with early bud break or with a better water use efficiency (WUE) that are found in the southern part of the range of *Fagus sylvatica*, is likely to reduce the current vulnerability of GCUs. This is similar to an assisted migration strategy that would have used southern genotypes further north in the range of the species. We first focused on the potential detrimental effects of improved water use efficiency (WUE). In fact, a quicker closure of the stomata (high WUE and low G_{lmax} , see 5.2.4) makes it possible to avoid cavitation (PLC) but tends to decrease carbon reserves (NSC) in the long run. We assessed how high WUE genotypes will affect the vulnerability of *Fagus sylvatica* GCUs using a scenario without silviculture (Figure 13). Results show that using genotypes with higher WUE decreases the vulnerability of GCUs to cavitation (Figure 13 top), but the price to pay is a much lower NSC (Figure 13 medium). As a consequence, vulnerability for some GCUs decreases with genotypes displaying higher WUE, but for other GCUs by contrast, vulnerability will actually increase (Figure 13 bottom).

Figure 13. Effect the use of high WUE genotypes on the distribution of different vulnerability indices for *Fagus sylvatica* GCUs between 1979 to 2008. Top left: proportion of loss of conductance (PLC) for all genotypes, Top right: proportion of loss of conductance (PLC) for genotypes displaying high WUE. Medium left: Biomass of Non-Structural Carbon (NSC in $gc. .m^{-2}_{soil}$) for all genotypes, Medium right: Biomass of Non-Structural Carbon (NSC in $gc. .m^{-2}_{soil}$) for genotypes displaying high WUE. Bottom left: Combined Vulnerability Index (CVI) for all genotypes, Medium right: Combined Vulnerability Index (CVI) for genotypes displaying high WUE



Then, we focused on the potentially detrimental effects of earlier budburst. In fact, an early spring budburst (low TSUM and low BBDA_Y see 5.2.4) increases vegetation length and NSC but also tends to increase the risk of damage from additional frost days. We assessed how the earlier budburst genotypes will affect the vulnerability of *Fagus sylvatica* GCUs using a scenario without silviculture (Figure 14). The use of earlier budburst genotypes increases frost risk. Thus, NSC was not positively affected since the increase in vegetation length is compensated by frost damages (Figure 14 medium). As a consequence, the vulnerability of most of the GCUs increased by using earlier budburst trees (Figure 14 bottom).

Figure 14. Effect the use of earlier budburst genotypes on the distribution of different vulnerability indices for *Fagus sylvatica* GCUs between 1979 to 2008. Top left: number of frost days (Frost) for all trees, Top right: number of frost days for genotypes displaying earlier budburst (Frost Early). Medium left: Biomass of Non-Structural Carbon (NSC in $gc. .m^{-2}_{soil}$) for all genotypes, Medium right: Biomass of Non-Structural Carbon (NSC) for genotypes displaying earlier budburst. Bottom left: Combined Vulnerability Index (CVI) for all genotypes, Medium right: Combined Vulnerability Index (CVI) for genotypes displaying earlier budburst



3.5 Conclusion

In the first part of this work, we showed that the vulnerability of beech trees at the southern margin of their distribution area could be apprehended and modeled using a risk index combining the risks of late frost, carbon starvation and hydraulic failure. This is the first time that this type of index has been used to assess vulnerability in the broad sense.

In the second part of this deliverable, we showed, also for the first time, that Non-Structural Carbon (NSC) is a relevant and reliable indicator for accounting for species niche suitability. However, NSC does not incorporate all vulnerability risks. Thus we created a combined vulnerability index (CVI) which characterizes the vulnerability of GCUs to late frosts, carbon starvation and hydraulic failure, for the past and in the future.

Using CVI, we showed that whereas beech and oak GCUs are the most vulnerable under past climate, it is the pine forests that will be the most negatively impacted by climate change. The silvicultural management we tested can indeed reduce the risk of drought but does not reduce the overall vulnerability of GCUs. However, our vulnerability index may not correctly take into account all the positive effects of a relaxation of competition. In addition, and on average, silviculture decreases the standing biomass and thus the average NSC without, in principle, making the stand more vulnerable to climate change.

Finally, in the last part of the deliverable, we tested, again for the first time, if transferring genetic material to mitigate the effect of climate change is an effective strategy. We showed that neither the use of water-efficient nor of early-unfolding genotypes make it possible to

significantly reduce the vulnerability of all stands, but only in specific cases. Thus, thinning and assisted migration have sometimes significant but low overall positive effect in mitigating vulnerability.

4 Partners involved in the work

EFI, INRA

5 Appendices

5.1 References

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5.2 Material and methods

We detail below the material and methods used to achieve objectives 2 to 4.

5.2.1 Climate data and scenarios

We used the Water and Global Change (**WATCH**)-**Forcing-Data-ERA-Interim** as a past climate (**Weedon et. al, 2014**). It is a meteorological forcing dataset extending into early 21st century (1979 – 2008) around the world at half-degree land grid points (0.5°*0.5°).

In order to take into account the uncertainties of future climate evolution, according to **McSweeney et al (2014)**, we used two climate models from EURO-CORDEX community (**Jacob et al 2014**), with rcp8 using HadGEM2-ES model. A bias correction and downscaling was performed using an anomaly method with R package “meteoland” (**De Cáceres et al. 2017**). The WATCH dataset was used as reference data.

5.2.2 Soil data

To simulate the variability of soil water capacity across Europe, we used the SoilGrids250m and the 3D soil hydraulic database (**Hengl et al 2017, Tóth et al 2017**). Both databases were aggregated from 1km resolution to 0.5°*0.5° with the R package “raster” (**Hijmans, 2016**). Then, the median value was extracted in each climate grid point. Soil depth prediction was modified to be consistent at least with soil depth measurement in France.

Table a1: List of climate and soil variables used for CASTANEA simulations

Daily climate variables	units	soil hydraulic variables	soil grid variables	Final units
Mean Temperature	°C	Water content at field capacity	Bulk density	g/cm ³
Max Temperature	°C	Water content at wilting point	Clay content	weight %
Min Temperature	°C		Silt content	weight %
Wind speed	m/s		Sand content	weight %
Relative humidity	%		Depth to bedrock	mm
Precipitation	mm		Coarse fragments	volumetric %
Radiation	MJ/m ²			

5.2.3 Forest management scenarios

Current scenarios

Current management practices were defined on the basis of harvest rules and regeneration methods proposed in Härkönen et al. (2019). We considered five possible silvicultural systems (SS):

- **SS1. No management.** No harvests nor regeneration was applied.
- **SS2. Even-aged forest management with shelterwood.** The main tree crop was simulated. The last thinning was defined as a shelterwood thinning. At the final cut we assumed that there was a new regenerated crop of trees of age specified for each region and species.
- **SS3. Even-aged forest management with clearcut.** After clearcut a new stand was planted the following year. Simulation started when the trees reached breast height, which took different lengths of time depending on the region and species.
- **SS4. Short rotation.** There were no thinnings, and the final cut was done at an early age, followed by planting (and assumed fertilisation to maintain nutrient balance).

Coppice was not simulated as Härkönen et al. (2019) report that harvesting rules are the same as SS3 (Even-aged forest management with clearcut) for the species under consideration. The only difference is that, roots remain after cutting and planting is not needed.

Harvesting rules were adapted from Härkönen et al. (2019) and varied among the five species and four ecoregions (North, Central East, Central West, South) They are detailed in Tables a2. below.

The shares of each silvicultural system at each grid point was derived from the EFISCEN database (Table a2).

Table a2. Harvesting rules in northern Europe (3 scenario files + No Management)

		Species	
		Pinus sylvestris & Picea abies	Quercus petraea & Fagus sylvatica
Silvicultural system	1	No management	
	2	Not applied	Thinnings: (Age 10,30, 50) if (H<20 & BA> -0.0179*H ² + 1.2214*H + 3.7714) : BA = - 0.0536*H ² + 2.4643*H - 12.886 if BA> 21: BA = 15 Final cutting: if (age =90): BA = 0
	3	Thinnings: (Age 10,25,65) if SWC > 100: if (H<20 & BA> -0.0893*H ² + 4.0071*H - 11.343): BA = -0.0536*H ² + 2.7643*H - 9.6857 else if BA> 33: BA = 24 if 100 > SWC > 60 if (H<20 & BA> -0.125*H ² + 4.95*H - 20.9): BA = -0.1071*H ² + 3.9286*H - 15.771 else if BA>28: BA = 20 if SWC < 60 if (H<20 & BA> -0.1071*H ² + 4.2286*H - 15.571): BA = -0.0714*H ² + 2.7857*H - 9.1143 else if BA>26: BA = 18 Final cutting: if (age = 85): BA = 0	Thinnings: (Age 10,30, 50) if (H<20 & BA> -0.0179*H ² + 1.2214*H + 3.7714) : BA = - 0.0536*H ² + 2.4643*H - 12.886 if BA> 21: BA = 15 Final cutting: if (age =70): BA = 0
	4	-	
	5	Each year: average annual values from 100 years of BAU management for that plot	

Table a2. Harvesting rules in East Central Europe (5 scenario files + No Management)

		Species group			
		<i>Pinus sylvestris</i>	<i>Picea abies</i>	<i>Quercus petraea</i>	<i>Fagus sylvatica</i>
Silvicultural system	1	No management			
	2	Thinnings: (Age 10, 25, 65, 80) if BA>10: $BA = 0.01432 \cdot H^3 - 0.6149 \cdot H^2 + 9.0863 \cdot H^1 - 22.5383$ if H>22: BA=30 Final cutting: if Age=100: old forest is cut, new trees of age 10 remain	Thinnings: : (Age 10, 25, 65, 80) if BA>10: $BA = -0.0004495 \cdot H^3 - 0.06473 \cdot H^2 + 3.5777 \cdot H^1 - 8.629$ if H>22: BA = 33 Final cutting: if Age=100: old forest is cut, new trees of age 10 remain	Thinnings: (Age 10, 30,60) if BA>10: $BA = 0.002678 \cdot H^3 - 0.1426 \cdot H^2 + 3.075 \cdot H^1 - 1.927, BA)))$ if H>22: BA = 26 Final cutting: if Age=80: old forest is cut, new trees of age 10 remain	Thinnings: (Age 10, 30,60) if BA>10: $BA = 0.0003842 \cdot H^3 - 0.02163 \cdot H^2 + 1.258 \cdot H^1 + 3.508, BA)))$ if H>29: BA = 30 Final cutting: if Age=80: old forest is cut, new trees of age 10 remain
	3	Thinnings: (Age 10, 25, 65) if BA>10: $BA = 0.01432 \cdot H^3 - 0.6149 \cdot H^2 + 9.0863 \cdot H^1 - 22.53$ if H>22: BA=30 Final cutting: if Age=80: BA=0. New seedlings assumed to be planted next year.	Thinnings: (Age 10, 25, 65) if BA>10: $BA = -0.0004495 \cdot H^3 - 0.06473 \cdot H^2 + 3.5777 \cdot H^1 - 8.629$ if H>22: BA = 33 Final cutting: if Age=80: BA=0. New seedlings assumed to be planted next year.	Thinnings: (Age 10, 30, 50) if BA>10: $BA = 0.002678 \cdot H^3 - 0.1426 \cdot H^2 + 3.075 \cdot H^1 - 1.927, BA)))$ if H>22: BA = 26 Final cutting: if Age=60: BA=0. New seedlings assumed to be planted next year.	Thinnings: (Age 10, 30, 50) if BA>10: $BA = 0.0003842 \cdot H^3 - 0.02163 \cdot H^2 + 1.258 \cdot H^1 + 3.508, BA)))$ if H>29: BA = 30 Final cutting: if Age=60: BA=0. New seedlings assumed to be planted next year.
	4	Final cutting: if Age=25, BA = 0			
	5	Each year: average annual values from 100 years of BAU management for that plot			

Table a2. Harvesting rules in West Central Europe (11 scenario files + No Management)

Species		<i>Pinus sylvestris</i>	<i>Picea abies</i>	<i>Pinus pinaster</i>	<i>Quercus petraea</i>	<i>Fagus sylvatica</i>
Silvicultural system	1	No management				
	2	<u>Thinnings: (Age 30,50,60)</u> if age>=30: BA = 15.7 if age>=35 D>11.9: BA = 20 if age>=50 D>17: BA = 23 if age>=60 D>19.9: BA = 23 <u>Final cutting:</u> if age>=85: old forest is cut, new trees of age 10 remain	<u>Thinnings: (Age 30,50, 70)</u> if age>=25: BA = 20.15 if age>=40 D>23.4: BA = 25 if age>=60 D>31.6: BA = 30 if age>=80 D>36.8: BA = 35 <u>Final cutting:</u> if age>=85: old forest is cut, new trees of age 10 remain	<u>Final cutting:</u> if age>=60 D>50: BA = 0	<u>Thinnings: (Age 30,60,80)</u> if age>=25: BA = 10.02 if age>=35 D>11.5: BA = 13 if age>=55 D>19.5: BA = 17 if age>=80 D>30.3: BA = 19 <u>Final cutting:</u> if age>=95: old forest is cut, new trees of age 10 remain	<u>Thinnings: (Age 30,60,80)</u> if age>=30: BA = 12.66 if age>=35 D>23.4: BA = 16 if age>=60 D>31.6: BA = 21 if age>=100 D>36.8: BA = 24 <u>Final cutting:</u> if age>=105: old forest is cut, new trees of age 10 remain
	3	<u>Thinnings: (Age 30,50,60)</u> if age>=30: BA = 15.7 if age>=35 D>11.9: BA = 20 if age>=50 D>17: BA = 23 if age>=60 D>19.9: BA = 23 <u>Final cutting:</u> if age>=85: BA=0. New seedlings assumed to be planted next year.	<u>Thinnings: (Age 30,50, 70)</u> if age>=25: BA = 20.15 if age>=40 D>23.4: BA = 25 if age>=60 D>31.6: BA = 30 if age>=80 D>36.8: BA = 35 <u>Final cutting:</u> if age>=85: BA=0. New seedlings assumed to be planted next year.	<u>Final cutting:</u> if age>=60 D>50: BA=0. New seedlings assumed to be planted next year.	<u>Thinnings:</u> if age>=25: BA = 10.02 if age>=35 D>11.5: BA = 13 if age>=55 D>19.5: BA = 17 if age>=80 D>30.3: BA = 19 <u>Final cutting:</u> if age>=95: BA=0. New seedlings assumed to be planted next year.	<u>Thinnings:</u> if age>=30: BA = 12.66 if age>=35 D>23.4: BA = 16 if age>=60 D>31.6: BA = 21 if age>=100 D>36.8: BA = 24 <u>Final cutting:</u> if age>=105 BA=0. New seedlings assumed to be planted next year.
	4			<u>Final cutting:</u> if age>25, BA = 0		
	5	Each year: average annual values from 100 years of BAU management for that plot				

Table a2. Harvesting rules in Southern Europe (5 different scenario files + No Management)

		Species				
		Pinus sylvestris	Picea abies	Pinus pinaster	Quercus petraea	Fagus sylvatica
Silvicultural system	1	No management				
	2		Thinnings: (Age 30,70,90,100) if (age>=30 BA>30): N = 700 if age>=70 BA>40): N = 400 Final cutting: if (age>120 BA>50): N = 0	Thinnings: (Age 20,40,60) if (age>=15): N = 1000 if (age>=20 D>20): N = 850 if (age>=40 D>24): N = 700 if (age>=60 D>30): N = 500 Final cutting: if ((age>=60 & D>=30) BA>50): N = 0	Thinnings: (Age 40,60,80,100) if (age>=40 D>=21): N = 500 if (age>=60 D>=35): N = 370 if (age>=80 D>=37): N = 290 if (age>=100 D>=40): N = 255 Final cutting: if (age>=120 D>=42 BA>50): N = 0	Thinnings: (Age 40,60,80,100) if (age>=40 D>=20): N = 550 if (age>=60 D>=30): N = 400 if (age>=80 D>=39): N = 360 if (age>=100 D>=46): N = 300 Final cutting: if (age>=120 D>53 BA>50): N = 0
	3	Thinnings: (Age 20, 40,60,80) if (H>=11): N = 550 if (H>=25): N = 300 Final cutting: if (age>100 BA>50): N = 0				
	4	if (age >= 15): N = 0	if (age >= 15): N = 0	if (age >= 15): N = 0	if (age >= 15): N = 0	if (age >= 15): N = 0
	5	Each year: average annual values from 100 years of BAU management for that plot				

Future scenarios of forest management

To consider future management practices, we first developed scenario storylines in the framework of the plausible futures of the European forestry sector that are predicted and published by the UNECE FAO section (European Forest Sector Outlook Study II – EFSOS II; FAO, 2011). We derived three possible narratives (Table a3).

Table a3: Scenario storylines

Name	Description
Reference scenario	This scenario assumes that current management practices are largely maintained; it assumes no changes in tree species composition and assumes a continuation of current regeneration methods and cutting regimes. This scenario does not assume a continuation of current trends in forest management practices, but serves to be able to assess impacts of the alternative forest management scenarios.
Enhanced nature-oriented management scenario	This scenario assumes that recent developments towards more nature-oriented management methods in Central parts of Europe will be gradually practiced in all parts of Europe. Compared to the Reference scenario, this scenario assumes: <ul style="list-style-type: none"> • a strong shift towards mixed and broadleaved-dominated forests, • a strong focus on natural regeneration methods • an increased focus on continuous cover forestry and shelterwood systems over even-aged clear-cut systems.
Enhanced adaptation scenario	The enhanced adaptation scenario assumes that forest owners are increasingly aware of the need to adapt the management of forests to climate change to ensure the health and resilience of European forests in the future. Compared to the Reference scenario, this scenario assumes: <ul style="list-style-type: none"> • a strong shift towards mixed and broadleaved-dominated forests; • a strong focus on assisted migration using artificial regeneration methods using improved breeding material, site-adapted tree species and introduction of more southern provenances; • intensified thinning; • shortened rotation lengths.

The long-term objectives are to investigate the scenarios developed in Table a4 below. In a first step, however, we only compared the reference scenario with a simplified enhanced adaptation scenario, where we did not change the thinning and cutting regimes rules, but simply considered that assisted migration was used.

Table a4: Scenario settings

Management decision	Reference scenario	Enhanced nature-oriented management scenario	Enhanced adaptation scenario
Tree species composition	<ul style="list-style-type: none"> No change in tree species composition 	<ul style="list-style-type: none"> Regenerate 25% of Norway spruce dominated forests by beech in Central Europe Increase share of pedunculate oak in Scots pine-dominated forests Central Europe by 25%-points 	<ul style="list-style-type: none"> Regenerate 25% of Norway spruce dominated forests by beech in Central Europe Increase share of pedunculate oak in Scots pine-dominated forests Central Europe by 25%-points
Provenance selection	<ul style="list-style-type: none"> No change in provenance selection 	<ul style="list-style-type: none"> No change in provenance selection 	<ul style="list-style-type: none"> Assisted migration through increased share of southern provenances
Regeneration method	<ul style="list-style-type: none"> No change in regeneration methods 	<ul style="list-style-type: none"> Increased share of natural regeneration by 25% 	<ul style="list-style-type: none"> Increased share of artificial regeneration by 25% points by 2050 and 50% points by 2100
Thinnings	<ul style="list-style-type: none"> Thinning as defined by Härkönen et al. (2019) 	<ul style="list-style-type: none"> Stronger reductions in BA during thinning to increase stand diversity, implemented by reducing BA by an additional 10% compared to the resulting BA defined by Härkönen et al. (2019) 	<ul style="list-style-type: none"> Stronger reductions in BA during thinning to reduce drought stress, implemented by reducing BA by an additional 10% compared to the resulting BA defined by Härkönen et al. (2019)
Rotation length	<ul style="list-style-type: none"> Target diameters as defined by Härkönen et al. (2019) 	<ul style="list-style-type: none"> Target diameters as defined by Härkönen et al. (2019) 	<ul style="list-style-type: none"> Shorter rotation cycles, implemented by starting final harvest by a 10% smaller BA as defined by Härkönen et al. (2019)
Cutting regime	<ul style="list-style-type: none"> Shares of unmanaged forests, continuous cover, even-aged with clear-cut and even-aged with shelterwood as defined by Härkönen et al. (2019) (no consideration of coppice or short rotation) 	<ul style="list-style-type: none"> Share of unmanaged forests as defined by Härkönen et al. (2019) Share of continuous cover increased by 20%-points Share of even-aged with clear-cut reduced by 40%-points Share of even-aged with shelterwood increased by 20%-points 	<ul style="list-style-type: none"> Shares as defined in Reference scenario

Timing of change	• No applicable	• Management change starting from 2020	• Management change starting from 2020
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5.2.4 Accounting for adaptive traits variability within and among populations

We accounted for the genetic variability in three major adaptive traits: (1) the date of budburst (TBB), related to vulnerability to late frosts, (2) the percentage of loss of conductance (PLC), related to vulnerability to cavitation and (3) water use efficiency (WUE), related to vulnerability to carbon starvation. The variability of these three traits is shaped both by environmental variability and by genetic variability. By explicitly considering the environmental variability in climate and soil properties across Europe, CASTANEA basically simulates the environmental component of variation in these adaptive traits. By contrast, the genetic component of the variation is usually neglected, and the key CASTANEA parameters controlling these adaptive traits are considered as fixed both within and among populations (Table X). We detail below for each trait the choice of the parameter for which we explicitly introduced variability as well as the data we used to do so.

Table a5: The plastically and genetically variable adaptive traits considered in this study, and their source of variation.

Adaptive trait	Code	Environmental drivers in Castanea	Genetic component in Castanea	Source of variation in literature
Date of budburst	TBB	Temperature	F _{CRITBB} , the sum of temperature required for budburst	Latitude
Percentage of loss of conductance	PLC	Temperature and precipitations	The Slope of the relationship between soil water potential and PLC	
water use efficiency	WUE	Temperature and precipitations	g _{lmax} , the slope of the relationship between assimilation and conductance.	Drought index

Model for TBB: In CASTANEA, the timing of budburst (TBB) is usually simulated following (eq. 9- 11 in Dufrêne et al. 2005):

$$R_{frcBB} = \begin{cases} T - T_2 & \text{if } T > T_2 \text{ and } N > N_{start1} \\ 0 & \text{if } T \leq T_2 \text{ or } N < N_{start1} \end{cases} \quad (\text{Eq 1})$$

where R_{frcBB} is the rate of forcing for bud break, T the mean daily temperature, T_2 the base temperature, N the day of year and N_{START1} the date of onset of rest.

$$S_{frcBB} = \sum_{N_{START1}}^N R_{frcBB} \quad \text{if} \quad S_{frcBB} < F_{critBB} \quad (\text{Eq 2})$$

$$TBB = N \quad \text{if} \quad S_{frcBB} \geq F_{critBB} \quad (\text{Eq 3})$$

with S_{frcBB} the state of forcing, F_{critBB} the critical value of state of forcing for the transition from quiescence to the active period and TBB the day when bud break occurred. Note that T_2 , N_{start1} and F_{CRITBB} are parameters, while R_{frcBB} , S_{frcBB} and TBB are dynamic variables of CASTANEA.

The simple one-phase phenological sub-model described by the equations 1-3 assumes that the variation in TBB is driven only by forcing temperatures; this hypothesis should be considered with caution in other cases. Note that diverse refined phenology models (including chilling) were recently integrated from Phenofit into CASTANEA, and could allow different hypotheses to be made.

Here, we considered that the parameter $F_{critTBB}$ could vary genetically among populations, and we used the study of (Kramer et al., 2017) to calibrate $F_{critTBB}$ values across Europe. Based on several beech provenance tests across Europe, this study investigated the variation of several phenological parameters, including $F_{critTBB}$ among provenances. A significant effect of the latitude of provenance was found on $F_{critTBB}$. Moreover, the INRA experiments on Mont Ventoux (France) allowed to estimate the variance of TBB within population ($\sigma^2_{BBday}=25$). Using this information, we considered in the simulation that:

The mean value of $F_{critTBB}$ for beech is 245°C, and the within-population range of variation around this mean value is always [-75°C; +75°C], which correspond to an average within-population standard deviation in TBB of 5. The mean $F_{critTBB}$ values vary linearly among populations with latitude, following the relationships: $MeanF_{critTBB} = a + b \cdot \text{latitude}$, $a=232$; $b=0.258$

TBB increases with increasing $F_{critTBB}$, as summarized by each regression line; moreover, the variation along each regression line corresponds to among-year variation in TBB for a given $F_{critTBB}$ -value. Also, the TBB values vary among grid points because of the average climatic variation among grid points.

Model for WUE: water use efficiency (WUE) can be defined at leaf level as the ratio of assimilation (A) to stomatal conductance (g_{sH_2O}):

$$WUE_i = A / g_{sH_2O} \text{ (Eq 4)}$$

In CASTANEA, three main equations determine assimilation A and g_{sH_2O} (eq 1,2 and 4 in Dufrêne *et al.* 2005), following the model from Ball *et al.* (1987).

First the carbon dioxide demand is:

$$A = V_C - R_d \text{ (Eq 5)}$$

where V_C is the carboxylation rate and R_d the respiration during the night.

Second, the carbon dioxide supply is:

$$A = g_{sCO_2} (C_s - C_l) \text{ (Eq 6)}$$

where g_{sCO_2} is the stomatal conductance for CO_2 and $(C_s - C_l)$ the gradient of CO_2 between evaporative site and leaf surface.

Third, the carbon dioxide control which allows the calculation of g_{sH_2O} is:

$$g_{sH_2O} = \frac{g_0 + g_1 \times A \times RH}{C_s} \text{ (Eq 7)}$$

where RH is the relative humidity in the surrounding air, g_1 depends on soil water stress and g_0 correspond to cuticle conductance of the leaf.

Re-arranging eq 7 shows that g_1 , the slope of the relation between photosynthesis and stomatal conductance, is inversely related to WUE :

$$\frac{A}{g_{sH_2O} - g_0 / C_s} = \frac{C_s}{g_1 \times RH} \text{ (Eq 8)}$$

Assuming $g_{sH_2O} \gg \frac{g_o}{C_s}$, the higher g_1 is, the lower WUE will be.

In CASTANEA, g_1 is assumed to decrease linearly when soil water storage decreases. The effect of soil water stress on photosynthesis is mediated through g_1 :

$$g_1 = (g_{1max} - g_{1min}) \times \text{reduc} + g_{1min}. \text{ (Eq 9)}$$

Where g_{1max} and g_{1min} are the maximal and minimal values taken by g_1 , and “reduc” is a soil water stress index varying between 0 (maximal soil water stress) and 1 (no water stress).

Here, we considered that the parameter g_{1max} could vary genetically among populations, and we used the study of (Hajek, Kurjak, von Wühlisch, Delzon, & Schuldt, 2016) to calibrate g_{1max} values across Europe. Based on ten beech provenance tests across Europe, this study investigated the variation of several physiological traits, including $\delta^{13}C$ among provenances. $\delta^{13}C$ is an indicator of WUE simulated in CASTANEA. A significant effect of the aridity index (FAI) at the provenance site was found on $\delta^{13}C$. Moreover, they estimated the standard deviation of $\delta^{13}C$ within population ($\sigma_{\delta^{13}C} = 0.263$). Based on this information, we considered in the simulation that :

- The mean value of g_{1max} for beech is 11.8, and the within-population range of variation around this mean value is always [-3.8; +3.8], which correspond to an average within-population standard deviation in $\delta^{13}C$ of 0.263.
- The mean g_{1max} values varies linearly among population with FAI

Model for PLC: The PLC depends on xylem pressure through a sigmoid function:

$PLC = 100 / (1 + \exp(\text{slope} / 25 \times (P - P50)))$, where $P50$ (MPa) is the xylem pressure inducing a 50% loss of hydraulic conductivity and slope (% MPa⁻¹) is the slope of the curve.

Assuming that $P50 = -3.175$ MPa in beech, we considered that the slope parameter could vary genetically among populations, and we used the study of (Stojnić et al., 2018) to calibrate slope values across Europe. Based on 15 beech provenance tests across Europe, this study investigated the variation of $P50$, $P88$, slope and conductance among provenances. The slope was found to vary significantly as a function of the latitude, longitude, altitude and climate of the provenance of origin. Based on these information, we considered in the simulation that:

- The mean value of *slope* for beech is 60, and the within-population range of variation around this mean value is always [-10; +10]

5.3 CASTANEA simulations plan

Step/Objective 2

Species	Climate scenario	Climate model	Silviculture
Fagus sylvatica	Current	Hadgem	Unmanaged forests
Quercus petrae	Future RCP 4.5	CM5	
Picea abies	Future RCP 4.5		
Pinus sylvestris			
Pinus pinaster			

5 species × 3 climate scenarios × 2 climate model × 3174 grid points = 95220 simulations

Step/Objective 3

Species	Climate scenario	Climate model	Silviculture
Fagus sylvatica	Current	Hadgem	Even-aged forest management with shelterwood
Quercus petrae	Future RCP 4.5	CM5	Even-aged forest with clear-cut
Picea abies	Future RCP 4.5		Short rotation
Pinus sylvestris			(Continuous cover forest management)*
Pinus pinaster			(Unmanaged forests)**

* Derived from silviculture SS2 and SS3

** Already simulated for Step 2

5 species × 3 climate scenarios × 2 climate model × 3174 grid points × 3 Silviculture = 285660 simulations

Step/Objective 4 (only Fagus sylvatica considered)

Species	Climate scenario	Climate model	Silviculture	Trait
Fagus sylvatica	Current	Hadgem	Even-aged forest management with shelterwood	Budburst phenology
Quercus petrae	Future RCP 4.5	CM5	Even-aged forest with clear-cut	PLC
Picea abies	Future RCP 4.5		Short rotation	Water use efficiency

Pinus sylvestris	(Continuous cover forest management)
Pinus pinaster	Unmanaged

1 species × 3 climate scenarios × 2 climate model × 3174 grid points × 4 Silviculture × {3 traits values for each of 3 traits = 27} = 2 056 752 simulations

Figure a1. Forest ecosystem fluxes of *Pinus sylvestris* across Europe from 1979 to 2008 without silviculture: Leaf Area Index (LAI in $\text{m}^2 \text{ leaves} \cdot \text{m}^{-2} \text{ soil}$), date of leaf unfolding (BBDAY in Julian day), Gross Primary Production (GPP in $\text{gC} \cdot \text{m}^{-2} \text{ soil}$), Net Primary Production (NPP in $\text{gC} \cdot \text{m}^{-2} \text{ soil}$), Autotrophic respiration (Rauto in $\text{gC} \cdot \text{m}^{-2} \text{ soil}$), yearly ring width increment (rw in $\text{mm} \cdot \text{year}^{-1}$), stand volume (Vha. m^3), Evapotranspiration (ETR in $\text{mm} \cdot \text{year}^{-1}$) and soil water stress index (WSI in $\text{Mpa} \cdot \text{year}^{-1}$)

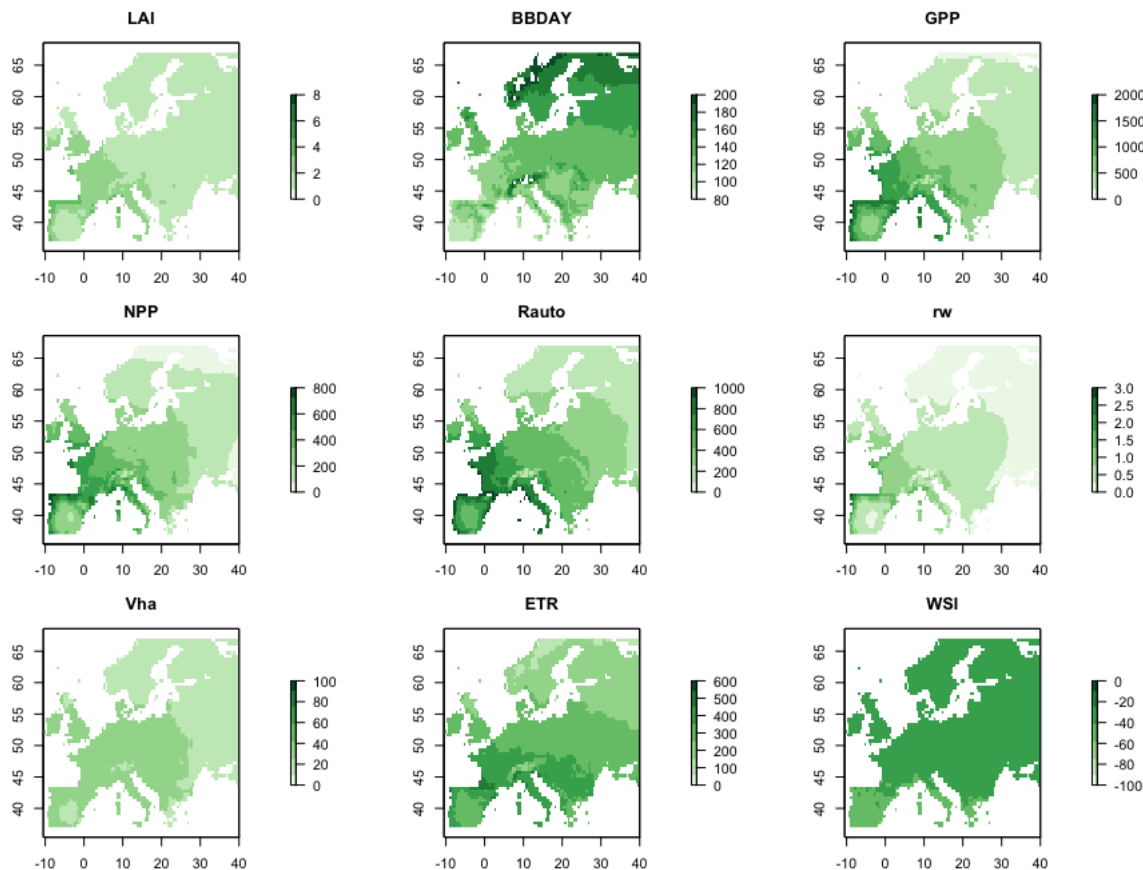


Figure a2. Forest ecosystem fluxes of *Quercus petraea* across Europe from 1979 to 2008 without silviculture: Leaf Area Index (LAI in $\text{m}^2 \text{ leaves} \cdot \text{m}^{-2} \text{ soil}$), date of leaf unfolding (BBDAY in Julian day), Gross Primary Production (GPP in $\text{gC} \cdot \text{m}^{-2} \text{ soil}$), Net Primary Production (NPP in $\text{gC} \cdot \text{m}^{-2} \text{ soil}$), Autotrophic respiration (Rauto in $\text{gC} \cdot \text{m}^{-2} \text{ soil}$), yearly ring width increment (rw in $\text{mm} \cdot \text{year}^{-1}$), stand volume (Vha. m^3), Evapotranspiration (ETR in $\text{mm} \cdot \text{year}^{-1}$) and soil water stress index (WSI in $\text{Mpa} \cdot \text{year}^{-1}$).

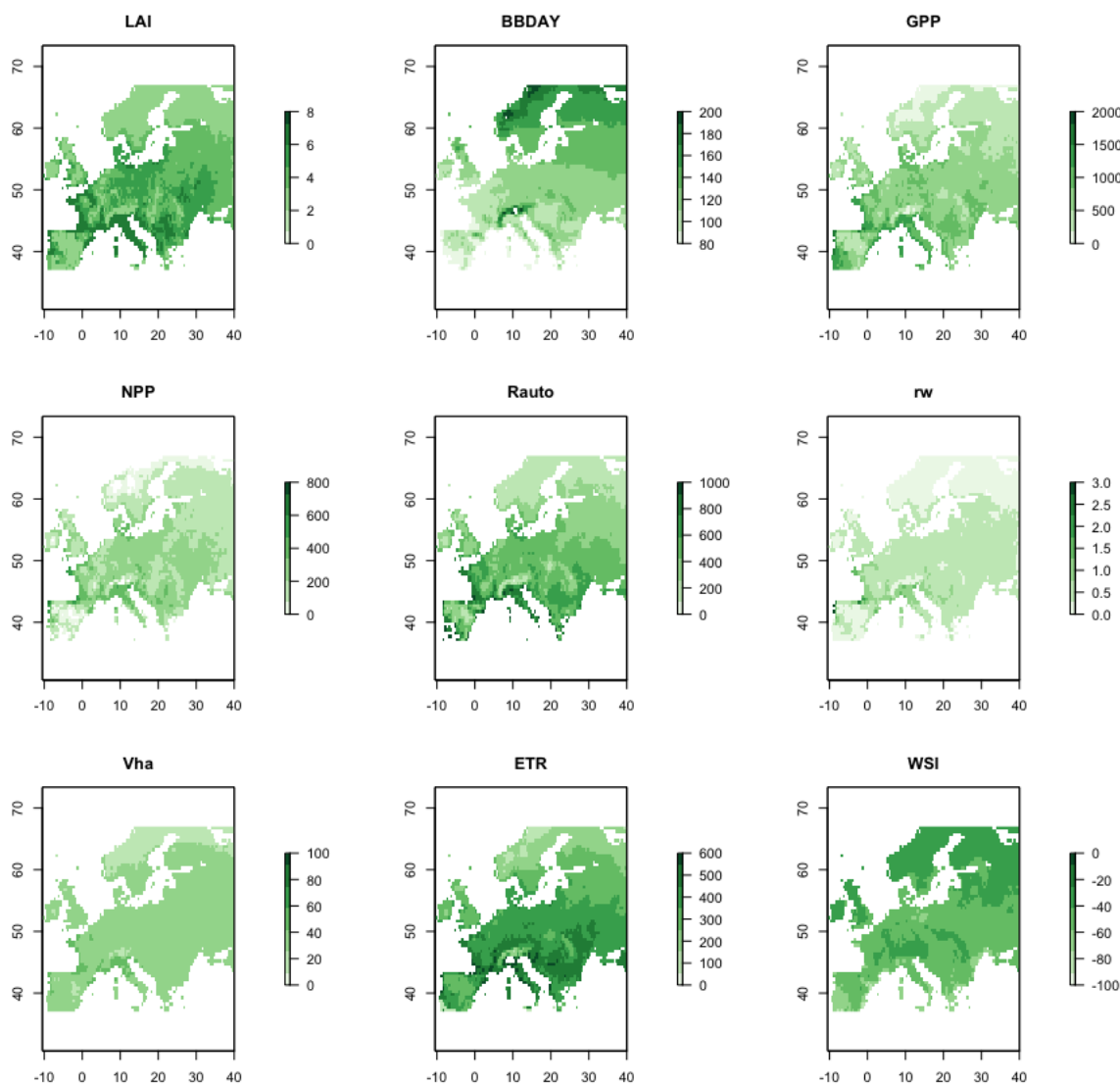


Figure a3. Forest ecosystem fluxes of *Pinus Pinaster* across Europe from 1979 to 2008 without silviculture: Leaf Area Index (LAI in $\text{m}^2 \text{ leaves} \cdot \text{m}^{-2} \text{ soil}$), date of leaf unfolding (BBDAY in Julian day), Gross Primary Production (GPP in $\text{gC} \cdot \text{m}^{-2} \text{ soil}$), Net Primary Production (NPP in $\text{gC} \cdot \text{m}^{-2} \text{ soil}$), Autotrophic respiration (Rauto in $\text{gC} \cdot \text{m}^{-2} \text{ soil}$), yearly ring width increment (rw in $\text{mm} \cdot \text{year}^{-1}$), stand volume (Vha. m^3), Evapotranspiration (ETR in $\text{mm} \cdot \text{year}^{-1}$) and soil water stress index (WSI in $\text{Mpa} \cdot \text{year}^{-1}$).

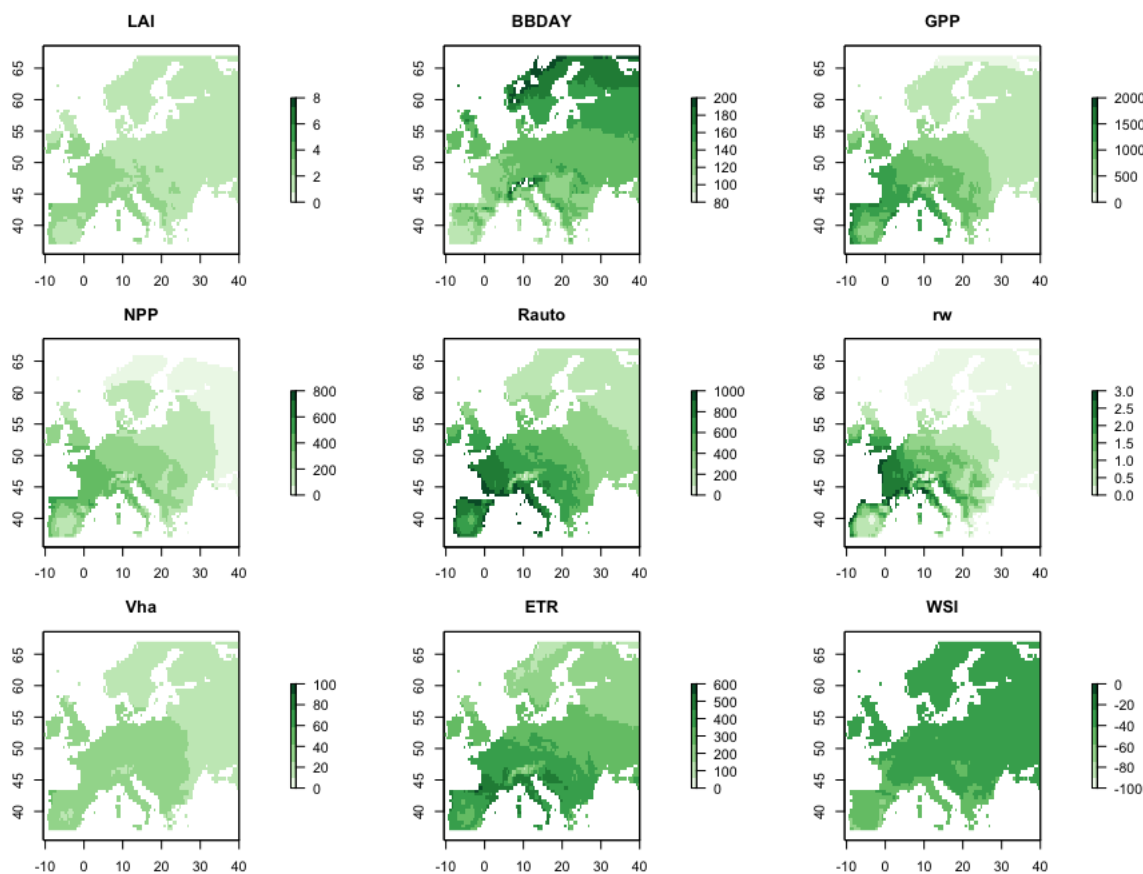


Figure a4. Forest ecosystem fluxes of *Picea abies* across Europe from 1979 to 2008 without silviculture: Leaf Area Index (LAI in $m^2 \text{ leaves} \cdot m^{-2} \text{ soil}$), date of leaf unfolding (BBDAY in Julian day), Gross Primary Production (GPP in $gC \cdot m^{-2} \text{ soil}$), Net Primary Production (NPP in $gC \cdot m^{-2} \text{ soil}$), Autotrophic respiration (Rauto in $gC \cdot m^{-2} \text{ soil}$), yearly ring width increment (rw in $mm \cdot year^{-1}$), stand volume (Vha. $\cdot m^3$), Evapotranspiration (ETR in $mm \cdot year^{-1}$) and soil water stress index (WSI in $Mpa \cdot year^{-1}$).

