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Analysis

An Economic Comparison of Adaptation Strategies Towards a Drought-induced Risk of Forest Decline

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ABSTRACT

Drought is a source of stress that affects forest growth, resulting in financial losses for forest owners and amenity losses for society. Due to climate change, such natural events will be more frequent and intense in the future. In this context, the objective of this paper is to compare, from an economic perspective, different forest adaptation strategies towards a drought-induced risk of decline. For that purpose, we focused on a case study of a beech forest in Burgundy (France) and we studied several adaptation options: density reduction, reduction of the rotation length, and substitution with Douglas-fir. We also considered two levels of drought risk (intermediate and low soil water capacity) and two climate scenarios from the IPCC (RCP 4.5 and RCP 8.5). We combined 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 scenarios considered. Combining strategies appears as a relevant way to adapt forests in view of a drought-induced risk of forest decline. We also demonstrated the importance of considering two disciplinary fields. Beneficial scenarios in an ecological perspective were not necessarily beneficial in an economic one and vice versa.

1. Introduction

Drought is the principal source of stress that limits forest health (Zierl, 2004), even if drought-induced impacts on forest health have been underestimated for a very long time due to inconspicuous damage 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 from soil erosion and biodiversity. In parallel, drought-induced tree decline is significantly increasing worldwide (Bréda and Badeau, 2008), even more with climate change that is increasing the frequency, duration and intensity of extreme events (Dale et al., 2001).

Human interventions also affect drought through silviculture. Indeed, sustainable forest management is needed to maintain the resilience of forest ecosystems and to cope with climate threats such as drought (Bréda and Badeau, 2008). In fact, forest owners can protect their forests through adaptation and several strategies seem to be well suited for adapting forests to increasing risks of drought. Some examples of these measures include the reduction of rotation length or stand density, as well as shifting to species better-adapted to drought (Spittlehouse and Stewart, 2003).

In this context, we can therefore ask ourselves what the relevant adaptation options are, from an economic perspective, to deal with the drought-induced risk of forest decline. We thus propose an analysis of the economic costs and benefits of adaptation for forest owners to the drought-induced risk of decline.

In the literature, few studies have tackled the question of adaptation to climate change using a forest economics approach. Such studies have typically performed a cost-benefit analysis through the maximization of the net present value (NPV) or Faustmann's land expectation value (LEV). In this context, several strategies are then analyzed. Hanewinkel et al. (2010) and Brunette et al. (2014) studied the shift to better-adapted species. The first paper deals with a shift from Norway spruce to European beech in Germany, while the second one deals with a change from Norway spruce to Douglas-fir in France. Whereas in Germany adaptation seems to correspond to financial loss, in France it seems that conversion to Douglas-fir may be a source of profit for the forest owner. The species mixture is analyzed in Yousefpour and Hanewinkel (2014) with the question of admixing beech into a Norway spruce stand. They found that the best solution in economic terms is to establish beech regeneration in 46% of the Norway spruce area. Bréda and Brunette (2019) focused on the reduction of rotation length for Douglas-fir in France as a potential adaptation strategy towards a drought-induced risk of forest decline. They showed that adaptation is

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always preferable in economic terms for the forest owner.

This short literature review reveals that past articles always focused on one strategy at a time. They never compared different strategies or analyzed combinations of them. An exception is probably the study by Jönsson et al. (2015), which compares different adaptation strategies against storms. However, the methodology is different and based on the impact of adaptive forest management on productivity and sensitivity to storms. Another observation is that only one article deals with the drought-induced risk of forest decline (Bréda and Brunette, 2019). Finally, climate scenarios are rarely considered.

The objective of this paper is to carry out an economic comparison of different adaptation strategies to fight against the drought-induced risk of forest decline. For that purpose, we adopted an original approach that combines CASTANEA, a process-based forest-growth model, with a classical forest economic analysis. CASTANEA is a mechanistic model for simulating the functioning of the main managed European tree species (Davi et al., 2005; Dufrêne et al., 2005). The model simulates the main stocks of the forest ecosystem (carbon, water, nitrogen) aboveground and belowground, at time steps ranging from half an hour to a century. Only a mechanistic model can precisely simulate forest growth in reaction to drought and climate change, as well as the impact in terms of carbon sequestration. CASTANEA was chosen because it is the only model that simulates both carbon sequestration (Davi et al., 2006) and tree growth (Davi et al., 2009), while integrating the risk of mortality related to water stress (Davi and Cailleret, 2017) and that takes the specificity of each species into account, contrary to global models. We simulated forest stands according to different adaptation strategies (density reduction, reduction of rotation length and species shift) under two climate scenarios from the 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 analysis based on Faustmann's formula and Hartman's formula. Faustmann's LEV takes the costs and the benefits from wood harvesting into account, whereas Hartman's LEV also considers the benefits from amenities, in our case, carbon sequestration. The maximization of these criteria showed that adaptation provided the best economic return, as opposed to the baseline or the “do-nothing” scenario. Indeed, substitution with 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 climate scenarios. From an economic perspective, the combination of different strategies was therefore more beneficial for the forest owner than each strategy separately (synergy vs. additionality). These results are discussed with regard to the financial balance and the carbon balance.

The rest of the paper is structured as follows. The material and the methods are presented in Section 2. Section 3 provides the results. The results are discussed in Section 4, and Section 5 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”. More precisely, from the ecophysiological point of view, drought is a reduction of the soil water reserve sufficiently severe to prevent the optimal functioning of trees due to insufficient precipitation, high temperature and large water uptake by trees. The definitions of drought vary greatly from country to country, but the literature identifies four different types of drought, including the edaphic (or agronomic) drought that is particularly of interest to us since it refers to the soil and to the impacts on living beings.

The precipitation regime is the first determinant in the development of a state of drought. It results from a pluviometric drought, which is a prolonged rainfall deficit compared to the mean or median (that is the normal state). However, drought also depends on the evapotranspiration level that is closely related to the temperature and atmospheric drought. The estimation of the water balance makes it possible to define the conditions under which precipitation distribution, soil water reserves and losses by evapotranspiration or drainage induce a negative effect on trees, referred to as 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. We use the available water content (AWC) to illustrate this water stress.

According to Crichton (1999), 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 intensity (i.e., the magnitude of the phenomenon), its severity (linked to the duration of the phenomenon), and its frequency (i.e., the probability of damage). Exposure is the level or the conditions at 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 (e.g., compact and shallow soils). Vulnerability refers to the internal characteristics of the stand, influenced by species ecology, soil characteristics or stand density. It shows the extent to which the stand is likely to suffer from damage related to the hazard. Consequently, it takes the sensitivity of individuals to the effects of a hazard into account, 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 natural risk therefore implies the perception of this hazard by the population and, subsequently, its management (for cohabitation with the danger) (Veyret et al., 2013). Adaptation strategies will consequently play a role on vulnerability through the implementation of a water-saving silviculture.

The impacts of drought may be classified as biological or socio-economic. Four categories of biological impacts can be distinguished: accommodation through changes in physiological functioning (Bréda and Badeau, 2008; Matesanz and Valladares, 2014), in phenology or in tree growth (Matesanz and Valladares, 2014; Solberg, 2004); genetic adaptation (de Miguel et al., 2012); and migration and tree mortality (Galiano et al., 2011; Galiano et al., 2012; Spiecker et al., 2004). 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, whereas at the ecosystem level, drought reduces most of the biological cycles that affect the functions of the forest and that lead to 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, a decrease in future stand value, the additional cost of forest restoration, and the loss of hunting 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 are likely to be intensified in the 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, the most important of which is carbon dioxide (CO_2) (IPCC, 2013). Climate will thus evolve towards an increase in average temperature, an escalation in the differences between wet and dry regions, a decrease in water availability, and an increase in the frequency and the intensity of extreme events such as severe drought (Spiecker, 2003). However, increasing CO_2 can also limit the drought effect by increasing the 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 can 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[1] given by the World Bank (2010): (1) the reduction of rotation length (soft adaptation); and (2) species substitution from beech to Douglas-fir (hard adaptation). These two strategies are analyzed separately as well as jointly, and in combination with a third strategy, density reduction (soft adaptation).

First, the reduction of rotation length reduces the time of exposure to a drought event and the vulnerability of trees due to aging (Bréda and Peiffer, 2014; Spiecker, 2003). Young and old trees are the most vulnerable to drought (Archaux and Wolters, 2006): special attention must therefore be paid to the establishment of young trees and to 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, i.e., species able to thrive in both the current and projected future climate (e.g., pine, Douglas-fir, *Robinia*).

Third, the reduction of the leaf area and, therefore, of the stand density, improves the resistance of forest stands to the lack of water (Archaux and Wolters, 2006; Bréda and Badeau, 2008), reduces the intensity and duration of water deficits, and increases water availability (Spiecker, 2003). This results in an increase in initial planting space (Spiecker, 2003) and more intensive and earlier thinning (Keskitalo, 2011; Spiecker, 2003) in order to stabilize and thus protect stands (i.e., to have a continuous forest cover and to protect it from all hazards) (Bernier and Schoene, 2009; Spiecker, 2003), to take advantage of CO_2 fertilization to maximize and accelerate growth (Bernier and Schoene, 2009), to increase resistance and resilience to future damage (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 major forest regions in France in terms of afforestation (30% afforestation rate), which has increased over the last 30 years. It has a great geographic (from valleys to mountains) and geological diversity. Its contrasted climate is of the Atlantic type with rainfall spread out throughout the year, ranging from 600 mm (Loire valley) to 1500–1800 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 due to forest mechanization) threaten the health of forests. Burgundy forests 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 can be 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 to thus avoid financial losses, and to respond to the growing demand for wood, with a more dynamic silviculture. Beech and Douglas-fir also produce commercially highly-valued wood in Burgundy, i.e., their annual production is 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 degree of atmospheric humidity and sufficient soil moisture (Latte et al., 2015), which can barely tolerate extreme conditions, as well as spring frosts (Godreau, 1992). More precisely, it is the climate criteria (annual distribution of precipitation and temperature) that determine the presence or the state of health of beech, rather than soil conditions (Godreau, 1992). However, due to climate change, this species could decline or even disappear (Charru et al., 2010). Indeed, the increase in the frequency and intensity of spring droughts and heat waves has already negatively affected the annual growth of beech trees (Latte et al., 2015). 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 to the increase in neighboring interactions and in the diversity of tree species (Chakraborty et al., 2017).

Overall, distribution in France is limited by temperature for Mediterranean species and by water supply for northern species as well as deciduous species (beech, oak) and conifers (Douglas-fir, spruce, fir). This is why the hydric constraints in the northern half of France cast doubts on the existence and the production of these latter species, particularly beech that has had many diebacks on superficial soils with low water reserves. Substitution with a species that is more productive under a 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 interest of the French public authorities (e.g., the National Forest Fund in France during the period 1946–2000) and some professionals (builders, wood producers, furniture industries) in the rapid growth, the lower cost of production and maintenance, and the standardized sawing techniques of conifers (pine, fir), the demand would be based on an accelerated national production of conifers. Since two-thirds of the French forest is composed of deciduous trees, the transition could be backed by a less water-consuming silvicultural system, which is linked to the subject of our study.

A native of western North America, Douglas-fir (*Pseudotsuga menziesii* Mirb.) is an introduced species valued by forest managers for its rapid growth and the quality of its wood (Da Ronch et al., 2016). It appears to be able to provide significant wood production under a relatively dry climate (Da Ronch et al., 2016; Eilman and Rigling, 2012). However, despite all these qualities, Douglas-fir is more sensitive to high temperatures due to its high leaf area (i.e., strong transpiration) than to droughts. This explains the damage reported in France after the drought in 2003 (because of its combination with a heat wave), in particular in the 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 does not seem to be well-adapted to the range and accumulation of intense and recurrent episodes of drought after a severe one, which could be explained by a lack of resilience, e.g., after the drought in 2003 (Sergent et al., 2014).

Beech and Douglas-fir are both 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 their high requirement for atmospheric moisture, although they are present in the plains. 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

[1] Soft adaptation consists of measures that are desirable, even in the absence of climate change, with soft and progressive change, while hard adaptation implies greater and more brutal changes to adapt the ecosystem.

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 consumes more water reserves than Douglas-fir in summer. However, edaphic drought can be aggravated by the existence of a high evaporation demand. Finally, (Bréda and Badeau, 2008) confirmed that the development of beech is dependent on water balance and drought, whereas for species such as Douglas-fir, its development is mainly related to temperature, supporting our suggestion to substitute beech with Douglas-fir.

2.2.3. Study scenarios

For this study, we chose to test two levels of drought risk defined according to the level of soil available water capacity (AWC). Three levels of AWC were considered: 150, 100 and 50 mm. These levels were chosen according to the range of AWC of current beech stands in Burgundy. The level of 150 mm represents optimal water conditions for beech growth, 100 mm is the initial risky scenario with one-third less of the baseline level of water availability for trees, and 50 mm is the 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 under 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 climate scenarios from the IPCC were analyzed: 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 scenario × 2 drought risks) × 2 climates], which is equal to 32 scenarios. The two baselines and the seven scenarios are summarized in Table 1.

The scenario is indicated by the following code for the benchmark (AWC of 150 mm): Baseline_Species (B for beech or D for Douglas-fir). The scenario is indicated by 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). Scenarios 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 plus 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 deal with the drought-induced risk of forest decline, we first simulated forest growth with different silvicultural treatments according to these different adaptation strategies, the three different levels of water content and the two climate scenarios. The simulations were run with the CASTANEA model. The economic approach was then applied to the outcome of the simulations.

Table 1
The different scenarios considered and their distinctive 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 an initial 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

2.3.1. Simulation of forest growth and silvicultural treatments

CASTANEA requires three different files as inputs: 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. R software makes it possible to generate the list of all the trees according to soil characteristics. The soil characteristics (height, stone content, etc.) are directly linked to the AWC and parameters of the managed stand (tree diameter, LAI, etc.). Second, the species file contains all the species-specific parameters that control the 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 climates (RCP 4.5 and RCP 8.5) came from the Meteo France network for four different SAFRAN points of 8 × 8 km (3202, 3710, 4303, 5121), chosen to represent the variety of climates in Burgundy. All of the results for each scenario are then taken from the average of the four SAFRAN points (see Fig. S1 in Supplementary Material).

CASTANEA simulates photosynthesis and respiration to estimate net primary production. Carbon is then allocated to six compartments following the allocation rules described in Davi and Cailleret (2017) and Davi et al. (2009): large roots, fine roots, reserves, leaves, branches and trunks. Biomass growth in the trunk is converted into volume growth from the density of the wood at the end of the year. This makes it possible to estimate growth in ring width and volume on an annual basis.

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 was 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 the midday leaf water potential drops below the P50 of the species (leaf water potentials below which 50% of conductivity loss occurs). The threshold of mortality on [NSC] is estimated by fitting the threshold to minimize the difference among simulated and measured annual mortality rates between 2000 and 2015 once the hydraulics failure was computed. The mortality measurements were taken from the French National Inventory on Burgundy.

The CASTANEA model simulated the forest growth of a stand of 1 ha through different silvicultural paths starting from a 125-year-old beech forest in Burgundy from 2000 to 2100. The silvicultural paths arise from the CRPF (Regional Center for Privately-Owned Forests) 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) that characterized the drought effect and two different IPCC scenarios (RCP 4.5 and RCP 8.5) that characterized the climate effect.

2.3.2. Economic approach

Fig. 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 the CASTANEA model) was the input of the economic approach.

Our objective was to compare the 32 LEVs among scenarios. All the comparisons of LEV are detailed according to Fig. 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.

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 (NR 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

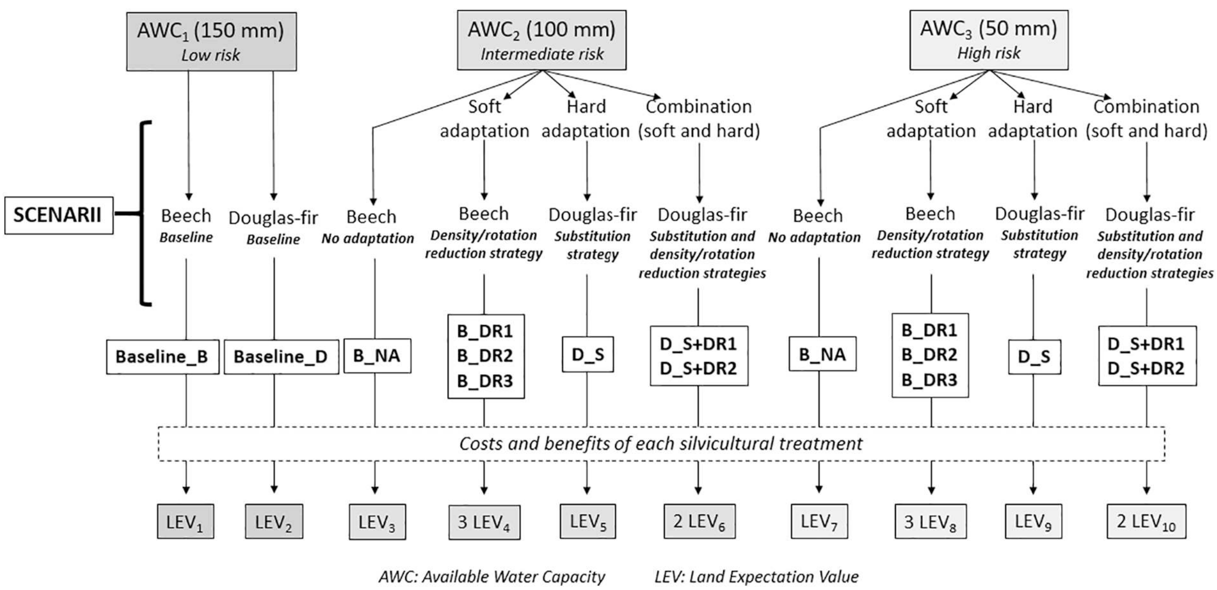


Fig. 1. Schematic representation of the methodology applied: From scenario structure to economic evaluation.

• (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 that of density/rotation reduction.

First, the sum of an infinite number of rotations made it possible to calculate the land expectation value, commonly referred to as the Faustmann criterion in forest economics (Faustmann, 1849), as follows:

$$\text{LEV (Faustmann)} = \sum_{i=0}^{\infty} \sum_{n=0}^{N-1} \frac{B_n - C_n}{(1+r)^{(i.N+n)}} \tag{1}$$

where B is the benefits, C the costs, r the discount rate, n the stand age, N the rotation length and i the rotation number.

It is assumed here that the forest owner has a single objective: to maximize LEV. The infinite horizon used by this criterion makes it possible to compare management options associated with different temporal horizons, assuming that the silvicultural path was identical for each subsequent rotation after the first one. 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. This may be seen as a limit of this criterion. However, other existing ones present greater limitations and are rarely adopted (Fraysse et al., 1990; Morel and Terreaux, 1995). Faustmann's LEV takes the costs and the benefits from wood harvesting into account. After discussion with forestry experts, a discount rate r of 3% was chosen. A sensitivity analysis on this parameter was performed and is presented in Section 4.2.

We also asked ourselves if the consideration of forest ecosystem services may impact the economic results. In the context of mitigation of climate change, we chose to consider carbon sequestration in particular. In fact, carbon loss is rarely considered in the literature in addition to economic loss (see Yousefpour and Hanewinkel, 2014 for an exception).

For that purpose, we also calculated Hartman's LEV, which makes it possible to consider the benefits from wood harvesting and from amenities simultaneously (Hartman, 1976), in our case, carbon sequestration[2]. The Hartman model was applied as follows:

$$\text{LEV (Hartman)} = \sum_{i=0}^{\infty} \sum_{n=0}^{N-1} \frac{B_n - C_n}{(1+r)^{(i.N+n)}} + \sum_{i=0}^{\infty} \sum_{n=0}^{N-1} \frac{B'_n}{(1+r)^{(i.N+n)}} \tag{2}$$

where B is the benefits from wood production, C the costs of the silvicultural treatment, B' the benefits from carbon sequestration provided by the forest stand, r the discount rate, n the stand age, N the rotation length and i the rotation number.

The discount rate r was also 3% for beech and Douglas-fir in order to be able to compare LEVs. To compute 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 generated by each ton of CO_2 that is spewed into the air" (Howard and Sterner, 2014). It therefore gives the total value of avoided damage caused by the flow of carbon to the atmosphere in the case of potential total deforestation.

[2] See Couture and Reynaud, 2011 for a short review of studies using Hartman's framework with carbon storage.

Table 3
Stand density (number of trees per hectare), volume of wood (in cubic meters per hectare) and associated net benefits from its production (in euros per hectare) for each silvicultural operation for the beech benchmark (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	12,524	249	12,457

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 scenarios are presented in the Appendices.

3. Results

3.1. Forest growth and mortality

Figs. 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 meters per hectare) and mortality (in percentage terms), respectively. Mortality was taken into account when computing volume.

In Fig. 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 mortality. There is no difference between scenarios when considering the same tree species. Climate change has a negative effect on mortality: Scenarios in RCP 8.5 (pessimistic climate scenario) present higher mortality rates 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 the mortality of Douglas-fir.

In Fig. 3, we can see that Douglas-fir presents a higher volume increment of wood than beech (baseline and scenarios). Drought has a negative effect for all the scenarios: We observe a lower growth in scenarios with high risk as opposed to those with intermediate risk. Climate change has a negative effect for all the scenarios too: they present lower growth in RCP 8.5 than in RCP 4.5. Combinations of different strategies (D_S + DR1 and D_S + DR2) have the best growth, unlike non-adaptation (B_NA), which is below the baseline.

These two figures presented interesting results from an ecological point of view. First, the scenarios with Douglas-fir showed the highest volume increment of wood, whereas they had the highest mortality rates. More precisely, the two scenarios that combined two strategies (D_S + DR1 and D_S + DR2) were the best ones, showing a higher growth in the more severe climate scenario (RCP 8.5) than in the small-temperature increment scenario (RCP 4.5). All these elements corroborate the literature describing Douglas-fir as a high productive species in dry climates (Da Ronch et al., 2016; Eilman and Rigling, 2012).

In contrast, the scenarios with beech showed the lowest volume increment of wood, whereas they had the lowest mortality rate. More precisely, they showed a lower growth rate under the high drought risk than under the intermediate one, which is consistent with its known sensitivity to drought (Chakraborty et al., 2017; Charru et al., 2010; Latte et al., 2015).

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

Generally speaking, drought negatively influences mortality and the volume increment of wood. Concerning climate change, the higher the intensity is, the more the mortality rate of the stand will increase. That is why, regarding these two outputs of the CASTANEA model, adaptation seemed more profitable than the baseline or the absence of adaptation.

3.2. Economic comparison

The resulting variations in LEVs compared to the baseline of beech (Baseline_B) are presented in Table 4. Faustmann's LEV ranges from −983 to 4916 EUR/ha and from −866 to 4717 EUR/ha for the RCP 4.5 and 8.5, respectively. In terms of implementation of adaptation strategies, scenarios with a positive variation of LEVs compared to the baseline represent the benefit of adaptation for forest owners: B_DR1, B_DR2 and D_S + DR2. In contrast, scenarios with a negative variation of LEVs compared to the baseline represent the potential cost of adaptation for forest owners: B_DR3, D_S and D_S + DR1.

Concerning the baseline, maintaining the current beech stand was more profitable than substituting it with Douglas-fir. Table 4 reveals that a substitution strategy combined with that of a density reduction (D_S + DR2) provides the best economic return, regardless of the level of drought risk and the climate scenario. In a second step, the density reduction of beech then provides the best economic return with the scenario B_DR2, followed by the scenario B_DR1. Note that the two other scenarios with Douglas-fir (D_S and D_S + DR1) are the worst options from an economic perspective, regardless of the level of drought risk and the climate scenario.

Based on Table 4, we can say that costs and benefits of adaptation strategies are clearly not additive, but synergies between adaptation strategies appear to be. For example, for an intermediate level of risk, considering only the reduction of the initial rotation length of the beech stand (B_DR1) allows a financial benefit (+79%), applying a first reduction of initial density (B_DR2) as well (+82%). However, a more intense density reduction (B_DR3) generates loss (−3%) due to the beech characteristics (shadow species). The same comment applied for high risk. In the same vein, implementing substitution alone (D_S) corresponds to financial loss (−67%), and adding a reduction of rotation length (D_S + DR1) increases the previous loss (−111%). However, combining the three strategies (substitution with a reduction of rotation length and stand density, D_S + DR2) makes it possible to generate the highest benefits (+216%). This observation is also true for high risk. Following these observations, it appears that the reduction of rotation length and density reduction are complementary.

3.3. Carbon sequestration

Fig. 4 shows the results of the simulations of the forest stand per scenario and per RCP, in terms of carbon sequestration (in grams of carbon per square meter of leaf per year).

Recall that mortality was considered in the computation of the volume. We can see that Douglas-fir presents a higher carbon sequestration than beech (baseline and scenarios). Drought has a negative effect for all the scenarios. They present lower carbon sequestration under a high risk than under an intermediate risk. Climate does not affect carbon sequestration (baseline and scenarios). 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 that combines different strategies has the best carbon sequestration, in contrast to scenario B_DR3 (reduced density and rotation length), which is the worst one and below the baseline.

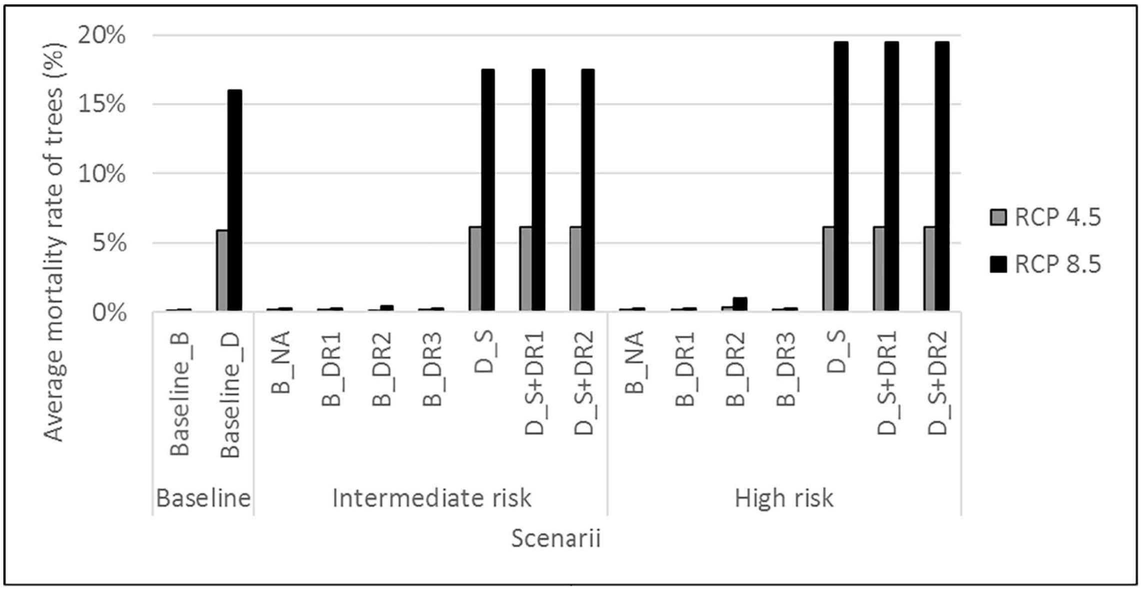


Fig. 2. Histogram representing the average mortality rate of trees (in percentage terms) for each scenario, for RCP 4.5 (gray) and RCP 8.5 (black).

In economic terms, the resulting variations in LEVs compared to the baseline of beech (Baseline_B) are presented in Table 5. The range of Hartman's LEV is from −230 to 5672 EUR/ha and from −969 to 5378 EUR/ha for the RCP 4.5 and 8.5, respectively. The same results are observed when considering Hartman's LEV: the scenario D_S + DR2 provides the best economic return, regardless of the climate and the level of drought risk.

4. Discussion

4.1. Adaptation from an economic perspective

From an economic point of view, our results suggest that adaptation may be relevant (Tables 4 and 5), and is consistent with the ecological point of view detailed in Section 3.1. More precisely, the substitution of beech with Douglas-fir combined with a reduced initial density and rotation length (D_S + DR2) provided the best economic return. Indeed, Douglas-fir wood is more valuable than that of beech because its wood has a natural durability that does not require chemical treatment to be used in outdoor construction. In contrast, beech is mainly used as firewood. Hotyat (1999) described its wood as having a low value and not being competitive compared to conifer wood due to its low durability, its red heart and its hydrophilic character. That is also why Latte et al. (2015) promoted substitution with Douglas-fir and, as of now, for the regeneration of old stands of beech.

However, two economic results were unexpected. First, despite its low quality and - as a result - 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 region. This implies that the regeneration of a beech stand was natural (seeds from old trees) and thus without costs, unlike that of a Douglas-fir stand which is obtained artificially (plantation) involving plantation costs. Forest owners may perceive these high plantation costs (compared to the natural regeneration of beech) as a brake to adaptation. It may be interesting then to encourage them to shift to better-adapted tree species. A way to incite them to choose adaptation may be the subsidization of plantation by the public authorities. Indeed, in a context of international negotiation to limit climate change, forests have to play a role and public authorities have an interest in adapting them. In France, forests are privately owned, so incentives to encourage owners to adapt, such as subsidization, may be required. On the other hand, the forest sector should adapt to these silvicultural changes and it is likely that the government may also have a role to play.

Second, while the scenarios D_S + DR1 and D_S + DR2 were the best ones in terms of growth (from an ecological point of view), they presented contrasted economic results. Indeed, scenario D_S + DR2 provides the best economic return, and scenario D_S + DR1 the worst one. This coincides with the objective of scenario D_S + DR2 that was to reduce plantation costs by starting with 660 trees/ha (instead of 1660 trees/ha for the other scenario as a way to meet industrial demand). This result also proves the importance of having an interdisciplinary vision. Bringing together the two fields leads to the emergence of a consensual and more relevant solution, scenario D_S + DR2. In addition, in terms of wood quality, the implementation of scenario D_S + DR2 is only possible with a “deciduous filler”. In our case, it would be an addition of beech (which regenerates naturally) at the understory to avoid branched Douglas-fir and to thus obtain good quality wood. This beech filler can also offer additional benefits such as the production of firewood.

Whether we consider scenario D_S + DR2 or scenario B_DR2, they both showed the success of combining different strategies. This agrees with the idea of Jönsson et al. (2015), who promote a portfolio of adaptation strategies to reduce the risk of damage. This result also supports the recommendation of the World Bank (2010) to combine soft and hard adaptation. This idea to combine strategies should be more widespread among forest owners. Indeed, adaptive management is part of the category of “no regret” or “win-win” strategies: reducing stand density makes it possible to save water in the soil in both scenarios and money as well in scenario D_S + DR2 under (or not) a drought risk. However, the lack of relevant information is seen as a brake to adaptation (Sousa-Silva et al., 2016; Yousefpour and Hanewinkel, 2015). Forest owners are reluctant to adapt due to a large uncertainty concerning the impact of the implemented adaptation strategies. In this sense, the combination of strategies offers flexibility to the owners in addition to adaptive capacity. The reduction of the rotation length increases the flexibility of forest management, thus reducing the decision horizon, particularly in scenario D_S + DR2, which has the shortest rotation length.

In general, drought had a greater impact on LEV than the climate: the higher the drought intensity was, the more the LEV decreased.

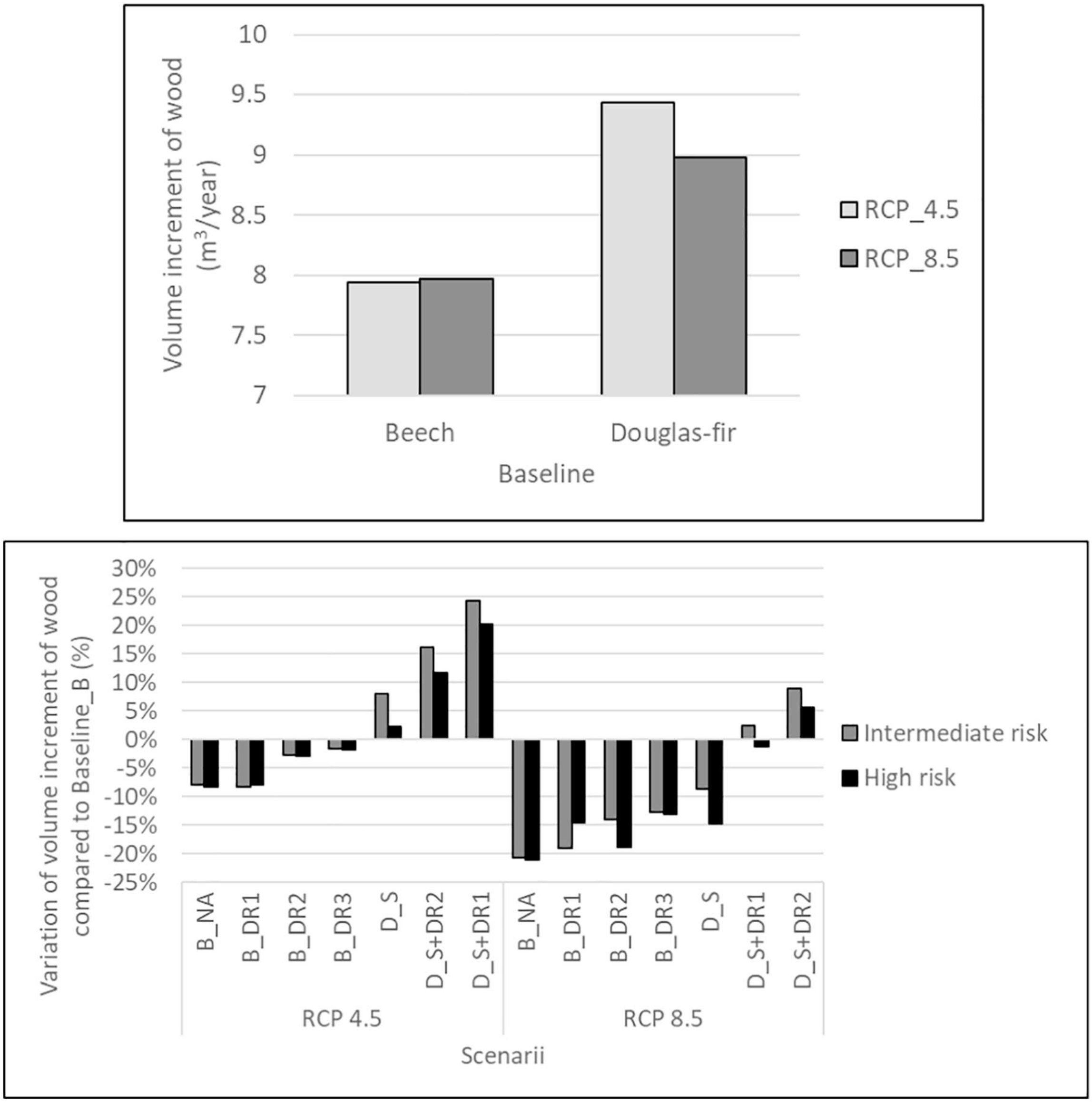


Fig. 3. Histograms representing the volume increment of wood (cubic meters per year) of the baselines (beech and Douglas-fir) (up) and the variation (in percentage terms) of each scenario compared to the beech baseline (down) for intermediate and high drought risks in RCP 4.5 and RCP 8.5.

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

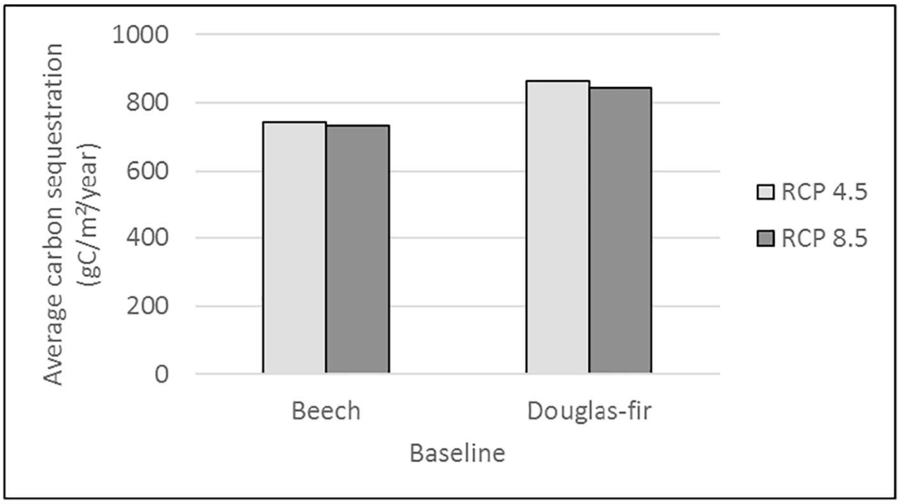
Scenario		RCP 4.5	RCP 8.5
Baseline	Beech	1555 EUR/ha	1572 EUR/ha
	Douglas-fir	−29%	−45%
Intermediate risk	B_NA	−13%	−14%
	B_DR1	79%	80%
	B_DR2	82%	82%
	B_DR3	−3%	−2%
	D_S	−67%	−80%
	D_S + DR1	−111%	−108%
	D_S + DR2	216%	200%
High risk	B_NA	−35%	−36%
	B_DR1	55%	55%
	B_DR2	57%	56%
	B_DR3	−27%	−26%
	D_S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

4.2. Carbon consideration

Fig. 4 showed that when considering scenarios of beech and those of Douglas-fir separately, the higher the initial stand density, the greater the amount of carbon 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 carbon sequestration into account, we underestimate the value of the forest stand. However, Hartman's LEVs present the most extreme values and, consequently, the greatest variation of values in the most severe climate scenario (RCP 8.5). This criterion therefore takes all of the externalities of carbon sequestration linked to the implied silviculture into account. These results prove the importance of considering carbon sequestration, mainly in the context of climate change, and not just wood production to compute the profitability.

This approach leads to an initial consideration of carbon in these analyses. Many debates exist around carbon accounting. That is why



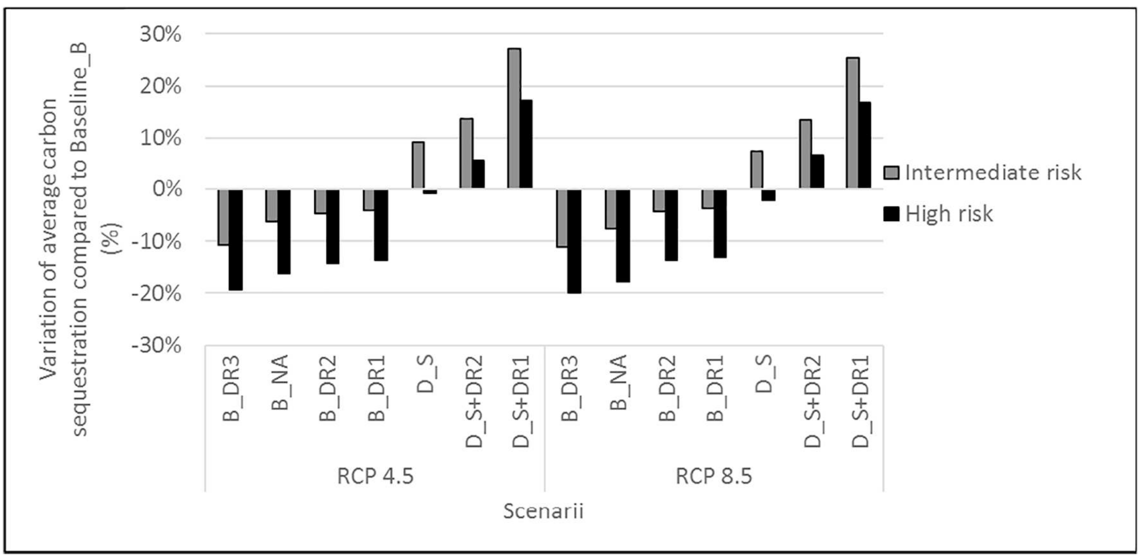


Fig. 4. Histograms representing the average carbon sequestration (in grams of carbon per square meter of leaf per year) of the baselines (beech and Douglas-fir) (up) and the variation (in percentage terms) of each scenario compared to the baseline of beech (down) for intermediate and high drought risks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

Table 5
Variation of 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-fir	−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%

this step can be developed in further studies. Indeed, it would be interesting to know how positive externalities from carbon sequestration can be managed in reality. Amenities can generate carbon credits, which 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). Any payment scheme has to be carefully plan (Guitart and Rodriguez, 2010) whether compensation is made at the final harvest or as continuous source of revenue every year. We can take the future use of wood products with different lifetimes into account, as well as the carbon stored in these products. This suggests that wood quality has to be integrated into our study. For example, firewood directly re-emits sequestered carbon, whereas carbon in a wooden table has a longer lifetime. With this approach in mind, the individual negative effect of the wood production of forest owners should be considered at the same time as the economic consequences for society, along with the social contribution through different wood products.

Finally, on the whole, adaptation makes society, as well as the economy, more resilient to hazards (Konkin and Hopkins, 2009), which refers 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 and also contributes to its mitigation by increasing the carbon-sink capacity, for example (Kolström et al.,

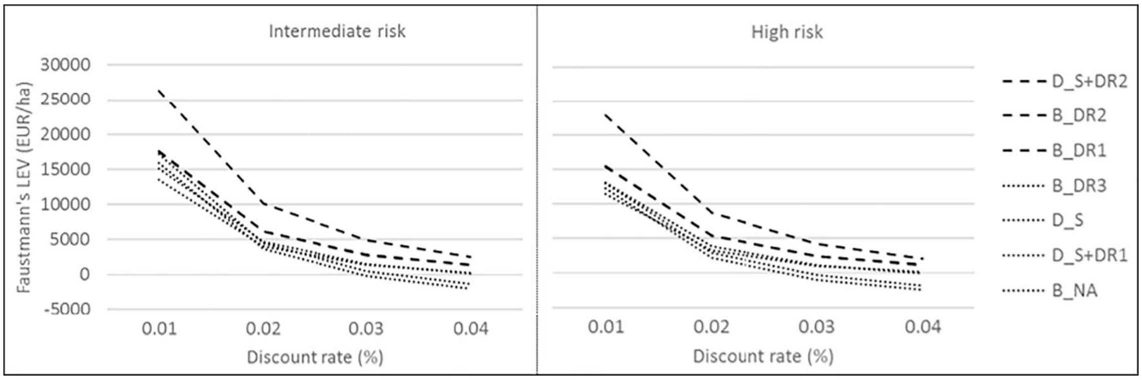


Fig. 5. Faustmann's LEV (EUR/ha) for each scenario as a function of the discount rate for RCP 4.5, for the intermediate risk (left) and the high risk (right).

2011). 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".

4.3. Sensitivity analysis

Economic evaluation often includes a sensitivity analysis of discount rates to test the robustness of the computed LEVs. Consequently, we evaluated the variation of the different LEV functions of the discount rate for each scenario analyzed. The results are presented in Fig. 5.

In Fig. 5, Faustmann's LEV of scenario D_S + DR2 is the highest, regardless of the discount rate for both risks. The second one is scenario B_DR2 since the discount rate for an intermediate risk is 1.5%, regardless of the discount rate for the high one. The order between scenarios does not change since the discount rate is 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.

4.4. Limits and perspectives

The CASTANEA model was used for the first time for the 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 in growing space and water resources in the first years. However, drought generates effects on growth for the year of the event and for one or more years after (Power et al., 1995; Rouault et al., 2006). These post-drought effects are taken into account in the model through the effect of Non-Structural Carbon on growth, but they are still not properly evaluated. Three adaptation strategies (density/rotation reduction and species substitution) were chosen as the most relevant and mentioned in the literature, but also on the basis of their technical feasibility with the CASTANEA model and in Burgundy. Indeed, substitution of beech stands with Douglas-fir has already been tested in the Morvan. The architecture of the CASTANEA model (inventory file for one species growing at the same age) did not make it possible to compute intraspecific (uneven-aged forests) and interspecific (mixture of species) stands, which explains why this well-documented measure was not studied here. Indeed, many studies have proved the effectiveness of mixed stands in terms of biodiversity objectives to reduce drought risk (FAO, 2011; Keskitalo, 2011). Mixtures make it possible to diversify 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 more extensively study mixed stands and the (aboveground and underground) interactions between species (competition and symbiosis) in order to be able to model them. Nonetheless, while all forest services must be taken into account in order to preserve the multifunctionality of forests, mixture strategy probably requires taking trade-offs between adaptation to drought and biodiversity objectives into account, which 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 varies with the tree diameter but also fluctuates with the supply, which are two parameters affected by climate change (see Section 3.1), and such variations are not considered in our study. Second, the wood prices increase together with the diversity of wood uses and the substitution effect of fossil fuels. More and more uses are being discovered for Douglas-fir wood, and its growing demand is not considered in this paper.

5. Conclusion

The productivity of forests is severely limited by water availability in the soil. We observed that drought induces extensive tree decline due to impacts over several years that result in high socio-economic losses, which will then be accentuated by climate change. Moreover, the literature describes the drought hazard at different levels, but without spatial analysis, as 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 given time.

Our study shows that the 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 analyze exposure to drought, to assess potential impacts, and to evaluate the adaptive capacity of both the forest stand and the management system. In addition to this, an important question was how to select suitable measures from the multitude of adaptation options. On the basis of growth and carbon sequestration simulations by the CASTANEA model, substitution of beech stands with Douglas-fir, combined with a reduction of the initial stand density and a reduction of the rotation length, provides the best economic return, regardless of the climate and the level of drought risk. Our paper is the first to compare different adaptation strategies to face the drought-induced risk of forest decline, and the synergy of both strategies provided a robust result. We also showed that adaptation is not always as economically beneficial as ecologically and, consequently, trade-offs between objectives may exist (Johnston and Withey, 2017).

When considering extreme events such as drought, forest management and its adaptation mainly depend on the given objectives (wood production, carbon sequestration), on the forest owner (government, territorial community or private), as well as on the type of stands (existing, to be created, to be reforested). Research in this field can improve our understanding of drought risk and its implied damage mechanisms. Therefore, to improve management options under severe drought, studies of this environmental hazard and risk should be pursued.

In the aim of promoting the best strategy to be combined with drought risk for decision-making, we showed the importance of the interconnection between different fields (ecology and economics), to take the multifunctionality of forests (wood production and carbon sequestration in this case), the need for general information about silvicultural treatments, and the collaboration between different sectors (forest managers and researchers) into account. In addition, since drought increases vulnerability to secondary attacks (pests and pathogens), current challenges for disturbance modeling would include carrying out multiple-risk analyses in dynamic ecosystem models for decision support in forest management.

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Appendix 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	Density	Wood	Benefits	Wood	Benefits	Wood	Benefits	Wood	Benefits
(tree age)	(N/ha)	(m^3/ha)	(EUR/ha)	(m^3/ha)	(EUR/ha)	(m^3/ha)	(EUR/ha)	(m^3/ha)	(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	11,599	202	10,094	230	11,476	199	9936

B_DR1		RCP 4.5				RCP 8.5			
		Intermediate risk		High risk		Intermediate risk		High risk	
Operations	Density	Wood	Benefits	Wood	Benefits	Wood	Benefits	Wood	Benefits
(tree age)	(N/ha)	(m^3/ha)	(EUR/ha)	(m^3/ha)	(EUR/ha)	(m^3/ha)	(EUR/ha)	(m^3/ha)	(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	13,666	246	12,321	267	13,368	239	11,934

B_DR2		RCP 4.5				RCP 8.5			
		Intermediate risk		High risk		Intermediate risk		High risk	
Operations	Density	Wood	Benefits	Wood	Benefits	Wood	Benefits	Wood	Benefits
(tree age)	(N/ha)	(m^3/ha)	(EUR/ha)	(m^3/ha)	(EUR/ha)	(m^3/ha)	(EUR/ha)	(m^3/ha)	(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	13,663	246	12,284	266	13,317	236	11,819

B_DR3		RCP 4.5				RCP 8.5			
		Intermediate risk		High risk		Intermediate risk		High risk	
Operations	Density	Wood	Benefits	Wood	Benefits	Wood	Benefits	Wood	Benefits
(tree age)	(N/ha)	(m^3/ha)	(EUR/ha)	(m^3/ha)	(EUR/ha)	(m^3/ha)	(EUR/ha)	(m^3/ha)	(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	11,535	208	10,379	226	11,321	201	10,074

Baseline_D		RCP 4.5		RCP 8.5	
Operations	Density	Wood	Benefits	Wood	Benefits
(tree age)	(N/ha)	(m^3/ha)	(EUR/ha)	(m^3/ha)	(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	12,734	236	12,958

D_S		RCP 4.5				RCP 8.5			
		Intermediate risk		High risk		Intermediate risk		High risk	
Operations	Density	Wood	Benefits	Wood	Benefits	Wood	Benefits	Wood	Benefits
(tree age)	(N/ha)	(m^3/ha)	(EUR/ha)	(m^3/ha)	(EUR/ha)	(m^3/ha)	(EUR/ha)	(m^3/ha)	(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	11,581	179	9865	216	11,888	181	9972

D_S + DR1		RCP 4.5				RCP 8.5			
		Intermediate risk		High risk		Intermediate risk		High risk	
Operations	Density	Wood	Benefits	Wood	Benefits	Wood	Benefits	Wood	Benefits
(tree age)	(N/ha)	(m^3/ha)	(EUR/ha)	(m^3/ha)	(EUR/ha)	(m^3/ha)	(EUR/ha)	(m^3/ha)	(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	12,405	198	10,896	239	13,165	215	11,828

D_S + DR2		RCP 4.5				RCP 8.5			
		Intermediate risk		High risk		Intermediate risk		High risk	
Operations	Density	Wood	Benefits	Wood	Benefits	Wood	Benefits	Wood	Benefits
(tree age)	(N/ha)	(m^3/ha)	(EUR/ha)	(m^3/ha)	(EUR/ha)	(m^3/ha)	(EUR/ha)	(m^3/ha)	(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	10,359	204	9158	238	10,724	214	9627

Baseline	Beech				Douglas-fir			
	RCP 4.5		RCP 8.5		RCP 4.5		RCP 8.5	
Tree age	Carbon	Benefits	Carbon	Benefits	Carbon	Benefits	Carbon	Benefits
(years)	(T/ha)	(EUR/ha)	(T/ha)	(EUR/ha)	(T/ha)	(EUR/ha)	(T/ha)	(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	Carbon	Benefits	Carbon	Benefits	Carbon	Benefits	Carbon	Benefits
(years)	(T/ha)	(EUR/ha)	(T/ha)	(EUR/ha)	(T/ha)	(EUR/ha)	(T/ha)	(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	Carbon	Benefits	Carbon	Benefits	Carbon	Benefits	Carbon	Benefits
(years)	(T/ha)	(EUR/ha)	(T/ha)	(EUR/ha)	(T/ha)	(EUR/ha)	(T/ha)	(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	Carbon	Benefits	Carbon	Benefits	Carbon	Benefits	Carbon	Benefits
(years)	(T/ha)	(EUR/ha)	(T/ha)	(EUR/ha)	(T/ha)	(EUR/ha)	(T/ha)	(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	Carbon	Benefits	Carbon	Benefits	Carbon	Benefits	Carbon	Benefits
(years)	(T/ha)	(EUR/ha)	(T/ha)	(EUR/ha)	(T/ha)	(EUR/ha)	(T/ha)	(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	Carbon	Benefits	Carbon	Benefits	Carbon	Benefits	Carbon	Benefits
(years)	(T/ha)	(EUR/ha)	(T/ha)	(EUR/ha)	(T/ha)	(EUR/ha)	(T/ha)	(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	Carbon	Benefits	Carbon	Benefits	Carbon	Benefits	Carbon	Benefits
(years)	(T/ha)	(EUR/ha)	(T/ha)	(EUR/ha)	(T/ha)	(EUR/ha)	(T/ha)	(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	Carbon	Benefits	Carbon	Benefits	Carbon	Benefits	Carbon	Benefits
(years)	(T/ha)	(EUR/ha)	(T/ha)	(EUR/ha)	(T/ha)	(EUR/ha)	(T/ha)	(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

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolecon.2019.04.006.

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