BETA
Bureau d'économie théorique et appliquée

Documents de travail

« An economic comparison of adaptation strategies towards a drought-induced risk of forest decline »

Auteurs

Sandrine Brèteau-Amores, Marielle Brunette, Hendrik Davi

Document de Travail n° 2018 – 38

Septembre 2018

Bureau d'Économie Théorique et Appliquée
BETA

www.beta-umr7522.fr

@beta_economics

Contact :
jaoulgrammare@beta-cnrs.unistra.fr

Université de Strasbourg · CNRS · Université de Lorraine · INRA Science & Impact · AgroParisTech

An economic comparison of adaptation strategies towards a drought-induced risk of forest decline

Sandrine Brèteau-Amores[*], Marielle Brunette[†], Hendrik Davi[‡]

Abstract

Drought is a source of stress affecting forest growth and resulting in financial losses for forest owners and amenity losses for society. Due to climate change, such natural event will be more frequent and intense in the future. In this context, the objective of the paper is to compare, from an economic perspective, different forest adaptation strategies towards drought-induced risk of decline. For that purpose, we focus on a case study of a forest of beech in Burgundy (France) and, we studied several adaptation options: density reduction, reduction of the rotation length and substitution by Douglas-fir. We also considered two levels of drought risk (intermediate and low soil water capacity) and two climatic scenarii from IPCC (RCP 4.5 and RCP 8.5). We combine a process-based forest-growth simulator (CASTANEA) with a traditional forest economics approach. The results showed that adaptation provided the best economic return in most of the scenario considered. Combining strategies appears as a relevant way to adapt forest towards a drought-induced risk of forest decline. The interest to consider two disciplinary fields was also demonstrated with beneficial scenarii in an ecological perspective that were not in an economic one and reversely.

Keywords: forest, drought, adaptation, climate change, economics, risk, carbon, CASTANEA.

JEL Classification: D81, Q23, Q54.

[*]Université de Lorraine, Université de Strasbourg, AgroParisTech, CNRS, INRA, BETA, 54000, Nancy, France. Phone: +33 (0)3 83 39 68 58. sandrine.breteau-amores@inra.fr

[†]Corresponding author: Université de Lorraine, Université de Strasbourg, AgroParisTech, CNRS, INRA, BETA, 54000, Nancy, France. Phone: +33 (0)3 83 39 68 56. marielle.brunette@inra.fr; Climate Economic Chair, Paris, France.

[‡]UR629, Écologie des Forêts Méditerranéennes, INRA, Avignon, France. Phone: +33 (0)4 32 72 29 99. hendrik.davi@inra.fr

1 Introduction

Drought is the principal source of stress limiting forest health (Zierl, 2004) even if drought-induced impacts on forest health have been underestimated for a very long time due to inconspicuous damages at first sight (Spiecker, 2003). A drought occurrence translates into economic and social losses. Indeed, forests play a role in wood production but also offer many ecosystem services such as carbon storage, preservation of soil erosion, biodiversity. In parallel, drought-induced tree decline is significantly increasing worldwide (Bréda and Badeau, 2008), even more with climate change which is raising frequency, duration and intensity of extreme events (Dale et al., 2001).

Human interventions also affect drought through silviculture. Indeed, a sustainable forest management is needed to maintain forest ecosystems' resilience and to cope with climate threats such as drought (Bréda and Badeau, 2008). In fact, forest owners can protect their forests through adaptation: several strategies seem well suited to adapt to such increasing risk of drought. For example, reducing the rotation length or the stand density, or also shifting with a best-adapted species to drought are parts of the different propositions (Spittlehouse and Stewart, 2003).

In this context, we ask ourselves what are the relevant adaptation options, from an economic perspective, to face drought-induced risk of forest decline. In other words, we propose to study the economic costs and benefits of adaptation to drought-induced risk of decline for the forest owners.

In the economic literature, few studies investigated forest adaptation. Hanewinkel et al. (2010) used a classical Faustmann approach to realize an economic evaluation of the effects of a predicted shift from Norway spruce to European beech in Germany, comparing two scenarii from IPCC (B1 and A2) for three different time horizons (2030, 2065, and 2100). They found a decrease of the land expectation value (LEV) related to the predicted loss in the potential area of Norway spruce. Yousefpour et al. (2010) performed an economic evaluation and optimization of management strategies for German pure stands of Norway spruce. They maximized the net present value (NPV) of carbon sequestration and timber production and compared different management options grouped in three scenarii (do-nothing, adaptation, mitigation). They found that mitigation was favoured. Brunette et al. (2014) ran a cost-benefit analysis of timber-species change from French Norway spruce to Douglas-fir stands, as a tool for adapting forests to climate change. They took uncertainty into account and compared three scenarii (regeneration and shifting at the end of the rotation, immediate shift, waiting additional information before choosing one of the both options). They found a high LEV of Douglas-fir conversion related to a high mortality of Norway spruce. However, they also showed that waiting for more information on the ambiguous impact of climate change on Norway spruce may be preferable to transition or status quo. Yousefpour and Hanewinkel (2014) realized a simulation-optimization approach for a multipurpose conversion of Norway spruce forests in Germany by admixing beech to adapt them to future climate. This approach allowed to analyse the trade-offs between objectives (species enrichment and carbon storage in the growing stock). The resulting balanced decision was to establish beech regeneration in 46% of Norway spruce area. The study of Bréda and Brunette (2014) was the only one that investigated drought-induced risk of decline: after an estimation of the probabilities and impacts of drought events quantified by water balance modelling (Biljou ®), they performed an economic evaluation of the reduction of rotation length from 55 to 40 years for a French Douglas-fir plantation to cope with this risk. Comparing three adaptation scenarii (absence of adaptation, immediate adaptation, delayed adaptation), they found that immediate reduction of rotation length gave the best economic return, followed by delayed adaptation, and then the absence of adaptation. However, if the loss of timber volume by drought was higher than 48%, the delayed adaptation appeared to be preferable to the immediate one.

All these studies focused on only one adaptation strategy at a time. They never compared different strategies or analyse combination of them. In the same vein, climatic scenarii are rarely considered. Only Jonsson et al. (2015) made an economic comparison of four different strategies to fight against storm risk (no adaptation, shorter rotation period, increased fraction of broadleaved trees, continuous cover forestry). They showed that a portfolio of adaptation strategies is needed to reduce the risk of storm damage and fulfil a variety of management goals (tree-species mixture, shorter rotation periods, salvage and sanitary cutting).

The objective of this paper is to realize an economic comparison of different adaptation strategies to fight against drought-induced risk of forest decline. For that purpose, we adopted an original approach using CASTANEA, a process-based forest-growth model, to simulate forest stands following different adaptation strategies (density reduction, reduction of rotation length and species shift) under two climatic scenarii from IPCC (RCP 4.5 and 8.5) and for two levels of drought risk related to a variation in soil water capacity (intermediate and high). We then used the outputs of CASTANEA to provide an economic comparison of the adaptation strategies. We performed a classical forest economics approach based on the Faustmann's formula and Hartman's formula. The maximisation of these criteria showed that adaptation provided the best economic return, as opposed to the baseline or the "do-nothing" scenario. Indeed, substitution by Douglas-fir combined with a reduced initial density and a reduction of the rotation length was the best strategy under both levels of drought risk and both climatic scenarii. From an economic perspective, the combination of different strategies was therefore more beneficial for the forest owner than each strategy separately (synergy vs. additionality). We discuss the results as regard to the financial balance and the carbon balance.

The rest of the paper is strucured as follows. Section 1 presents the material and the methods. Section 2 provides the results. Section 3 disscusses the results and the last section, Section 4, concludes.

2 Material and methods

2.1 Some definitions

2.1.1 Characterization of drought and risk

According to the IPCC (2002), drought is defined as "a phenomenon that occurs when precipitation is significantly below normal recorded levels and that causes significant hydrological imbalances that are detrimental to systems of land resources production". From the ecophysiological point of view, drought is a reduction of the soil water reserve sufficiently severe to prevent the optimal functioning of the trees, due to insufficient precipitation, high temperature and large water uptake by trees. However, the definitions of drought vary greatly from country to country, ranging from a large area receiving less than 10% (Australia), through 30% or less over a minimum of 21 days (United States), to less than 75% (India) in relation to the annual or seasonal average. In France, drought is a period of at least 15 days where less than 0.2 mm of precipitation has fallen (Ozer, 2009).

Different types of drought are distinguished in the literature, including the edaphic (or agronomic) drought that is particularly in our interest: It refers to the soil and to the impacts on living beings. The regime of the precipitation is the first determinant in the development of a state of drought. It results from a pluviometric drought, which is as a prolonged rainfall deficit compared to the mean or median (that is the normal state). But the drought also depends on evapotranspiration levels that is tightly related to the temperature and atmospheric drought. The estimation of the water balance allows defining the conditions under which precipitation distribution, soil water reserves, and losses by evapotranspiration or drainage induce a negative effect on trees, called water stress. According to Lebourgeois et al. (2005), water stress is the most important concept for the forest manager, since water is the determinant of good stand health.

Following Crichton (1999), the drought risk can be described in terms of three components: the hazard, the stand exposure to the hazard and the stand's vulnerability. The hazard is characterized by its magnitude, its severity and its probability of damages. Exposure is the level or the conditions for which the stand may be in contact with the hazard. It is a function of the geographical location and the physical context, which can limit or accentuate the hazard. Vulnerability refers to the internal characteristics of the stand, influenced by species ecology, soils characteristics or stand density. It shows the extent to which the stand is susceptible to suffer damages related to the hazard: It therefore takes into account the sensitivity of the individuals to the effects of a hazard, as well as their ability to resist, adapt to them, and to return to the baseline situation (i.e. resilience) (UNEO, 2007). A hazard (which is only a natural process) becomes a natural risk only when there is an interaction between the hazard and the population, goods and activities affected (Veyret et al., 2013). The risk, defined according to its intensity and its frequency, implies therefore the perception of this hazard by the population and subsequently its management (for cohabitation with the danger) (Veyret et al., 2013).

The impacts of drought may be classified as biological or socio-economical. Four categories of biological impacts can be distinguished: Accommodation by changes in physiological functioning (Bréda and Badeau, 2008; Matesanz and Valladares, 2014), in phenology or in tree growth (Solberg, 2004; Matesanz and Valladares, 2014), genetic adaptation (de Miguel et al., 2012), migration and tree mortality (Spiecker et al., 2004; Galiano et al., 2011, 2012). The biological impacts begin at the tree level, which result in impacts at the stand level, which, in turn, result in impacts at the ecosystem level. Thus, at the stand level, loss of growth proportional to drought intensity induces loss of productivity, while, at the ecosystem level, drought reduces most of the biological cycles affecting the functions of the forest and causes a loss of ecosystem services: mainly wood production and carbon sequestration (Maroschek et al., 2009). In terms of socio-economic impacts, drought generates financial losses linked to the current value of felled timber resulting from the loss of marketability, decrease in future stand value, additional cost of forest restoration, loss of hunting income and other regular income (Birot and Gollier, 2001). In addition, drought is also linked to the loss of carbon sequestration, which generates financial and social losses, as well as the loss of other amenities such as recreation (Thürig et al., 2005).

These impacts should be enhanced in a near future due to climate change. Indeed, climate change is a global phenomenon due to an anthropogenic cause: the increase in the atmospheric concentration of greenhouse gases, among which the most important carbon dioxide (CO_2) (IPCC, 2013). Climate will thus evolve towards an increase in average temperature, an emphasis of the differences among wet and dry regions, a decrease in water availability, an increase of the frequency and the intensity of extreme events such as severe drought (Spiecker, 2003). But increasing CO_2 can also limit the drought effect by increasing water use efficiency of plants (Davi et al., 2006; Keenan et al., 2013).

2.1.2 Adaptation strategies

In order to try to limit the increasing impacts of drought, several adaptation strategies may be identified. We chose to test two main adaptation strategies, according to their importance in the literature and according to the classification of soft and hard adaptation strategies given by the World Bank (2010): the reduction of rotation length (soft adaptation) and the species substitution from beech to Douglas-fir (hard adaptation). These two strategies are analysed separately, but also jointly and in combination with a third strategy, density reduction.

First, the reduction of rotation length reduces the time of exposure to drought event and the vulnerability of trees due to ageing (Spiecker, 2003; Bréda and Peiffer, 2014). Young and old trees are the most vulnerable to drought (Archaux and Wolters, 2006): Special attention therefore must be paid to the installation of young trees and avoiding long rotations.

Second, the introduction of drought-tolerant species and provenances reduces the aerial carbon balance, while using the same forest area (Keskitalo, 2011; FAO, 2011). Moreover, it would be preferable to introduce so-called transitional species or varieties, that is to say species able to thrive in both current climate and future announced climate (e.g. pines, Douglas-fir, robinia).

Third, the reduction of the leaf area, and therefore of the stand density, improves the resistance of forest stand to the lack of water (Archaux and Wolters, 2006; Bréda and Badeau, 2008), reduce the intensity and duration of water deficits and increase water availability (Spiecker, 2003). This results in an increase of initial planting space (Spiecker, 2003) and more intensive and earlier thinning (Spiecker, 2003; Keskitalo, 2011) in order to stabilize and thus protect stands (i.e. to have a continuous forest cover and to protect them from all hazard) (Spiecker, 2003; Bernier and Schoene, 2009), to exploit CO_2 fertilization to maximize and accelerate growth (Bernier and Schoene, 2009), to increase resistance and resilience to future damages (Kerhoulas et al., 2013), and to stimulate the growth of trees remaining after a drought (Kerhoulas et al., 2013).

2.2 Case study

2.2.1 Case study area: Burgundy region

Burgundy is a rural region and one of the first forest regions in France in terms of afforestation (30% afforestation rate), which has increased over the last 30 years. It has a great geographical (from valley to mountain) and geological diversity. Its contrasted climate is of the Atlantic type with rainfall spread throughout the year ranging from 600 mm (Loire valley) to 1,500-1,800 mm (Morvan peaks), average temperatures between 9.5 and 11.5°C, events of snow and frost, as well as frequent late frosts in May. However, biotic (pests and pathogens such as canker and bark beetle) and abiotic factors (e.g. late frosts, repeated water deficits, soil compaction by mechanization of forestry) threaten the health of forests. The forests of Burgundy are characterized by private property (68% according to IGN, the French National Forest Inventory), a primary function of production, and a dominance of deciduous trees except in the Morvan. Indeed, beech and oak represent 90% of the forest areas. However, these two species are sensitive to summer water deficit and many beech diebacks are observed, which may be amplified by a weakly dynamic silviculture. This is why, during the turnover of Burgundy stands, deciduous forests gradually shift to forests with more productive and valuable species such as Douglas-fir, in order to anticipate future climate changes, and thus to avoid financial losses, and to respond to the growing demand for wood, with a more dynamic silviculture. Beech and Douglas-fir also produce commercially high-valued wood in Burgundy, i.e. their annual production are 221,000 m^3 and 898,000 m^3 respectively in private forests.

2.2.2 Species of interest

Beech (*Fagus sylvatica* L.) is a natural species representing 15% of the forest production area in France. It is a typical shade tolerant species, requiring a certain atmospheric humidity and sufficient soil moisture (Latte et al., 2015), which can hardly tolerate extreme conditions, as well as spring frosts (Godreau, 1992). More precisely, it is the climatic criteria (distribution of precipitation and temperature of the year) that determine the presence or the state of health of beech, rather than soil conditions (Godreau, 1992). However, due to climate change, it could decline or even disappear (Charru et al., 2010). Indeed, the increase in the frequency and intensity of spring droughts and heat waves have already negatively affected the annual growth of beech trees (Latte et al., 2015). Some damage can lead to the death of beech when the proportion of dead aerial biomass exceeds a threshold of 58% (i.e. percentage of foliar deficit reached) (Chakraborty et al., 2017). This mortality is directly related to the availability of water and light resources, as well as the increase in neighbouring interactions and in diversity of trees (Chakraborty et al., 2017).

Overall, in France, distribution is limited by temperature for Mediterranean species and by water supply for northern species, as well as deciduous species (beech, oak) and conifers species (Douglas-fir, spruce, fir). This is why the hydric constraints on the northern half of France question the existence and the production of these latter species, in particular the beech that has many diebacks on superficial soils with low water reserves. Substitution by a species more productive under dry climate and more valuable, such as Douglas-fir, seems to be a better economic solution, as suggested by Latte et al. (2015) for the regeneration of old beech stands. In addition, with the attraction of the French public authorities (e.g. National Forest Fund in France in the period 1946–2000) and some professionals (buildings, wood producers, furniture industries) by the rapid growth, the lower cost of production and maintenance, and the standardized sawing techniques of conifers (pines, firs), the demand would be based on an accelerated national production of conifers. Since the French forest is composed of two-thirds of deciduous trees, the transition could be supported by a less water-consuming silviculture, which is linked to the subject of our study.

Native from western North America, Douglas-fir (*Pseudotsuga menziesii* Mirb.) is an introduced species appreciated by forest managers for its rapid growth and the quality of its wood (Ronch et al., 2016). It appears to be able to provide a significant wood production under relatively dry climate (Eilman and Rigling, 2012; Ronch et al., 2016). However, despite all these qualities, Douglas-fir is more sensitive to high heats due to its high leaf area (i.e. strong transpiration) than to droughts. This explains the damages reported in France after the drought in 2003 (because of its combination with a heat wave), in particular in Burgundy region (Sergent et al., 2014). Moreover, although Douglas-fir is described by some authors as a drought-resistant species (Eilman and Rigling, 2012), it seems to not support the range and accumulation of intense and recurrent episodes of drought after a severe one, which could be explained by a lack of resilience like after the drought in 2003 (Sergent et al., 2014).

Comparing both species, beech and Douglas-fir are two mesophilous species, i.e. species that grow in habitats that are neither extremely dry nor extremely humid (ONF, 1999). They prefer mountainous areas, due to a high requirement for atmospheric moisture, although they are present in the plain. They are therefore sensitive to heat. Douglas-fir and beech have the same skewed and moderately deep rooting, but with different transpiration control during drought (ONF, 1999). Indeed, beech has a higher midday soil water potential and consequently a higher sensitivity to drought compared to Douglas-fir (ONF, 1999; Pierangelo and Dumas, 2012). In addition, deciduous trees have a higher demand for available water content than conifers (ONF, 1999): beech therefore consume more water reserves than Douglas-fir in summer. But edaphic drought can be aggravated by the existence of a high evaporation demand. Finally, Bréda and Badeau (2008) confirm that the development of beech is dependent on water balance and drought, whereas for species such as Douglas-fir their development is mainly related to temperatures: this supports our suggestion of substitution of beech by Douglas-fir.

2.2.3 Scenarii of the study

For the study, we chose to test two levels of drought risk defined according to the level of soil available water capacity (AWC) in the soil. Three levels of AWC were considered: 150, 100, 50 mm. These levels were chosen according to the range of AWC of current beech stands in Burgundy. 150 mm represents optimal water conditions for beech growth. 100 mm is a first risky scenario with one third less of the baseline level of water availability for trees. 50 mm is a second risky scenario in which the water availability is below 40% of the baseline. This threshold of 40% of the maximum AWC represents the conditions from which beech starts to regulate water consumption and thus has difficulties to grow and survive (Lebourgeois et al. (2005)).

With respect to the uncertainty of future climate, the consequences of the two extreme climatic scenarii from IPCC were analysed: RCP 4.5 and RCP 8.5 (IPCC, 2013). RCP 4.5 represents the most optimistic scenario, and RCP 8.5 represents the most pessimistic one (higher temperature, higher CO_2 concentration, etc.). All of these elements result in [(2 baselines + 7 scenarii × 2 drought risks) × 2 climates] that is equal to 32 scenarii. The two baselines and the seven scenarii are summarized in Table 1.

Table 1: The different scenarii considered with their code

Code	Scenario
Baseline_B	Benchmark, current beech stand
Baseline_D	Benchmark, Douglas-fir in current conditions
B_NA	Beech stand without adaptation
B_DR1	Beech stand with a reduced rotation length
B_DR2	Beech stand with a first reduced initial density and rotation length
B_DR3	Beech stand with a second reduced initial density and rotation length
D_S	Douglas-fir stand (substitution of beech)
D_S+DR1	Douglas-fir stand (substitution of beech) combined with a reduced rotation length
D_S+DR2	Douglas-fir stand (substitution of beech) combined with a reduced initial density and rotation length

The scenario is indicated with the following code for the benchmark (AWC of 150 mm): Baseline_Species (B for beech or D for Douglas-fir). The scenario is indicated with the following code for both levels of drought risk (AWC of 100 mm and 50 mm): Species (B for beech or D for Douglas-fir)_Silviculture (NA for no adaptation, DR for density/rotation reduction and S for substitution). Scenarii for beech were composed of a classical path (Baseline_B and B_NA) and three dynamic ones (B_DR1, B_DR2 and B_DR3) representing the silviculture of the density/rotation reduction strategy. Simulations for Douglas-fir were composed of a classical path (Baseline_D and D_S) representing the silviculture of the substitution strategy and also two dynamic ones (D_S+DR1 and D_S+DR2) in order to test the combination of the two strategies.

2.3 Methods

To compare the adaptation options to face drought-induced risk of forest decline, we first simulated forest growth with different silvicultures according to these different adaptation strategies, the three different levels of water content and the two climatic scenarii. The simulations were run with CASTANEA model. The economic approach was then mobilized on the outcome of the simulations.

2.3.1 Simulation of forest growth and silviculture

CASTANEA is a mechanistic model for simulating the functioning of monospecific and even-aged forests of the main managed European tree species (Davi et al., 2005; Dufrêne et al., 2005). The model simulates stocks (carbon, water, nitrogen) and the main exchanges of matter and energy between the forest and the atmosphere, at time steps ranging from half an hour to the century.

CASTANEA required as inputs, three different files: the inventory file, the species file and the weather file. First, the inventory file contains all the trees with their characteristics related to the simulated stand. Through R software, soil characteristics (height, stone content, etc) that are directly linked to the AWC and characteristics of the managed stand (tree diameter, LAI, etc) allowed to generate the list of all the trees according to these parameters. Second, the species file contains all the species-specific parameters controlling energy budget, growth (photosynthesis, respiration), carbon allocation and water consumption (see Table S1 in supplementary material). Third, the weather file contains the climatic characteristics of the studied site (global radiation, air temperature, relative air humidity, wind speed, precipitation). These georeferenced data for current and future climate (RCP 4.5 and RCP 8.5) came from Meteo France network for four different SAFRAN points of 8×8 km (3202, 3710, 4303, 5121) chosen to represent the variety of climate in Burgundy. All the results for each scenario then will come from the average of the four SAFRAN points (see Figure S1 in supplementary material).

The annual output data were the volume of wood, the mortality rate, and the carbon sequestrated into the forest stand.

Risk of mortality by carbon starvation and hydraulic failure were assessed according to Davi and Cailleret (2017). For this purpose, we simulated Non Structural Carbohydrates ([NSC]) and midday leaf water potential. Hydraulic failure is computed when midday leaf water potential drops below species P50 (leaf water potentials below which 50% of conductivity loss occurs). Threshold of mortality on [NSC] is estimated by fitting the threshold to minimize the difference among simulated and measured annual mortality rate between 2000 and 2015 once the hydraulics failure was computed. The mortality measurements come from the French National Inventory on Burgundy.

CASTANEA model simulated forest growth of a stand of one hectare through different silvicultural paths starting from a 125-year-old beech forest of Burgundy from 2000 to 2100. The silvicultural paths arise from CRPF (Regional Center for Forest Ownership) of Burgundy for both species. Table 2 presents the different characteristics of each silvicultural path. The seven silvicultural paths were simulated through three different AWC (50, 100 and 150 mm) characterizing the drought effect and two different IPCC scenarii (RCP 4.5 and RCP 8.5) characterizing the climate effect.

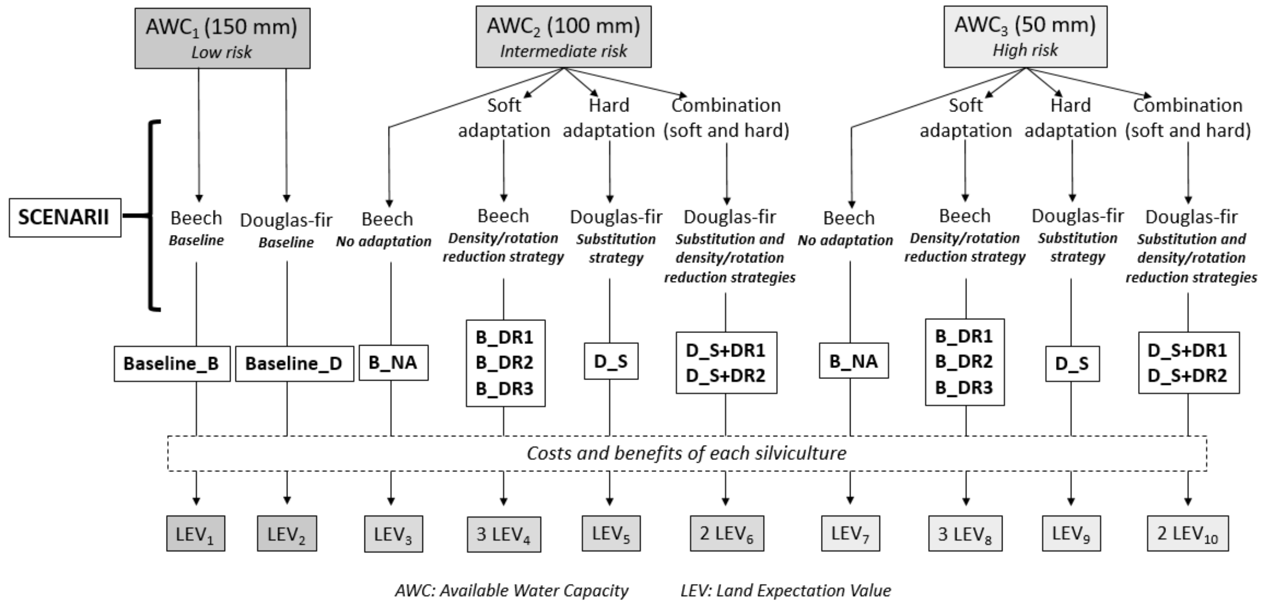
Table 2: Characteristics of the different silvicultural paths used for beech and Douglas-fir: initial stand density (number of trees per hectare), regeneration mode (natural regeneration NR or plantation P), number of thinnings and rotation length (years) (source: CRPF)

Scenario	Initial stand density (trees/ha)	Regeneration mode (RN or P)	Number of thinnings	Rotation length (years)
Baseline_B and B_NA	5000	NR	9	95
B_DR1	5000	NR	7	80
B_DR2	3000	NR	7	80
B_DR3	1000	P	6	80
Baseline_D and D_S	1300	P	6	55
D_S+DR1	1660	P	3	45
D_S+DR2	660	P	3	45

2.3.2 Economic approach

Figure 1 illustrates, for one given IPCC scenario, the structure of the applied methodology from the simulation of forest growth to economic results. The resulting volume of wood for each scenario (outputs of CASTANEA model) was the input of the economic approach.

Figure 1: Schematic representation of the methodology applied: From scenario structure to economic evaluation



Our objective is to compare the 32 LEV among scenarii. All the comparisons of LEV are detailed according to Figure 1 as follows (taking only one IPCC scenario into account):

• (LEV 1 with LEV 3) and (LEV 1 with LEV 7): effect of drought.

• (LEV 3 with LEV 4) and (LEV 7 with LEV 8): effect of density/rotation reduction strategy.

• (LEV 1 with LEV 2) and (LEV 3 with LEV 5) and (LEV 7 with LEV 9): effect of species substitution strategy.

• (LEV 3 with LEV 6) and (LEV 3 with LEV 10): effect of species substitution strategy combined with density/rotation reduction one.

First, the sum of an infinite number of rotations allowed calculating the land expectation value, commonly referred as Faustmann criteria in forest economics (Faustmann, 1849), as follows:

$$LEV(Faustmann) = \sum_{i=0}^{\infty} \sum_{n=0}^{N} \frac{B_i - C_i}{(1+r)^{(i.R+n)}}$$

with B the benefits, C the costs, r the discount rate, i the stand age and R the rotation length.

The forest owner is supposed here to have a single objective: maximize LEV. The infinite horizon used by this criterion allowed comparing management options associated to different temporal horizons, assuming that silvicultural path was identical for each subsequent rotation beyond the first. In other words, each silvicultural operation (thinning, maintenance, harvest) was implemented at the same age and for the same cost or benefit an infinite number of times. Faustmann's LEV takes into account the costs and the benefits from the harvest of wood. The discount rate r used throughout in this paper is 3%.

An example of silvicultural operations with associated net benefits from wood production is given in Table 3 for the benchmark. The tables for the other scenarii are presented in Appendices.

Table 3: Stand density (number of trees per ha), volume of wood (in cubic metres per hectare) and associated net benefits from its production (in euro per hectare) for each silvicultural operation for the benchmark of beech (Baseline_B)

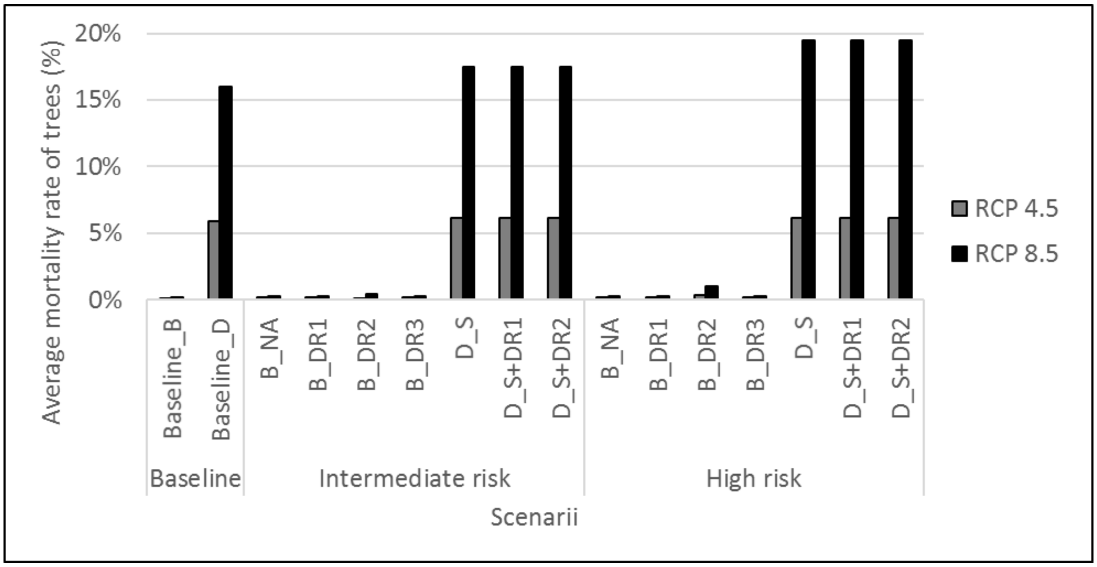
Baseline_B		RCP 4.5		RCP 8.5	
Operations (tree age)	Stand density (N/ha)	Volume of wood (m^3/ha)	Net benefits (EUR/ha)	Volume of wood (m^3/ha)	Net benefits (EUR/ha)
Maintenance (5)	5000	24	-595	24	-595
Thinning 1 (15)	3000	106	-665	107	-665
Thinning 2 (30)	1500	170	852	168	841
Thinning 3 (35)	757	113	560	118	584
Thinning 4 (41)	523	104	483	111	514
Thinning 5 (49)	361	142	661	150	696
Thinning 6 (57)	249	168	1042	172	1067
Thinning 7 (65)	172	186	1437	185	1426
Thinning 8 (75)	119	210	2130	208	2114
Thinning 9 (85)	82	224	2781	219	2723
Harvest (95)		250	12524	249	12457

3 Results

3.1 Forest growth and mortality

Figures 2 and 3 show the results of the simulations of the forest stand per scenario and per RCP, in terms of growth (volume increment of wood in cubic metres per hectare) and mortality (in percentage terms) respectively. Mortality was taken into account in the calculation of the volume.

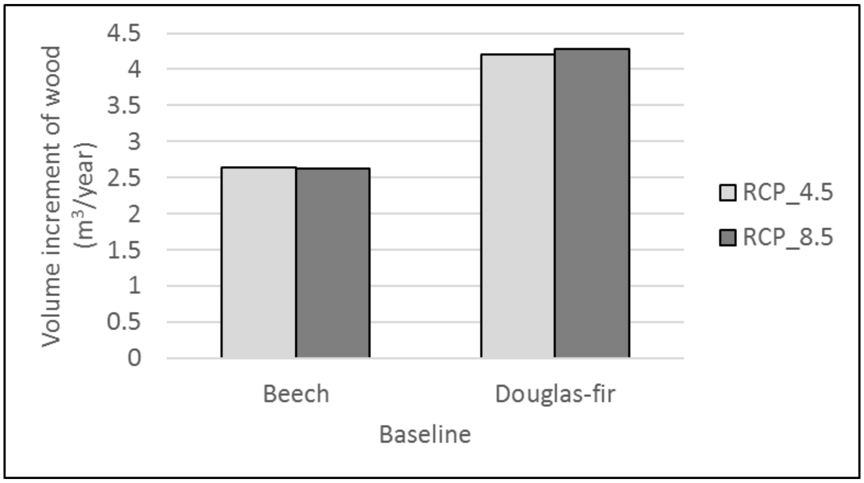
Figure 2: Histogram representing the average mortality rate of trees (in percentage terms) for each scenario, for RCP 4.5 (grey) and RCP 8.5 (black)

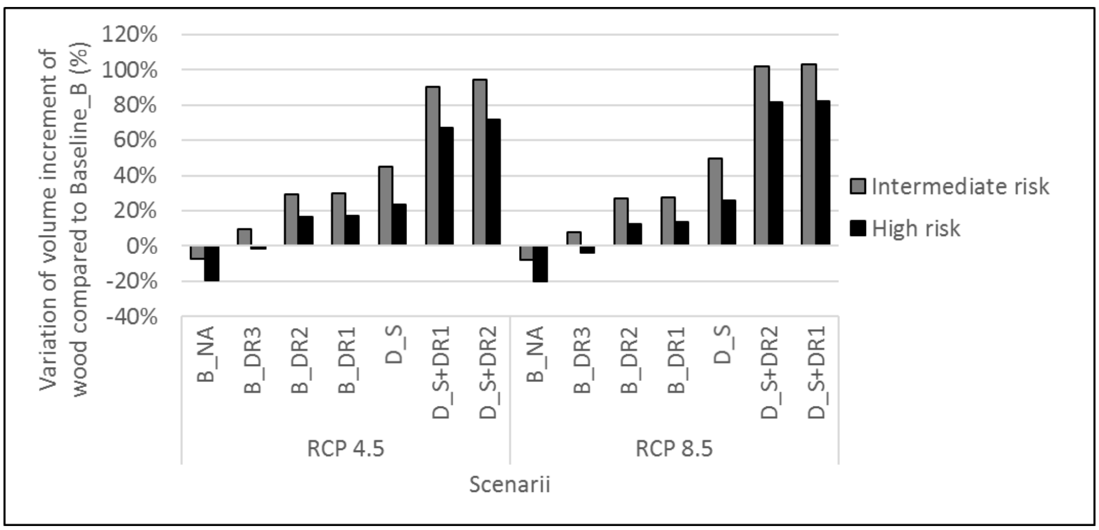


In Figure 2, we can see that Douglas-fir has the highest mortality rate compared to beech and thus the baseline (Baseline_B). Adaptation does not affect the mortality: There is no difference between scenarii, considering the same tree species. Climate has a negative effect on mortality: Scenarii in RCP 8.5 (pessimistic climate scenario) present higher mortality than in RCP 4.5 (optimistic climate scenario). Regarding drought, in RCP 4.5, both levels of drought risk present the same pattern. In RCP 8.5, the high risk emphasizes mortality of Douglas-fir.

In Figure 3, we can see that Douglas-fir presents a higher volume increment of wood than beech (baseline and scenarii). Drought has a negative effect for all the scenarii: They present lower growth in a high risk than in an intermediate risk. Climate has a slightly positive effect on Douglas-fir : Scenarii has a higher growth in RCP 8.5 than in RCP 4.5, which can be explained by the CO_2 fertilization (higher CO_2 concentration in RCP 8.5 than in RCP 4.5). There is no climate effect for beech and for the baseline of both tree species. Considering only beech, growth decreases with the reduction of stand density (5000, 3000 and 1000 trees/ha for B_DR1, B_DR2 and B_DR3 re-

Figure 3: Histograms representing the volume increment of wood (cubic metres per year) of the baselines (beech and Douglas-fir) (up) and the variation (in percentage terms) of each scenario compared to the baseline of beech (down) for intermediate and high drought risks in RCP 4.5 and RCP 8.5





spectively). Combinations of different strategies (D_S+DR1 and D_S+DR2) has the best growth unlike non-adaptation (B_NA) which is below the baseline.

These two figures presented interesting results in an ecological point of view.

First, the scenarii with Douglas-fir showed the highest volume increment of wood, while they had the highest mortality. More precisely, the two scenarii combining two strategies (D_S+DR1 and D_S+DR2) were the best ones, showing a higher growth in the more severe climatic scenario (RCP

8.5) than in the small-temperature increment scenario (RCP 4.5). All these elements corrobate the literature describing Douglas-fir such as a high productive species in dry climate (Eilman and Rigling, 2012; Ronch et al., 2016).

Then, the scenarii with beech showed reversely the lowest volume increment of wood, while they has the lowest mortality. More precisely, they showed a lower growth in the high drought risk than in the intermediate one, which agree with its known sensitivity to drought (Charru et al., 2010; Latte et al., 2015; Chakraborty et al., 2017).

These two points demonstrate different sensitivity to drought and climate change. Indeed, beech reacts and is thus more sensitive to drought (precipitation effect) than to climate (temperature effect) (Latte et al., 2015; Chakraborty et al., 2017), and reversely for Douglas-fir (Sergent et al., 2014).

In a general overview, drought influences negatively mortality and volume increment of wood. Concerning climate change, the higher the intensity, the more the mortality of the stand increased. That is why, regarding these two outputs of CASTANEA model, adaptation seemed more profitable than the baseline or the absence of adaptation.

3.2 Economic comparison

The resulted variation of LEVs compared to the baseline of beech (Baseline_B) are presented in Table 4. The range of values of Faustmann's LEV is from -983 to 4,916 EUR/ha and from -866 to 4,717 EUR/ha for the RCP 4.5 and 8.5 respectively. In terms of implementation of adaptation strategies, scenarii with a positive variation of LEV compared to the baseline represent the benefit of adaptation for forest owners: B_DR1, B_DR2 and D_S+DR2. Reversely, scenarii with a negative variation of LEV compared to the baseline represent the potential cost of adaptation for forest owners: B_DR3, D_S and D_S+DR1.

Table 4: Variation of the Faustmann's LEV (in percentage terms) of each scenario compared to the baseline of beech, for RCP 4.5 and RCP 8.5

Scenario		RCP 4.5	RCP 8.5
Baseline	Beech	1555 EUR/ha	1572 EUR/ha
	Douglas	-29%	-45%
Intermediate risk	B_NA	-13%	-14%
	B_DR1	79%	80%
	B_DR2	82%	82%
	B_DR3	-3%	-2%
	D_S	-67%	-80%
	D_S+DR1	-111%	-108%
	D_S+DR2	216%	200%
High risk	B_NA	-35%	-36%
	B_DR1	55%	55%
	B_DR2	57%	56%
	B_DR3	-27%	-26%
	D_S	-123%	-137%
	D_S+DR1	-163%	-155%
	D_S+DR2	167%	154%

Concerning the baseline, keeping the current beech stand was more profitable than substituting it to the Douglas-fir. Table 4 lets appear that substitution strategy combined with a density reduction one (D_S+DR2) provides the best economic return regardless the level of drought risk and the climatic scenario. Then, at a second step, the density reduction of beech provides the best economic return with the scenario B_DR2 followed by the scenario B_DR1. Note that the two others scenarii with Douglas-fir (D_S and D_S+DR1) are the worst options from an economic perspective regardless the level of drought risk and the climatic scenario.

Based on Table 4, we can say that costs and benefits of adaptation strategies are clearly not additive, and that synergies between adaptation stategies appear. Implementing substitution alone (D_S) corresponds to financial loss (-67%), implementing substitution and density reduction (D_S+DR1) increases the previous loss (-111%) while adding reduction of rotation length to these two strategies (D_S+DR2) allows to generate benefits (+216%). Research should be conducted to deepen the understanding of these synergies.

3.3 Carbon sequestration

In this paper, we wondered what are the relevant adaptation options, from an economic perspective, to face drought-induced risk of forest decline. In this part, we also wonder if the consideration of forest ecosystem services may impact the economic results. In the context of mitigation of climate change, we chose to consider in particular carbon sequestration. In fact, carbon loss is rarely considered in the literature, in addition to economic loss (see Yousefpour and Hanewinkel (2014) for an exception).

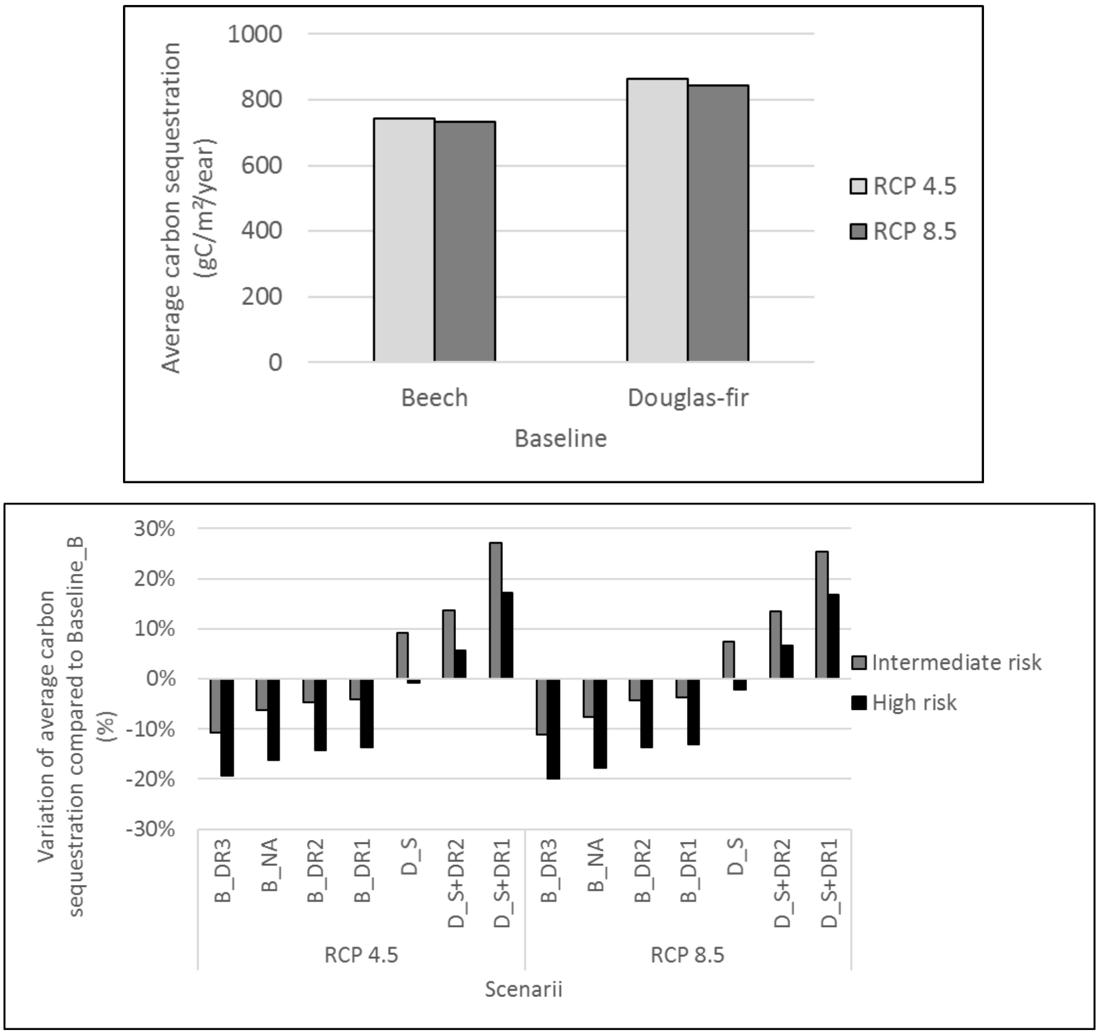
Figure 4 shows the results of the simulations of the forest stand per scenario and per RCP, in terms of carbon sequestration (in grammes of carbon per square metres of leaf per year). Mortality was taken into account in the calculation of the volume

In Figure 4, we can see that Douglas-fir presents a higher carbon sequestration than beech (baseline and scenarii). Drought has a negative effect for all the scenarii: They present lower carbon sequestration in a high risk than in an intermediate risk. Climate does not affect carbon sequestration (baseline and scenarii). Considering only beech, carbon sequestration decreases with the reduction of stand density (5000, 3000 and 1000 trees/ha for B_DR1, B_DR2 and B_DR3 respectively). Scenario D_S+DR1 combining different strategies has the best carbon sequestration, in contrast to the scenario B_DR3 (reduced density and rotation length) which is the worst one and below the baseline.

In addition, we also calculated the Hartman's LEV. It allows to take the benefits from the harvest of wood and also from amenities (Hartman, 1976), in our case carbon sequestration (see Couture and Reynaud (2011) for a short review of studies relying on Hartman's framework with carbon storage). The Hartman's model was applied as follows:

$$LEV(Hartman) = \sum_{i=0}^{\infty}\sum_{n=0}^{N} \frac{B_i - C_i}{(1+r)^{(i.R+n)}} + \sum_{i=0}^{\infty}\sum_{n=0}^{N} \frac{B_i'}{(1+r)^{(i.R+n)}}$$

Figure 4: Histograms representing the average carbon sequestration (in grammes of carbon per square metres of leaf per year) of the baselines (beech and Douglas-fir) (up) and the variation (in percentage terms) of each scenario compared to the baseline of beech (down) for intermediate and high drought risks in RCP 4.5 and RCP 8.5



with B the benefits from wood production, C the costs of the silviculture, B' the benefits from carbon sequestration provided by forest stand, r the discount rate, i the stand age and R the rotation length.

The discount rate r was also 3% for beech and Douglas-fir. To calculate the benefits from carbon sequestration, we considered the additional sequestration of the standing wood and we chose the social cost of carbon of 44 EUR/T (Watkiss and Downing, 2008). The social cost of carbon is "an estimate of the total cost of damages done by each ton of CO_2 that is spewed into the air" (Howard and Sterner, 2014). It gives therefore the total value of avoided damage caused by a flow of carbon to the atmosphere in the case of potential total deforestation.

The resulted variation of LEVs compared to the baseline of beech (Baseline_B) are presented in Table 5.

Table 5: Variation of the Hartman's LEV (in percentage terms) of each scenario compared to the baseline of beech, for RCP 4.5 and RCP 8.5

Scenario		RCP 4.5	RCP 8.5
Baseline	Beech	2789 EUR/ha	2829 EUR/ha
	Douglas	-27%	-39%
Intermediate risk	B_NA	-11%	-12%
	B_DR1	37%	37%
	B_DR2	40%	40%
	B_DR3	-18%	-17%
	D_S	-51%	-62%
	D_S+DR1	-75%	-77%
	D_S+DR2	103%	90%
High risk	B_NA	-29%	-134%
	B_DR1	19%	19%
	B_DR2	21%	21%
	B_DR3	-35%	-34%
	D_S	-87%	-98%
	D_S+DR1	-108%	-107%
	D_S+DR2	72%	62%

The range of Hartman's LEV is from -230 to 5,672 EUR/ha and from -969 to 5,378 EUR/ha for the RCP 4.5 and 8.5 respectively. The same results are observed considering the Hartman's LEV: the scenario D_S+DR2 provides the best economic return regardless the climate and the level of drought risk. In addition, Figure 4 showed that, considering scenarii of beech and those of Douglas-fir separately, the higher the initial stand density, the more the carbon was sequestered. This does not coincide with drought adaptation strategies. That is why the combination of two strategies through the best scenario (D_S+DR2) is a good trade-off between adaptation and mitigation of climate change.

Hartman's LEV gives the highest values compared to Faustmann's LEV: Without taking into account carbon sequestration, we under-estimate the value of forest stand. However, Hartman's LEVs present the highest extreme values and thus the highest variation of values in the more severe climatic scenario (RCP 8.5): This criteria therefore takes into account all the externalities of carbon sequestration linked to the implied silviculture. These results proves the importance to take carbon sequestration into account, mainly in the context of climate change, and not only wood production to compute the profitability.

This part promotes a first consideration of carbon in these analysis. Many debates exist about carbon accounting. That is why this step can be develop in further investigations. Indeed, it would be interesting to know how positive externalities from carbon sequestration can be managed in reality. Amenities can generate carbon credits: it can result in a payment to forest owners for the total sequestered carbon or the annual increment of sequestered carbon of the past year (Dwivedi et al., 2012). A payment implies thinking about the manner to provide it (Guitart and Rodriguez, 2010), at the final harvest or a revenue each year. We can take into account the future use of wood products having different lifetime and so does the carbon stocked in these products. This suggests that wood quality have to be integrated in our study. For example, firewood re-emit directly the sequestered carbon, while carbon in a wooden table has a longer lifetime. With this approach in mind, one may consider at the same time the individual negative effect of wood production of forest owners, but also the economic consequences for society with the social contribution through different wood products.

Finally, in a general overview, adaptation makes society as well as the economy more resilient to hazards (Konkin and Hopkins, 2009), which referred to the "forests for adaptation" of Locatelli et al. (2010). However, the implementation of effective adaptation measures depends on the availability of human resources and skills (Maroschek et al., 2009). Adaptive management is part of the "no regret", reversible and non-technical strategies and the ones that reduce the decision horizon, due to its flexibility with respect to the evolution of climate change and its beneficial investments even in the absence of drought risk (Courbaud et al., 2010). Adaptive management is thus part of the adaptation measures to climate change, but contributes also to its mitigation such as increasing the carbon-sink capacity (Kolström et al., 2011). Indeed, FAO (2011) emphasizes that "effective management of global forests not only reduces the risk of damage from potential disasters, but also has the potential to mitigate and adapt to climate change".

4 Discussion

We discuss these results as regard to the financial balance for forest owners and the carbon balance for society.

4.1 Adaptation in an economic perspective

From an economic point of view, our results suggest that adaptation may be relevant (Tables 4 and 5), and corroborates with the ecological point of view detailed in section 3.1. More precisely, the substitution of beech by Douglas-fir combined with a reduced initial density and rotation length (D_S+DR2) provided the best economic return. Indeed, the wood of Douglas-fir is more valuable than those of beech: its wood had a natural durability that did not need chemical treatment to use in exterior construction. At the opposite, beech is mainly used as firewood: Hotyat (1999) described its wood as a low valuable one and not competitive compared to the wood of conifers, due to its low durability, its red heart and its hydrophilic characteristic. That is also why Latte et al. (2015) promoted the substitution by Douglas-fir and since now for the regeneration of old stands of beech.

However, two economic results were unexpected. First, despite its low quality and thus value, the reduced initial density and rotation length scenario B_DR2 provides the second best return.

Indeed, while Douglas-fir can be more interesting (as described above), beech is the natural species of this stand. This implies that the regeneration of beech stand was natural (seeds from old trees) and thus without costs, unlike for Douglas-fir stand obtained artificially (plantation) involving in plantation costs.

Second, while the scenarii D_S+DR1 and D_S+DR2 were the best ones in terms of growth (ecological point of view), they presented opposite economic results. Indeed, the scenarii D_S+DR2 provides the best economic return and the scenarii D_S+DR1 the worst one. This coincide with the objective of the scenario D_S+DR2 that was to reduce plantation costs starting with 660 trees/ha (instead of 1660 trees/ha for the other scenario in the way to meet industrial demand). This result proves also the importance to have an interdisciplinary vision (here ecological and economic points of view collide).

Whether we consider the scenario D_S+DR2 or the scenario B_DR2, they showed the success of the combination of different strategies. This agrees with the idea of Jonsson et al. (2015) who promote a portfolio of adaptation strategies to reduce the risk of damage.

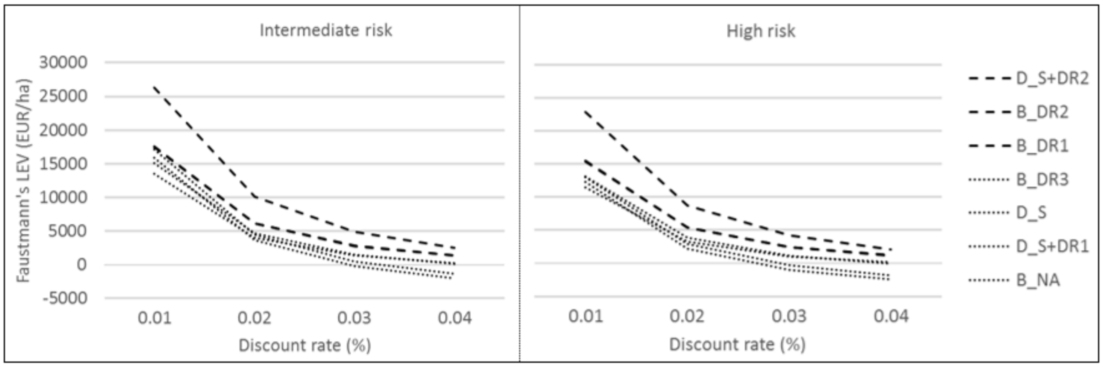
In a general overview, drought impacted more the LEV than the climate: the higher the drought intensity, the more the LEV decreased.

4.2 Sensitivity analysis

Economic evaluation often include a sensitivity analysis of discount rate to test the robustness of calculated LEV. Consequently, we analysed the variation of the different LEV function of the discount rate for each scenario analysed. Results are presented in Figure 5.

In Figure 5, the Faustmann's LEV of the scenario D_S+DR2 is the highest regardless of the discount rate for both risk. The second one is the scenario B_DR2 since a discount of rate of 1.5% for an intermediate risk and regardless of the discount rate for the high one. The order between

Figure 5: Faustmann's LEV (EUR/ha) for each scenario function of the discount rate for the RCP 4.5, for the intermediate risk (left) and the high risk (right)



scenario does not change since a discount rate of 3.5%.

The same results are observed considering the RCP 8.5 and Hartman's LEV. All these elements demonstrate the robustness of our results.

4.3 Limits and perspective

CASTANEA model was used for the first time for a purpose of forest management. A good reaction of volume increment was observed after a thinning, i.e. a boost of growth because of the increase of space to grow and water resources in the first years. However, drought generates effects on growth on the year of the event and during one or more years after (Power et al., 1995; Rouault et al., 2006). These post-effects of drought are taken into account in the model through the effect of Non Structural Carbon on growth, but they are still not properly evaluated. The three adaptation strategies (density/rotation reduction and species substitution) were chosen as the most relevant and mentioned in the literature, but also according to the technical feasibility with CASTANEA model and in Burgundy. Indeed, substitution of beech stands by Douglas-fir has already been tested in the Morvan. The architecture of CASTANEA model (inventory file for one species growing at the same age) did not allow computing intraspecific (uneven-aged forests) and interspecific (mixture of species) stands, which explains why this well-documented measure was not studied here. Indeed, many studies proved the effectiveness of mix stands that deal with biodiversity objectives to reduce drought risk (FAO, 2011; Keskitalo, 2011). Mixture permits diversifying wood production instead of opposing the different uses, with in general conifers providing lumber wood and deciduous trees providing energy wood. Therefore, to investigate this strategy, we need to develop the investigation on mix stands and the (aboveground and underground) interactions between species (competition and symbiosis) to develop then their modelling. Nonetheless, while all forest services must be taken into account in order to preserve the multifunctionality of forests, mixture strategy probably required to consider trade-offs between adaptation to drought and biodiversity objectives, that may be conflicting.

Another potential limitation of this study is that our model considers a fixed wood price grid depending on tree diameter. First, the wood price variates with the tree diameter, but also fluctuates with the supply, which are two parameters affected by climate change (cf. section 3.1), and such variations are not considered in our study. Second, the wood price increases in concert with the diversity of uses of wood and the substitution effect of fossil fuels: more and more uses are discovered for Douglas-fir wood and its growing demand is not considered in this paper.

5 Conclusion

Productivity of forests is severely constrained by water availability in the soil. We saw that drought induces large tree decline due to impacts for several years resulting in high socio-economic losses, which will be accentuated by climate change. Moreover, the literature describes the drought hazard on different levels, but without spatial analysis, as it is the case for storms and especially fire hazard (monitoring, prevention by creating transects). Indeed, a mapping based on synthetic water deficit indices would be interesting to "spatialize" the estimation of available water reserves at any time.

Our study shows that adaptation of beech stands in Burgundy is needed to fight against drought-induced decline. Adaptation is costly for forest owners. Therefore, in order to consider adaptation to drought in forest management, the forest owner needs to analyse exposure to drought, assess potential impacts, and evaluate the adaptive capacity of both the forest stand and the management system. Added to this, an important question was how to select suitable measures from the multitude of adaptation options. Through growth and carbon sequestration simulations by CASTANEA model, substitution of beech stands by Douglas-fir combined with a reduction of the initial stand density and a reduction of the rotation length provides the best economic return, regardless the climate and the level of drought risk. Our paper is the first comparing different adaptation strategies to face drought-induced risk of forest decline and the synergy of both strategies gave a robust result. We showed also that adaptation is not always beneficial economically as well as ecologically, and then that trade-offs between objectives may appear (Johnston and Withey, 2017).

Taking extreme events such as drought into account, forest management and its adaptation depend mainly on the assigned objectives (wood production, carbon sequestration), on the forest owner (State, territorial community or private), but also on the type of stands (existing, to be created, to be reforested). Research in this field can improve the understanding of drought risk and its implied mechanisms in damages. Therefore, to improve management options under severe drought, investigations should continue on this environmental hazard and risk.

In the aim to promote the best strategy to be coupled with drought risk for decision-making, we show the importance of the interconnection between different fields (ecology and economics), to take into account multifonctionnality of forests (wood production and carbon sequestration here), the need of general information of silviculture and the collaboration between different sectors (forest managers and researchers). In addition, drought increasing the vulnerability to secondary attacks (pests and pathogens), current challenges for disturbance modelling would include to perform multiple-risks analysis in dynamic ecosystems models for decision support in forest management.

Acknowledgments

This work was performed in collaboration with Bruno Borde and Alexandre Guerrier from the CRPF of Burgundy. The authors acknowledge the suggestions of Pablo Andrés-Domenech, Vincent Badeau, Philippe Delacote, Antoine Leblois, Anne Rozan and David Desmarchelier and the help of Nicolas Beudez, Nathalie Bréda, and François De Coligny. The UMR BETA is supported by a grant overseen by the French National Research Agency (ANR) as part of the "Investissements d'Avenir" program (ANR–11–LABX–0002–01, Lab of Excellence ARBRE). This work was funded by the Meta-Programme ACCAF of INRA through the project FORADAPT.

References

F. Archaux and V. Wolters. Impact of summer drought on forest biodiversity: What do we know? Annals of Forest Science, 63(6):645–652, 2006.

World Bank. Economics of adaptation to climate change: Social synthesis report. 2010.

P. Bernier and D. Schoene. Adapting forests and their management to climate change: an overview. Unasylva, 60(231-232):5–11, 2009.

Y. Birot and C. Gollier. Risk assessment, management and sharing in forestry, with special emphasis on wind storms. 14th Convocation of Academies of Engineering and Technological Sciences, 2001.

N. Bréda and V. Badeau. Forest tree responses to extreme drought and some biotic events: Towards a selection according to hazard tolerance? Comptes Rendus Geoscience, 340(9-10):651–662, 2008.

N. Bréda and M. Brunette. Are 40 years better than 55 ? an analysis of the reduction of forest rotation to face drought event. Cahiers du LEF, 2014-03, 2014.

N. Bréda and M. Peiffer. Vulnerability to forest decline in a context of climate changes: new prospects about an old question in forest ecology. Annals of forest science, 71(6):627–631, 2014.

M. Brunette, S. Costa, and F. Lecocq. Economics of species change subject to risk of climate change and increasing information: a (quasi-) option value analysis. Annals of Forest Science, 71 (2):279–290, 2014.

T. Chakraborty, S. Saha, A. Matzarakis, and A. Reif. Influence of multiple biotic and abiotic factors on the crown die-back of european beech trees at their drought limit. Flora, 229:58–70, 2017.

M. Charru, I. Seynave, F. Morneau, and J.D. Bontemps. Recent changes in forest productivity: an analysis of national forest inventory data for common beech (fagus sylvatica l.) in north-eastern france. Forest Ecology and Management, 260(5):864–874, 2010.

B. Courbaud, G. Kunstler, X. Morin, and T. Cordonnier. Quel futur pour les services ecosystémiques de la forêt alpine dans un contexte de changement climatique? Journal of Alpine Research. Revue de Géographie Alpine, 98(4), 2010. doi: 10.4000/rga.1308.

S. Couture and A. Reynaud. Forest management under fire risk when forest carbon sequestration has value. Ecological Economics, 70:2002–2011, 2011.

D. Crichton. The risk triangle. Natural Disaster Management, 102(3), 1999.

V. Dale, L. Joyce, S. McNulty, R. Neilson, M. Ayres, M. Flannigan, P. Hanson, L. Irland, A. Lugo, C.J. Peterson, D. Simberloff, F. Swanson, B. Stocks, and M. Wotton. Climate change and forest disturbances. BioScience, 51:723–734, 2001.

H. Davi and M. Cailleret. Assessing drought-driven mortality trees with physiological process-based models. Agricultural and forest meteorology, 232:279–290, 2017.

H. Davi, E. Dufrêne, A. Granier, V. Le Dantec, C. Barbaroux, C. François, and N. Bréda. Modelling carbon and water cycles in a beech forest. part ii: Validation of the main processes from organ to stand scale. Ecological Modelling, 185(2):387–405, 2005.

H. Davi, E. Dufrêne, C. François, G. Le Maire, D. Loustau, A. Bosc, S. Rambal, A. Granier, and E. Moors. Sensitivity of water and carbon fluxes to climate changes from 1960 to 2100 in european forest ecosystems. Agricultural and Forest Meteorology, 141(1):35–56, 2006.

M. de Miguel, D. Sanchez-Gomez, M. Teresa Cervera, and I. Aranda. Functional and genetic characterization of gas exchange and intrinsic water use efficiency in a full-sib family of pinus pinaster ait in response to drought. Tree Physiology, 32:94–103, 2012.

E. Dufrêne, H. Davi, C. François, G. Le Maire, V. Le Dantec, and A. Granier. Modelling carbon and water cycles in a beech forest. part i: Model description and uncertainty analysis on modelled nee. Ecological Modelling, 185(2):407–436, 2005.

P. Dwivedi, R. Bailis, A. Stainback, and D.R. Carter. Impact of payments for carbon sequestered in wood products and avoided carbon emissions on the profitability of nipf landowners in the us south. Ecological Economics, 78:63–69, 2012.

B. Eilman and A. Rigling. Tree-growth analyses to estimate tree species' drought tolerance. Tree Physiology, 32(2):178–187, 2012.

FAO. Abiotic disturbances and their influence on forest health: a review. Forest Health and Biosecurity Working Paper, 2011.

M. Faustmann. Calculation of the Value which Forest Land and Immature Stands Possess for Forestry. Translated by W. Linnard from Allgemeine Forst und Jagd Zeitung, 1849. Gane editions edition, 1849.

L. Galiano, J. Martínez-Vilalta, and F. Lloret. Carbon reserves and canopy defoliation determine the recovery of scots pine 4 yr after a drought episode. New Phytologist, 190(3):750–759, 2011. doi: 10.1111/j.1469-8137.2010.03628.x.

L. Galiano, J. Martínez-Vilalta, S. Sabaté, and F. Lloret. Determinants of drought effects on crown condition and their relationship with depletion of carbon reserves in a mediterranean holm oak forest. Tree Physiology, 32(4):478–489, 2012. doi: 10.1093/treephys/tps025.

V. Godreau. Les stations à hêtre des plateaux de bourgogne. Tome II, Conseil Régional de Bourgogne, 1992.

A.B. Guitart and L.C.E. Rodriguez. Private valuation of carbon sequestration in forest plantations. Ecological Economics, 69:451–458, 2010.

M. Hanewinkel, S. Hummel, and D.A. Cullmann. Modelling and economic evaluation of forest biome shifts under climate change in southwest germany. Forest Ecology and Management, 259 (4):710–719, 2010.

R. Hartman. The harvesting decision when a standing forest has value. Economic Inquiry, 14(1): 52–58, 1976.

M. Hotyat. Internal and external dynamics of coniferous forests: the shift to beech trees and the issue of beech wood uses. Annales de Géographie, 609-610:583–594, 1999.

P.H. Howard and T. Sterner. Raising the temperature on food prices: Climate change, food security, and the social cost of carbon. 2014.

IPCC. Climate change and biodiversity. Technical report, ISBN: 92-9169-104-7, 2002.

IPCC. Fifth assessment report. Technical report, ISBN: 92-9169-104-7, 2013.

C.M.T. Johnston and P. Withey. Managing forests for carbon and timber: A markov decision model of uneven-aged forest managementwith risk. Ecological Economics, 138:31–39, 2017.

A.M. Jonsson, F. Lagergren, and B. Smith. Forest management facing climate change - an ecosystem model analysis of adaptation strategies. Mitigation and Adaptation Strategies for Global Change, 20(2):201–220, 2015.

T.F. Keenan, D.Y. Hollinger, G. Bohrer, D. Dragoni, J.W. Munger, H.P. Schmid, and A.D. Richardson. Increase in forest water-use efficiency as atmospheric carbon dioxide concentrations rise. Nature, 499(7458):324, 2013.

L.P. Kerhoulas, T.E. Kolb, M.D. Hurteau, and G.W. Koch. Managing climate change adaptation in forests: a case study from the u.s. southwest. Journal of Applied Ecology, 50(6):1311–1320, 2013.

E.C.H. Keskitalo. How can forest management adapt to climate change? possibilities in different forestry systems. Forests, 2(1):415–430, 2011.

M. Kolström, M. Lindner, T. Vilén, M. Maroschek, R. Seidl, M.J. Lexer, S. Netherer, A. Kremer, S. Delzon, A. Barbati, M. Marchetti, and P. Corona. Reviewing the science and implementation of climate change adaptation measures in european forestry. Forests, 2(4):961–982, 2011. ISSN 1999-4907. doi: 10.3390/f2040961.

D. Konkin and K. Hopkins. Learning to deal with climate change and catastrophic forest disturbances. Unasylva, 60(231/232):17–23, 2009. ISSN 0251-1053.

N. Latte, V. Kint, T. Drouet, V. Penninckx, F. Lebourgeois, S. Vanwijnsberghe, and H. Claessens. Dendroécologie du hêtre en forêt de soignes: les cernes des arbres nous renseignent sur les changements récents et futurs. Forêt Nature, 137:24–37, 2015.

F. Lebourgeois, N. Bréda, E. Ulrich, and A. Granier. Climate-tree-growth relationships of european beech (fagus sylvatica l.) in the french permanent plot network (renecofor). Trees, 19(4):385–401, 2005.

B. Locatelli, M. Brockhaus, A. Buck, and I. Thompson. Forests and Adaptation to Climate Change: Challenges and Opportunities, volume 25 of IUFRO World Series. IUFRO, 2010. ISBN 978-3-901347-93-1.

M. Maroschek, R. Seidl, S. Netherer, and M.J. Lexer. Climate change impacts on goods and services of european mountain forests. Unasylva, 60(231/232):76–80, 2009. ISSN 0251-1053.

S. Matesanz and F. Valladares. Ecological and evolutionary responses of mediterranean plants to global change. Environmental and Experimental botany, 103:53–67, 2014.

ONF. L'eau et la forêt. Bulletinn Technique de l'ONF, 37, 1999.

P. Ozer. Introduction aux risques naturels. 2009.

A. Pierangelo and S. Dumas. Impact des sécheresses estivales sur la croissance radiale du hêtre et du sapin dans le bugey: Quelles conséquences pour la gestion? RDV Techniques, 35:62–67, 2012.

S. Power, M.R. Ashmore, and K.A. Ling. Recent trends in beech tree health in southern britain and the influence of soil type. Water, air, and soil pollution, 85(3):1293–1298, 1995.

F. Da Ronch, G. Caudullo, and D. de Rigo. Pseudotsuga menziesii in Europe: distribution, habitat, usage and threats. In: J. San-Miguel-Ayanz et al. (Eds.), European Atlas of Forest Tree Species. Publ. Off. EU, Luxembourg. 2016.

G. Rouault, J-N. Candau, F. Lieutier, L-M. Nageleisen, J-C. Martin, and N. Warzée. Effects of drought and heat on forest insect populations in relation to the 2003 drought in western europe. Annals of Forest Science, 63(6):613–624, 2006.

A.S. Sergent, P. Rozenberg, and N. Bréda. Douglas-fir is vulnerable to exceptional and recurrent drought episodes and recovers less well on less fertile sites. Annals of Forest Science, 71(6): 697–708, 2014.

S. Solberg. Summer drought: a driver for crown condition and mortality of norway spruce in norway. Forest Pathology, 34(2):93–104, 2004. ISSN 1437âĂŞ-4781.

H. Spiecker. Silvicultural management in maintaining biodiversity and resistance of forests in europe-temperate zone. Journal of Environmental Management, 67(1):55–65, 2003.

H. Spiecker, J. Hansen, E. Klimo, J. Skovsgaard, H. Sterba, and K. von Teuffel. Norway spruce conversion: Options and consequences. Research report 18, s. brill, leiden, boston, koln, European Forest Institute, 2004.

D.L. Spittlehouse and R.B. Stewart. Adaptation to climate change in forest management. BC Journal of Ecosystems and Management, 4(1), 2003.

E. Thürig, T. Palosuo, J. Bucher, and E. Kaufmann. The impact of windthrow on carbon sequestration in switzerland: a model-based assessment. Forest Ecology and Management, 210(1):337–350, 2005.

UNEO. Future of the global environment. Technical report, 4th ONUE Report on the Future of the Global Environment: Environment for Development, 2007.

Y. Veyret, R. Laganier, and A. Boissière. Atlas des Risques en France: Prévenir les Catastrophes Naturelles et Technologiques: Atlas Autrement. Autrement, 2013. ISBN 9782746734357.

P. Watkiss and T. Downing. The social cost of carbon: Valuation estimates and their use in uk policy. Integrated Assessment, 8(1), 2008.

R. Yousefpour and M. Hanewinkel. Balancing decisions for adaptive and multipurpose conversion of norway spruce (picea abies l. karst) monocultures in the black forest area of germany. Forest Science, 60(1):73–84, 2014.

R. Yousefpour, M. Hanewinkel, and G. Le Moguédec. Evaluating the suitability of management strategies of pure norway spruce forests in the black forest area of southwest germany for adaptation to or mitigation of climate change. Environmental Management, 45(2):387–402, 2010.

B. Zierl. A simulation study to analyse the relations between crown condition and drought in switzerland. Forest Ecology and Management, 188(1):25–38, 2004.

Appendices

A Silvicultural operations with associated net benefits from wood production and carbon sequestration for each scenario

B_NA		RCP 4.5				RCP 8.5			
		Intermediate risk		High risk		Intermediate risk		High risk	
Operations (tree age)	Density (N/ha)	Wood (m^3/ha)	Benefits (EUR/ha)	Wood (m^3/ha)	Benefits (EUR/ha)	Wood (m^3/ha)	Benefits (EUR/ha)	Wood (m^3/ha)	Benefits (EUR/ha)
Maintenance (5)	5000	24	-595	23	-595	23	-595	22	-595
Thinning 1 (15)	3000	97	-665	83	-665	97	-665	83	-665
Thinning 2 (30)	1500	157	786	132	660	152	760	129	644
Thinning 3 (35)	757	102	506	85	422	107	530	92	455
Thinning 4 (41)	523	93	432	79	367	101	470	87	404
Thinning 5 (49)	361	128	594	108	503	136	633	115	534
Thinning 6 (57)	249	153	948	130	808	157	976	134	830
Thinning 7 (65)	172	172	1330	148	1142	170	1315	148	1141
Thinning 8 (75)	119	197	1998	174	1769	192	1951	167	1693
Thinning 9 (85)	82	209	2602	183	2281	202	2509	176	2194
Harvest (95)		232	11599	202	10094	230	11476	199	9936

B_DR1		RCP 4.5				RCP 8.5			
		Intermediate risk		High risk		Intermediate risk		High risk	
Operations (tree age)	Density (N/ha)	Wood (m^3/ha)	Benefits (EUR/ha)	Wood (m^3/ha)	Benefits (EUR/ha)	Wood (m^3/ha)	Benefits (EUR/ha)	Wood (m^3/ha)	Benefits (EUR/ha)
Maintenance (5)	5000	28	-61	27	-61	27	-61	26	-61
Thinning 1 (15)	1100	106	-705	94	-705	105	-705	91	-705
Thinning 2 (22)	500	83	452	74	404	79	429	68	372
Thinning 3 (31)	350	112	506	96	432	115	517	99	445
Thinning 4 (36)	200	118	1011	101	870	125	1068	110	946
Thinning 5 (44)	130	132	1156	116	1011	142	1241	125	1098
Thinning 6 (52)	70	154	2350	135	2055	160	2442	143	2178
Thinning 7 (60)	60	153	875	135	772	154	879	138	788
Harvest (80)		273	13666	246	12321	267	13368	239	11934

B_DR2		RCP 4.5				RCP 8.5			
		Intermediate risk		High risk		Intermediate risk		High risk	
Operations (tree age)	Density (N/ha)	Wood (m^3/ha)	Benefits (EUR/ha)	Wood (m^3/ha)	Benefits (EUR/ha)	Wood (m^3/ha)	Benefits (EUR/ha)	Wood (m^3/ha)	Benefits (EUR/ha)
Maintenance (5)	3000	25	-61	24	-61	24	-61	23	-61
Thinning 1 (15)	1000	104	-705	91	-705	105	-705	92	-705
Thinning 2 (22)	500	93	467	83	415	89	445	77	386
Thinning 3 (31)	350	120	539	102	459	121	546	104	466
Thinning 4 (36)	200	122	1047	104	896	128	1097	112	963
Thinning 5 (44)	130	134	1173	117	1022	143	1252	126	1099
Thinning 6 (52)	70	155	2366	135	2062	161	2462	143	2180
Thinning 7 (60)	60	153	878	135	772	154	883	137	786
Harvest (80)		273	13663	246	12284	266	13317	236	11819

B_DR3		RCP 4.5				RCP 8.5			
		Intermediate risk		High risk		Intermediate risk		High risk	
Operations (tree age)	Density (N/ha)	Wood (m^3/ha)	Benefits (EUR/ha)	Wood (m^3/ha)	Benefits (EUR/ha)	Wood (m^3/ha)	Benefits (EUR/ha)	Wood (m^3/ha)	Benefits (EUR/ha)
Maintenance (5)	1000	26	-1525	25	-1525	25	-1525	24	-1525
Thinning 1 (31)	500	197	984	171	853	196	978	169	846
Thinning 2 (36)	350	124	558	107	480	130	587	115	518
Thinning 3 (44)	200	144	1238	124	1068	155	1331	135	1160
Thinning 4 (52)	130	150	1311	129	1128	157	1374	138	1209
Thinning 5 (60)	70	165	2522	145	2209	167	2549	148	2266
Thinning 6 (70)	60	180	1029	162	928	175	1003	155	887
Harvest (80)		231	11535	208	10379	226	11321	201	10074

Baseline_D		RCP 4.5		RCP 8.5	
Operations (tree age)	Density (N/ha)	Wood (m^3/ha)	Benefits (EUR/ha)	Wood (m^3/ha)	Benefits (EUR/ha)
Maintenance (5)	1300	29	-4310	24	-4310
Thinning 1 (25)	750	228	966	199	840
Thinning 2 (30)	520	175	1076	154	945
Thinning 3 (35)	360	160	1727	147	1583
Thinning 4 (40)	280	153	1361	144	1278
Thinning 5 (45)	230	166	1340	155	1253
Thinning 6 (50)	200	185	1204	172	1118
Harvest (55)		232	12734	236	12958

D_S		RCP 4.5				RCP 8.5			
		Intermediate risk		High risk		Intermediate risk		High risk	
Operations (tree age)	Density (N/ha)	Wood (m^3/ha)	Benefits (EUR/ha)	Wood (m^3/ha)	Benefits (EUR/ha)	Wood (m^3/ha)	Benefits (EUR/ha)	Wood (m^3/ha)	Benefits (EUR/ha)
Maintenance (5)	1300	27	-4310	25	-4310	22	-4310	20	-4310
Thinning 1 (25)	750	209	885	177	747	177	747	144	610
Thinning 2 (30)	520	159	979	133	820	138	846	114	699
Thinning 3 (35)	360	144	1552	121	1299	132	1422	111	1196
Thinning 4 (40)	280	138	1225	116	1031	130	1156	110	980
Thinning 5 (45)	230	150	1212	127	1025	141	1134	119	960
Thinning 6 (50)	200	168	1092	143	928	156	1014	129	841
Harvest (55)		211	11581	179	9865	216	11888	181	9972

D_S+DR1		RCP 4.5				RCP 8.5			
		Intermediate risk		High risk		Intermediate risk		High risk	
Operations (tree age)	Density (N/ha)	Wood (m^3/ha)	Benefits (EUR/ha)	Wood (m^3/ha)	Benefits (EUR/ha)	Wood (m^3/ha)	Benefits (EUR/ha)	Wood (m^3/ha)	Benefits (EUR/ha)
Maintenance (5)	1660	29	-5110	27	-5110	24	-5110	22	-5110
Thinning 1 (25)	800	242	1256	212	1099	207	1072	175	909
Thinning 2 (31)	560	171	1025	149	892	151	906	128	769
Thinning 3 (38)	430	180	1673	157	1460	171	1582	151	1398
Harvest (45)		226	12405	198	10896	239	13165	215	11828

D_S+DR2		RCP 4.5				RCP 8.5			
		Intermediate risk		High risk		Intermediate risk		High risk	
Operations (tree age)	Density (N/ha)	Wood (m^3/ha)	Benefits (EUR/ha)	Wood (m^3/ha)	Benefits (EUR/ha)	Wood (m^3/ha)	Benefits (EUR/ha)	Wood (m^3/ha)	Benefits (EUR/ha)
Maintenance (5)	660	30	-1200	28	-1200	24	-1200	22	-1200
Thinning 1 (30)	520	282	1194	247	1046	241	1021	206	871
Thinning 2 (35)	360	253	2729	222	2390	223	2401	193	2082
Thinning 3 (40)	280	213	1891	188	1668	193	1711	168	1496
Harvest (45)		230	10359	204	9158	238	10724	214	9627

Baseline	Beech				Douglas			
	RCP 4.5		RCP 8.5		RCP 4.5		RCP 8.5	
Tree age (years)	Carbon (T/ha)	Benefits (EUR/ha)	Carbon (T/ha)	Benefits (EUR/ha)	Carbon (T/ha)	Benefits (EUR/ha)	Carbon (T/ha)	Benefits (EUR/ha)
0	-85	-3734	-84	-3714	-78	-3451	-80	-3512
15	36	1574	36	1588				
25					77	3406	67	2961
30	22	966	21	919	-18	-793	-15	-667
35	-19	-852	-17	-749	-5	-225	-2	-106
40					-2	-102	-1	-44
41	-3	-135	-2	-105				
45					4	194	4	173
49	13	565	13	576				
50					6	281	6	246
55					16	691	22	948
57	9	388	8	336				
65	6	266	4	185				
75	8	352	8	349				
85	5	208	4	162				
95	9	402	10	451				

B_NA	RCP 4.5				RCP 8.5			
	Intermediate risk		High risk		Intermediate risk		High risk	
Tree age (years)	Carbon (T/ha)	Benefits (EUR/ha)	Carbon (T/ha)	Benefits (EUR/ha)	Carbon (T/ha)	Benefits (EUR/ha)	Carbon (T/ha)	Benefits (EUR/ha)
0	-79	-3458	-68	-3009	-78	-3421	-67	-2962
15	33	1444	28	1235	33	1452	28	1235
30	20	898	17	733	19	815	16	685
35	-19	-818	-16	-697	-15	-671	-13	-551
41	-3	-136	-2	-93	-2	-85	-2	-71
49	12	515	10	432	12	519	9	416
57	9	376	8	332	7	318	6	280
65	7	287	6	260	4	189	5	207
75	8	364	9	391	7	325	6	282
85	4	188	3	138	3	145	3	146
95	8	340	6	276	9	414	8	333

B_DR1	RCP 4.5				RCP 8.5			
	Intermediate risk		High risk		Intermediate risk		High risk	
Tree age (years)	Carbon (T/ha)	Benefits (EUR/ha)	Carbon (T/ha)	Benefits (EUR/ha)	Carbon (T/ha)	Benefits (EUR/ha)	Carbon (T/ha)	Benefits (EUR/ha)
0	-93	-4074	-83	-3673	-91	-3986	-81	-3558
15	36	1577	32	1395	36	1563	31	1361
22	-8	-339	-7	-288	-9	-390	-8	-344
31	10	437	7	326	12	541	10	457
36	2	82	2	79	3	143	4	169
44	5	212	5	211	6	259	5	227
52	7	329	7	287	6	273	6	260
60	0	-17	0	3	-2	-98	-2	-77
80	41	1794	38	1661	39	1696	34	1505

B_DR2	RCP 4.5				RCP 8.5			
	Intermediate risk		High risk		Intermediate risk		High risk	
Tree age (years)	Carbon (T/ha)	Benefits (EUR/ha)	Carbon (T/ha)	Benefits (EUR/ha)	Carbon (T/ha)	Benefits (EUR/ha)	Carbon (T/ha)	Benefits (EUR/ha)
0	-93	-4073	-83	-3662	-90	-3970	-80	-3524
15	35	1547	31	1359	36	1562	31	1369
22	-4	-154	-3	-121	-5	-236	-5	-219
31	9	391	6	284	11	482	9	394
36	1	35	1	35	2	99	3	129
44	4	178	4	183	5	227	5	200
52	7	316	6	275	6	274	6	258
60	-1	-25	0	-3	-2	-106	-2	-82
80	41	1786	37	1650	38	1669	34	1475

B_DR3	RCP 4.5				RCP 8.5			
	Intermediate risk		High risk		Intermediate risk		High risk	
Tree age (years)	Carbon (T/ha)	Benefits (EUR/ha)	Carbon (T/ha)	Benefits (EUR/ha)	Carbon (T/ha)	Benefits (EUR/ha)	Carbon (T/ha)	Benefits (EUR/ha)
0	-78	-3439	-70	-3095	-77	-3375	-68	-3004
31	67	2935	58	2543	66	2917	57	2522
36	-25	-1086	-22	-953	-22	-974	-18	-807
44	7	302	6	265	8	370	7	301
52	2	82	2	67	1	27	1	43
60	5	233	5	237	3	152	4	156
70	5	215	6	258	3	121	2	96
80	17	759	15	677	17	762	16	692

D_S	RCP 4.5				RCP 8.5			
	Intermediate risk		High risk		Intermediate risk		High risk	
Tree age (years)	Carbon (T/ha)	Benefits (EUR/ha)	Carbon (T/ha)	Benefits (EUR/ha)	Carbon (T/ha)	Benefits (EUR/ha)	Carbon (T/ha)	Benefits (EUR/ha)
0	-71	-3139	-61	-2674	-73	-3222	-61	-2703
25	71	3121	60	2632	60	2633	49	2151
30	-17	-745	-15	-642	-13	-578	-10	-454
35	-5	-230	-4	-194	-2	-89	-1	-42
40	-2	-90	-1	-66	-1	-25	0	-9
45	4	186	4	167	4	158	3	131
50	6	263	5	231	5	227	3	150
55	14	634	12	545	20	896	18	775

D_S+DR1	RCP 4.5				RCP 8.5			
	Intermediate risk		High risk		Intermediate risk		High risk	
Tree age (years)	Carbon (T/ha)	Benefits (EUR/ha)	Carbon (T/ha)	Benefits (EUR/ha)	Carbon (T/ha)	Benefits (EUR/ha)	Carbon (T/ha)	Benefits (EUR/ha)
0	-76	-3362	-67	-2953	-81	-3568	-73	-3206
25	82	3614	72	3163	70	3084	59	2615
31	-24	-1067	-21	-946	-19	-832	-16	-705
38	3	141	3	129	7	290	8	336
45	15	674	14	607	23	1027	22	960

D_S+DR2	RCP 4.5				RCP 8.5			
	Intermediate risk		High risk		Intermediate risk		High risk	
Tree age (years)	Carbon (T/ha)	Benefits (EUR/ha)	Carbon (T/ha)	Benefits (EUR/ha)	Carbon (T/ha)	Benefits (EUR/ha)	Carbon (T/ha)	Benefits (EUR/ha)
0	-78	-3432	-69	-3034	-81	-3553	-72	-3189
30	95	4199	84	3677	82	3590	70	3064
35	-10	-424	-8	-373	-6	-270	-4	-184
40	-14	-599	-11	-504	-10	-447	-8	-369
45	6	256	5	233	15	680	15	678

Highlights

- Drought affects forest growth resulting in timber production and carbon losses.
- We combined a forest growth simulator with a classical forest economics approach.
- We compared and combined different options of forest adaptation under two climates.
- Forest needs adaptation and combining strategies provided the best economic return.
- Ecological results and economics ones sometimes collide.

Table S1: Parameters of CASTANEA model for Douglas based on the parametrization for *Abies alba* and literature survey

Variable	Value	Unit
Leaf construction cost	1.21	$g_C.g_C^{-1}$
Coarse roots construction cost	1.2	$g_C.g_C^{-1}$
Fine roots construction cost	1.28	$g_C.g_C^{-1}$
Wood construction cost	1.18	$g_C.g_C^{-1}$
Rate of alive cells in stem	0.46	%
Rate of alive cells in branches	0.46	%
Rate of alive cells in coarse roots	0.46	%
[lignines] in roots	0.25	$g_{Lignines}.g_{DM}$
[lignines] in fine roots litter	0.38	$g_{Lignines}.g_{DM}$
[lignines] in leaf litter	0.38	$g_{Lignines}.g_{DM}$
[lignines] in fine branches litter	0.35	$g_{Lignines}.g_{DM}$
[lignines] in coarse branches litter	0.35	$g_{Lignines}.g_{DM}$
[lignines] in coarse roots litter	0.38	$g_{Lignines}.g_{DM}$
initial [NSC] in living tissue	0.15	$g_{Lignines}.g_{DM}$
[nitrogen] in leaves	0.017	$g_N.g_{DM}^{-1}$
[nitrogen] in coarse roots	0.00094	$g_N.g_{DM}^{-1}$
[nitrogen] in fine roots	0.0036	$g_N.g_{DM}^{-1}$
[nitrogen] in branches	0.01027	$g_N.g_{DM}^{-1}$
[nitrogen] in stem	0.00094	$g_N.g_{DM}^{-1}$
[nitrogen] in reserves	0.0004	$g_N.g_{DM}^{-1}$
Predawn potential for growth cessation	-1.6	Mpa
Carbon allocation coefficient to wood	0.42	$g_C.g_C^{-1}$
Fine roots turn over	1	$g_C.g_C^{-1}.year^{-1}$
Ratio between branches and total aboveground biomass	0.15	$g_C.g_C^{-1}$
Ratio between coarse roots and total wood biomass	0.20382166	$g_C.g_C^{-1}$
Ratio between fine roots and leaves biomass	0.3	$g_C.g_C^{-1}$
Branches mortality rate	0.00007	$g_C.g_C^{-1}.year^{-1}$
Needle area	0.0005	m2
Leaf Mass per Area of sun leaves	360	g/m2
Extinction coefficient of Leaf Mass per Area within the canopy	0.0729	m^{-2}
Leaf angle	40	°
Branches angle	8.7	°
Slope of the crown area to dbh relation	0.08151	m^2.cm-1
Intercept of the crown area to dbh relation	0.69535	m^2
Slope of the LAI-dbh relationship	1.5	$m^2.cm^{-1}$
Power coeffiecient of the LAI-dbh relationship	0.45	cm^{-1}
Power coeffiecient of the [NSC] effect on the LAI-dbh relationship	0.3	g_C^{-1}
Slope of the height-dbh relationship	1.52	m
Power coeffcient of the height-dbh relationship	0.7972	cm^{-1}
Form coeffcient of stem	0.447	$m^3.m^{-3}$
Wood density	550	$Kg.m^{-3}$

canopy clumping coefficient	0.46	$m^{-2}.m^{-2}$
Wood reflectance in PIR domain	0.3	$J.J^{-1}$
Wood reflectance in PAIR domain	0.15	$J.J^{-1}$
Leaf reflectance in PIR domain	0.33	$J.J^{-1}$
Leaf transmittance in PIR domain	0.225	$J.J^{-1}$
Leaf reflectance in PAR domain	0.09	$J.J^{-1}$
Leaf transmittance in PAR domain	0.045	$J.J^{-1}$
Water storage capacity per unit of leaf area	0.4	$mm.m^{-2}$
Water storage capacity per unit of bark area	0.32	$mm.m^{-2}$
Slope of the water interception coeficient	0.85	$mm.mm^{-1}$
Intercept of the water interception coeficient	1.5	mm
Ratio between stemflow and throughfall	0.35	$mm.mm^{-1}$
Intercept of ball and berry relation	0.001	$mmol.m^{-2}.s^{-1}$
Slope of ball and berry relation	9.5	Dimensionless
Roots to leaves resistance to flow transport per Area Sapwood basis	28747	$g_{H2O}.Mpa^{-1}.m\text{-}2.s^{-1}.g_C^{-1}$
Capacitance of trunk	0.04	Kg/m3/Mpa
Water potential inducing 50% loss of conductivity	-3.6	Mpa
Dependency between VCmax and leaf nitrogen density	23.3210084	$mol_{CO2}.gN^{-1}.s^{-1}$
Curvature of the quantum response of the electron transport rate	0.7	Dimensionless
Base temperature for forcing budburst	1	°C
Base temperature for leaf growth	0	°C
Base temperature for forcing leaf fall	20	°C
Date of onset of rest	70	Julian day
Date of onset of ageing	213	Julian day
Critical value of state of forcing (from quiescence to active period)	400	°C
Critical value of state of forcing (from leaf development to maximum LAI)	350	°C
Critical value of state of forcing (from leaf development to leaf maturity)	424	°C
Critical value of state of forcing (from NStart2 to leaf fall period)	100	°C
Critical value of state of forcing from NStart2 to end of wood growth	300	°C
Minimal temperature below which frost has an effect on young buds	-3	°C
Phenologie type (1\: deciduous 2\: evergreen)	2	
Maximum needle or leaves lifespan	11	years

Figure S1: The four SAFRAN points (3202, 3710, 4303, 5121) function of the summer precipitation and mean temperature