An economic comparison of adaptation strategies towards a drought-induced risk of forest decline: financial vs. carbon balance (preliminary version)

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Abstract

Drought is a 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 economical 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 and, we studied two adaptation options: density reduction and substitution by Douglas-fir. We also considered two levels of risks (intermediate and high), two climatic scenarii from IPCC (RCP 4.5 and RCP 8.5) and two types of loss (financial and in terms of carbon sequestration). We combine a 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. The results were discussed as regard to the importance of multidisciplinary approach and to the role of the multifonctionnality of forests.

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

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1 Introduction

Drought is the principal 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 have a role in terms of wood production but also offer many ecosystem services such as carbon storage. In parallel, tree decline is significantly increasing in the world (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 wonder what are the relevant adaptation options, from an economic perspective, to face drought-induced risk of forest decline. We also wonder if the consideration of forest ecosystem services, in particular carbon sequestration, may impact the economic results.

In the literature, few studies investigated forest adaptation following an economic approach. More in detail, 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 scales (2030, 2065, and 2100). They found a decrease of the Land Expectation Value (LEV) (from 690 million to 3.1 billion €) 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, maximizing the Net Present Value of carbon sequestration and timber production and comparing different management options grouped in three scenarii (do-nothing, adaptation, mitigation). They found that mitigation was favoured, while adaptation was limited to youngest age-classes in the optimal solution, and a higher carbon sequestration of the "do-nothing" (between 1.72 and 1.85 million tons higher) than the other scenarii for the entire forest area. 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 (sensitivity analysis and quasi-option value calculations) and compared three scenarii (regeneration and shifting at the end of the rotation, immediate shift, waiting for more information about climate change impact before choosing regeneration or shift). They found a high LEV of Douglas-fir conversion related to a high mortality of Norway spruce, but 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). Their resulting balanced decision gave an overall average of the Net Present Value of 12,158 €/ha by establishing beech regeneration in 46% of Norway spruce area and storing 39.5 kg/ha carbon in forest biomass. The study of Bréda and Brunette (2014) was the only one that investigated on 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 of 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 the 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 only on one adaptation strategy at a time, but never compared different strategies between them and under different climatic scenarii. Only Jonsson et al. (2015) realized 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). In addition, carbon loss is rarely considered in these analysis, in addition to economic loss (see Yousefpour and Hanewinkel (2014) for an exception).

The objective of this paper is then to realize an economic comparison of different strategies to fight against drought-induced risk of forest decline. For that purpose, we adopt an original approach using CASTANEA, a forest-growth model, to simulate forest stand according to two different adaptation strategies (density reduction and species shift), under two climatic scenarii from IPCC (RCP 4.5 and 8.5) and for two levels of risk (intermediate and high). After that, we used the outputs of CASTANEA to provide an economic comparison of the two adaptation strategies and considering both the production of wood and the carbon sequestration. We performed a classical forest economics approach based on the Faustmann's formula and Hartman's formula. The maximisation of these criterion showed that adaptation provided the best economic return, as compared to the status quo or the "do-nothing" scenario. Indeed, substitution by Douglas-fir was the best strategy under an intermediate drought risk. It was also the best strategy under a high drought risk for RCP 8.5, but not in RCP 4.5. Reduction of beech density was the best strategy under a high drought risk for RCP 4.5. The highest LEV using Hartman's formula support that carbon sequestration must be taken into account to not under-estimate the value of forest stand.

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 concludes (Section 4).

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 and the large uptake by trees in spring. 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. It results from a pluviometric drought, which is as a prolonged rainfall deficit compared to the mean or median (that is the normal state); because it is firstly the regime of the precipitation that will be determinant in the development of a state of 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 risk of drought can be described in terms of three components: the hazard, the stand exposure to the hazard and the stand 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 intrinsic characteristics of the stand, influenced by extreme events such as drought and climate change. It shows the extent to which the stand is susceptible to suffer damages related to the hazard: it therefore takes into account the exposure and 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 (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); Galiano et al. (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 (Thurig et al. (2005)).

These impacts should be stressed 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 CO_2 (IPCC (2013)). The climate will thus evolve towards an increase in average temperature, an emphasis of the differences between wet and dry regions, a decrease in water availability, an increase of the frequency and the intensity of extreme events such as droughts (Spiecker (2003)).

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 the classification of soft and hard adaptation strategies given by the World Bank (2010): the reduction of stand density (soft adaptation) and the species substitution from beech to Douglas-fir (hard adaptation).

First, 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)).

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).

Finally, 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 carbonsink 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”.

2.2 Case study

2.2.1 Burgundy Region

Burgundy is a rural region and one of the first forest regions in France because of its afforestation rate (30%), 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 (peaks of the Morvan), 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 apart from 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 weak dynamic silviculture. This is why, during the turnover of Burgundy stands, deciduous forests gradually shift to forests with more suitable species such as Douglas-fir, in order to anticipate future climate changes, mainly in water reserves, and to respond to the growing demand for wood, with a more dynamic silviculture. Beech and Douglas-fir are also considered to be two species of high commercial value in Burgundy with respective to annual production of 221,000 m^3 and 898,000 m^3 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 shadow 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)). Pierangelo and Dumas (2012) show that moisture conditions in June (and July) are important determinants of beech growth and that water deficits in this period are all the more unfavourable when the station is dry (e.g. low maximum available water content of soil, hot exposure). However, due to climate change, it could decline or even disappear. 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 tolerant to droughts, 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 (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 (soils with low available water content) (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 the two species, two mesophilous species are observed, 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 oblique and moderately deep rooting, but with different transpiration control during drought (ONF (1999)). Indeed, beech has a very low basic water potential (from -1.5 to -2.5 MPa) compared to Douglas-fir (-3 MPa) (ONF (1999); Pierangelo and Dumas (2012)). In addition, there is a higher demand for available water content in deciduous trees than conifers (ONF (1999)): beech therefore consume more and control less its water reserves than Douglas-fir. 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 Available Water Content (AWC). The status quo had an AWC of 150 mm and the two alternative scenarii considered were 100 mm and 50 mm: these levels were chosen according to the range of AWC of current beech stands in Burgundy. 150 mm represents favourable conditions to growth for beech. 100 mm is a first risk scenario with one third less of the status quo level of water availability for trees. 50 mm is a second risk scenario in which the water availability is below 40% of the status quo. This threshold of 40% of the maximum AWC represents the conditions from which beech starts to regulate water consumption and thus has difficulties to growth and survive (Lebourgeois et al. (2005)).

With respect to the uncertainty of future climate, the consequences of two climatic scenarii from IPCC were analysed: RCP 4.5 and RCP 8.5 (IPCC (2013)). RCP 4.5 represents the most optimistic scenario with a total radiative forcing of 4.5 W/m^2, and RCP 8.5 represents the most pessimistic scenario with a total radiative forcing of 8.5 W/m^2.

All of these elements result in 7 scenarii per IPCC scenarii, i.e. a total of 14 scenarii. The scenario is indicated with the following code: Species (BEECH or DOUGLAS)_Silviculture (C for classical or D for dynamic)_ AWC(50, 100 or 150 mm). The scenarii are defined as follows:

1. BEECH_C_150: benchmark, current beech stand.

2. BEECH_C_100: beech stand without adaptation under an intermediate drought risk.
3. BEECH_D_100: beech stand with a reduced initial density under an intermediate drought risk.
4. DOUGLAS_C_100: Douglas-fir stand (substitution of beech) under an intermediate drought risk.
5. BEECH_C_50: beech stand without adaptation under a high drought risk.
6. BEECH_D_50: beech stand with a reduced initial density under a high drought risk.
7. DOUGLAS_D_50: Douglas-fir stand (substitution of beech) under a high drought risk.

2.3 Methods

To compare the two adaptation options to face drought-induced risk of forest decline (density reduction and species substitution), we first simulated forest growth with different silvicultures according to these two main 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); Dufrene 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 the different species “module”. A module is the overall characteristics of ecophysiological processes that is to say the specific parameters controlling growth (photosynthesis, respiration), nutrient allocation (carbon, nitrogen), water consumption, etc. These parameters are fixed and related to one specific species. 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 (SAFRAN point 3215).

The annual output data were the volume of wood, two proxy (start of cavitation on the vessels of the tree and carbon reserves that allow tree to grow and survive) to calculate mortality rate post-simulation, and the carbon sequestrated into the forest stand.

CASTANEA model simulated forest growth (time steps: year) of a stand of one hectare through different silvicultural paths (Table 1) starting from a 125-year-old beech forest of Burgundy.

Table 1: Table of the three silvicultural paths for beech (classical and dynamic paths) and Douglas-fir (classical path) according to the time range of the simulation in CASTANEA model (source: ONF and IDF)

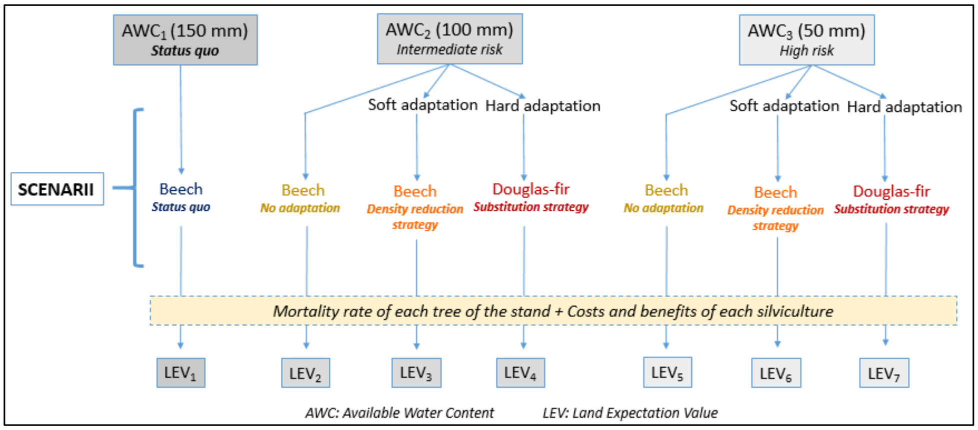
	CLASSICAL BEECH		DYNAMIC BEECH		CLASSICAL DOUGLAS-FIR	
Year	Tree age (years)	Stand density (trees/ha)	Tree age (years)	Stand density (trees/ha)	Tree age (years)	Stand density (trees/ha)
1997	5	6000	5	3000	5	1100
2015					23	715
2018			26	1000		
2022					30	535
2023			31	600		
2025	33	1100				
2028			36	380		
2030	38	700				
2033			41	260		
2035	43	450			43	345
2039			47	185		
2041	49	310			49	275
2045			53	140		
2047	55	225				
2051			59	107		
2055	63	165				
2059			67	80		
2063	71	120				
2067			75	65		
2071	79	90				
2081	89	70				

The silviculture paths arise from ONF (national forestry office of France) for beech and from IDF (institute for the forest development of France) for Douglas-fir. Simulations for beech were composed of a classical path and a dynamic one. Simulations for Douglas-fir were only composed of a classical path. The classical path of beech was characterized by an initial stand of 6,000 trees/ha obtained by a natural regeneration, associated with a LAI of 8. It represents the silviculture of the status quo and the "do-nothing" scenario. It includes 9 thinnings and a final harvest at 98 years. The dynamic path of beech was characterized by an initial stand of 3,000 trees/ha obtained by a natural regeneration, associated with a LAI of 5. It represents the silviculture of the density reduction strategy. It includes 9 thinnings and a final harvest at 90 years. The classical path of Douglas-fir was characterized by an initial stand of 1,100 trees/ha planted, associated with a LAI of 8. It represents the silviculture of the substitution strategy. It includes 4 thinnings and a final harvest at 55 years. The three silvicultural paths were simulated through three different AWC (50, 100 and 150 mm) and two different IPCC scenarii (RCP 4.5 and RCP 8.5).

2.3.2 Economic approach

Figure 1 illustrates, for one 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 our applied methodology from the structure of simulated adaptation scenarii to their economic evaluation for one IPCC scenario



Our objective is to compare the 14 LEV among scenarii. All the comparisons of LEV are detailed according to Figure 1 as follows (taking only one IPCC scenario into account):

1. (LEV 1 with LEV 2) and (LEV 1 with LEV 5): effect of drought.
2. (LEV 2 with LEV 3) and (LEV 5 with LEV 6): effect of density reduction strategy.

3. (LEV 2 with LEV 4) and (LEV 5 with LEV 7): effect of species substitution strategy.

First, the sum of an infinite number of rotations allowed calculating the Land Expectation Value (LEV), the criterion commonly used in the forest sector (Faustmann (1849)), as follows:

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

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

The forest owner's objective was supposed to maximize the LEV. The infinite horizon used by this criterion allowed comparing management options associated to different temporal horizons, assuming that silviculture path was identical for each rotation. 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.

More precisely, two LEV were calculated: the Faustmann's LEV, explained just before and taking into account only the benefits from the harvest of wood, and the Hartman's LEV, taking the benefits from the harvest of wood and also from the carbon sequestration (Hartman (1976)), as follows:

$$LEV(Hartman) = \sum_{i=0}^{\infty} \frac{B_i - C_i}{(1+r)^i} + \sum_{i=0}^{\infty} \frac{B'_i}{(1+r)^i}$$

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 and i the rotation length.

The discount rate r was 2% for beech and Douglas-fir. To calculate the benefits from carbon sequestration, we chose the average (January-July, 2017) carbon price of 5.41 €/T (source: stock exchange of Paris).

An example of silvicultural operations with associated net benefits from wood production and benefits from carbon sequestration is given in Table 2 for the benchmark. The tables for the other scenarios are presented in Appendix A.

Table 2: Table with volume of wood (“Wood” in m^3) and associated net benefits from its production (“Benefit W” in €/ha), annual stand carbon sequestration (“Carbon” in gC/m^2/year), resulting carbon sequestered in the harvested wood (“C wood” in T) and its associated benefits (“Benefit C” in €/ha) per silvicultural operations for scenario 1, the benchmark

	RCP 4.5					RCP 8.5				
Operations (tree age)	Wood	Benefit W	Carbon	C wood	Benefit C	Wood	Benefit W	Carbon	C wood	Benefit C
Maintenance (17)	66	-2085	559	0	0	66	-2085	559	0	0
Thinning 1 (32)	119	1423	553	81	436	110	1373	500	79	427
Thinning 2 (37)	53	220	897	14	77	52	180	847	13	70
Thinning 3 (42)	74	550	889	17	92	66	370	846	13	70
Thinning 4 (48)	90	445	955	15	79	68	400	770	14	73
Thinning 5 (54)	95	720	773	16	84	89	680	890	15	81
Thinning 6 (62)	122	1125	785	18	97	116	1075	747	17	93
Thinning 7 (70)	146	1846	823	21	114	140	1780	804	20	110
Thinning 8 (78)	164	1813	769	21	112	161	1681	783	19	104
Thinning 9 (88)	183	2160	732	20	108	170	2120	840	20	106
Harvest (98)	206	10100	679	70	378	203	9950	769	69	372

3 Results

3.1 Forest growth and mortality

Figure 2 shows the results of the simulations of the forest stand per scenario and per RCP.

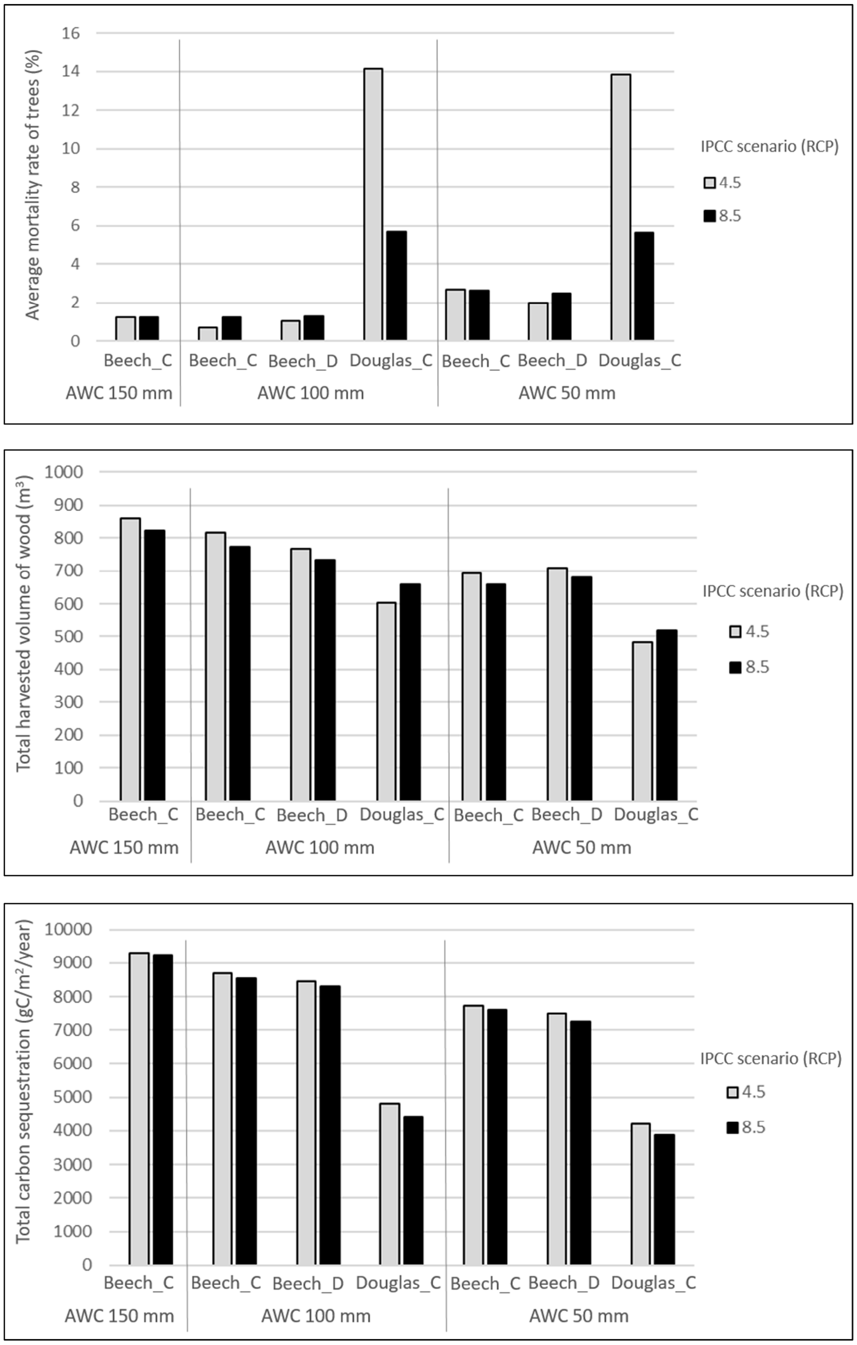
Then, we can observe that the average mortality rate of Douglas-fir is higher, mainly in the RCP 4.5 (14%), than beech for all the scenarii analysed (between 1 and 3%). The total harvested volume of wood takes into account the wood harvested at the end of the rotation with those coming from the thinnings. This total harvested volume is lower for Douglas-fir than beech for all the scenarii analysed. The volume of the status quo is higher than the other scenarii. Finally, the total carbon sequestration by the forest stand is lower for Douglas-fir than beech for all the scenarii. The highest level of this parameter is reached by the status quo.

3.2 Economic comparison

The resulted LEVs are presented in Table 3.

Concerning the status quo, the substitution by Douglas-fir was more profitable under the AWC of 150 mm than beech (BEECH_C_150). Table 3 lets appear that substitution strategy (DOUGLAS_C_100) provides the best economic return regardless the level of drought risk and the climatic scenario. From an economic point of view, under the highest drought risk (AWC of 50

Figure 2: Histograms representing: the average mortality rate of trees (%), the total harvested volume of wood (m^3) and the total carbon sequestration (gC/m^2/year), respectively



mm), the density reduction dominates the substitution strategy in the RCP 4.5, which is the opposite in the RC 8.5. Substitution by Douglas-fir presents higher LEV for RCP 8.5 than for RCP 4.5, conversely for all the strategies with beech. Note that the absence of adaptation under the AWC of

Table 3: Faustmann's LEV (€/ha) and Hartman's LEV (€/ha) for each scenario, for RCP 4.5 and RCP 8.5

	RCP 4.5		RCP 8.5	
Scenario	Faustmann's LEV (€/ha)	Hartman's LEV (€/ha)	Faustmann's LEV (€/ha)	Hartman's LEV (€/ha)
1. BEECH_C_150	3546.2	4155.3	3262.3	3841.1
2. BEECH_C_100	3222.4	3795.4	2925.9	3462.4
3. BEECH_D_100	4177.9	4759.0	3876.2	4422.4
4. DOUGLAS_C_100	5038.2	5353.4	6204.6	6541.1
5. BEECH_C_50	2297.6	2781.1	2086.6	2533.4
6. BEECH_D_50	3678.0	4207.2	3416.9	3916.0
7. DOUGLAS_C_50	3130.4	3379.3	3749.2	4003.4

50 mm is the worst option from an economic perspective and then the absence of adaptation under the AWC of 100 mm.

4 Discussion

4.1 Wood production and carbon sequestration

On the one hand, the high mortality rate of Douglas-fir was unexpected (Figure 2) considering the literature that describes it as a suitable species to fight against drought risk. However, the lowest level in RCP 8.5 (6%) compare to RCP 4.5 (14%) can be due to its resistance to drought. This high mortality can explain the lowest levels of harvested wood and carbon sequestration that came from these Douglas-fir stands. In fact, added to its low carbon sequestration, Douglas-fir was losing its carbon reserves, which can explain this high mortality: the variation of the proxies to calculate mortality rate was about 15% for carbon reserves and 5% for the start of cavitation. For beech, a slightly highest mortality rate was observed for the RCP 8.5 compared to the RCP 4.5, which agreed with its known sensitivity to drought.

On the other hand, Douglas-fir decline due to severe droughts in Burgundy has ever been observed (Sergent et al. (2014)).

Nevertheless, in future climate simulations in CASTANEA model, an over-estimation of CO_2 fertilization (i.e. positive effect of climate change) for beech stands can occur. Adding this element with no competition between trees ran, it results in high growth (in diameter) simulated, which can explain the difference between beech and Douglas-fir stands. However, the mortality was not included in simulation (i.e. implemented post-simulation), which can compensate the absence of competition modelling.

Regarding the total harvested volume and the total carbon sequestration, adaptation seemed less profitable than the status quo or the absence of adaptation. In all the cases, beech produced more wood than Douglas-fir. But Douglas-fir might be expected to have a much higher volume growth rate than observed with respect to its drought tolerance. Nevertheless, this difference can come from the different origins of silvicultural paths of each species, resulting from the difficulty to find complete paths with associated costs and benefits. Indeed, public forests (public path of beech) are more managed (i.e. more thinnings, thus more wood harvested) than private forests (private path for Douglas-fir), which affect our results but also the adaptation: the reaction of forest stand with respect to the implementation of adaptation strategies will not be the same according to its management. The current management of beech in private forests as uneven-aged stand can be one of the reasons of these difficulties (communication with forest experts). In addition, we did not find a dynamic silvicultural path for Douglas-fir, which did not allow us to test the additionality of the two adaptation strategies.

4.2 Adaptation in an economic perspective

From an economic point of view, our results suggest that adaptation may be relevant. This proves the importance to have an interdisciplinary vision (here environmental and economical points of view collide) and to take carbon sequestration into account, mainly in the context of climate change, and not only wood production to compute the profitability.

While Douglas-fir presented lower wood production and carbon sequestration than beech, it provides the best economic return under the AWC of 100 mm. Indeed, Douglas-fir is the most valuable species: 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.

Under the AWC of 50 mm, substitution by Douglas-fir was also the strategy that provided the best economic return for RCP 8.5. However, for RCP 4.5, density reduction of beech was the most profitable strategy. This difference between the two LEVs illustrates therefore the effect of climate change. While Douglas-fir can be more interesting (as described above), beech is the natural species of this stand: there was no plantation costs unlike for Douglas-fir. In addition to this element, its regeneration was natural (seeds from old trees) and not artificial like for Douglas-fir (plantation).

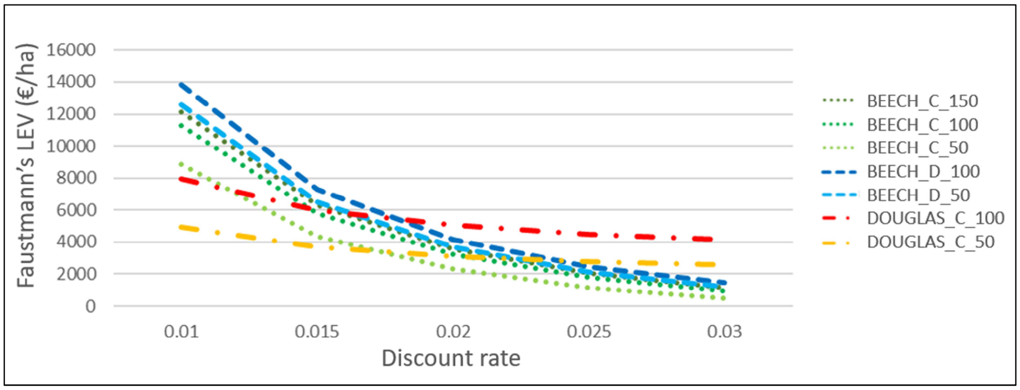
Hartman's LEVs were higher than Faustmann's LEVs (range of LEV of 0-20,000 €/ha against 0-17,000 €/ha), that is to say, without taking into account carbon sequestration, we under-estimate the value of forest stand.

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. A payment implies thinking about the manner to provide it (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.

4.3 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 3.

Figure 3: Faustmann's LEV (€/ha) for each scenario function of the discount rate for the RCP 4.5



In Figure 3, the Faustmann's LEV of dynamic silviculture of beech (BEECH_D_100/50) is the highest until a discount rate of 2.2% under the AWC of 100 mm and 2.7% under the AWC of 50 mm. Since these levels of discount rate, the substitution by Douglas-fir (DOUGLAS_C_100/50) is more profitable than the other strategies.

The same results are observed considering the Hartman's LEV.

Concerning the RCP 8.5, Douglas-fir is profitable for discount rates below 1.5% under the AWC of 100 mm and 2.1% under the AWC of 50 mm for both Faustmann's LEV and Hartman's LEV.

4.4 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. This interannual variation of the growth in diameter was not visible in the simulations. The two adaptation strategies (density 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. 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.

Moreover, in this study, we do not take into account the perception and reaction of forest owners and society towards drought risk and possible trade-offs between carbon production and sequestration to be made: the results could be changed by considering a forest owner who has risk aversion or is risk lover (instead of a risk neutral owner). When it comes to drought like with any other risk, forest owners can present loving, indifference or aversion to risk, which depend on their individual preferences and perception of the drought risk. Yousefpour and Hanewinkel (2015) showed that forest managers were aware of climate change (real risk, anthropogenic cause), even though they considered themselves to be under-informed. They thought that climate change mitigation had small potential compared to adaptation (more suitable species and provenances, risk mapping) despite the evolution of uncertainty. Verifying and improving knowledge of forest owners on the risks linked to climate change (such as drought) are therefore necessary to achieve adequate adaptation of forests. Schou et al. (2015) also showed that the rotation length and the choice of species for stand regeneration depend on possible developments, damages and uncertainty. This uncertainty depends on the perception of time for a certain harvest, the magnitude of impacts on the harvest and the probability or belief on the harvest. Indeed, they showed that the longer the manager's waiting time to obtain certainty about climate change (or to have a more false distribution of belief), the more decisions will be based on *ex ante* evaluations. This suggested that if forest managers believe that the uncertainty of climate change will prevail for a long period, they may make sub-optimal *ex-ante* decisions.

With respect to the perception of risk by the population, only intensity and frequency define a risk. Veyret et al. (2013) showed an ignorance of the society of infrequent events causing major damage, whereas there is an acceptance of repetitive hazards with little damage. Therefore, a poor perception of the dangers exists with respect to natural hazards, i.e. individuals deny, are uninformed or are accustomed to risk. This acceptance would come from a habit, because of the adaptation of population: a natural risk is thus a threat only if it disrupts the population (and since there is adaptation, the notion of risk disappears). Public risk perception are thus important to consider in decision-making for adaptation, because it results from their knowledge about the threats and can influence the effectiveness of measures to prevent natutal risk (Leiserowitz (2005)).

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 provide the best economic return for an intermediate drought risk. For a higher one, the climate effect influence the choice of the adaptation strategy to adopt (density reduction of beech stands for RCP 4.5 and substitution by the Douglas-fir for RCP 8.5).

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 such as our study 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 (biology 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.

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Appendices

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

BEECH_C_100	RCP 4.5					RCP 8.5				
Operations (tree age)	Wood	Benefit W	Carbon	C wood	Benefit C	Wood	Benefit W	Carbon	C wood	Benefit C
Maintenance (17)	60	-2085	511	0	0	60	-2085	511	0	0
Thinning 1 (32)	108	1223	493	74	400	98	1143	432	71	385
Thinning 2 (37)	49	200	849	14	73	47	140	774	12	62
Thinning 3 (42)	69	505	843	16	86	60	310	762	12	62
Thinning 4 (48)	85	430	882	14	77	61	370	678	13	70
Thinning 5 (54)	92	680	730	15	81	84	660	833	15	79
Thinning 6 (62)	118	1100	721	18	95	113	1025	683	17	90
Thinning 7 (70)	142	1813	785	21	112	134	1714	735	20	106
Thinning 8 (78)	163	1747	734	20	108	156	1615	743	19	101
Thinning 9 (88)	178	2040	693	19	103	166	2040	803	19	103
Harvest (98)	196	9600	608	66	359	197	9650	745	67	361

BEECH_C_50	RCP 4.5					RCP 8.5				
Operations (tree age)	Wood	Benefit W	Carbon	C wood	Benefit C	Wood	Benefit W	Carbon	C wood	Benefit C
Maintenance (17)	51	-2085	440	0	0	51	-2085	440	0	0
Thinning 1 (32)	86	873	443	62	335	75	733	367	57	310
Thinning 2 (37)	41	130	773	11	60	38	80	669	9	51
Thinning 3 (42)	58	385	726	13	71	50	205	652	9	49
Thinning 4 (48)	71	325	774	12	64	49	265	569	11	57
Thinning 5 (54)	78	540	669	13	68	69	520	769	12	66
Thinning 6 (62)	97	925	635	15	82	94	850	611	14	77
Thinning 7 (70)	123	1516	723	18	95	115	1450	631	17	92
Thinning 8 (78)	139	1483	635	17	93	134	1384	691	16	88
Thinning 9 (88)	152	1720	629	16	88	144	1840	729	17	93
Harvest (98)	169	8250	543	57	310	178	8700	737	60	326

BEECH_D_100	RCP 4.5					RCP 8.5				
Operations (tree age)	Wood	Benefit W	Carbon	C wood	Benefit C	Wood	Benefit W	Carbon	C wood	Benefit C
Maintenance (17)	35	-2085	568	0	0	35	-2085	568	0	0
Thinning 1 (25)	96	443	525	41	220	89	363	455	38	205
Thinning 2 (30)	60	260	649	16	84	56	230	677	15	79
Thinning 3 (35)	69	490	747	16	84	65	445	696	15	79
Thinning 4 (40)	80	550	790	17	92	74	460	711	15	81
Thinning 5 (46)	108	740	749	16	86	95	600	635	14	73
Thinning 6 (52)	116	825	597	14	75	99	775	700	13	71
Thinning 7 (58)	127	1285	691	15	82	122	1219	658	15	79
Thinning 8 (66)	146	1648	689	19	103	138	1516	655	18	95
Thinning 9 (74)	166	2160	699	20	108	154	2160	670	20	108
Harvest (90)	255	12550	493	86	467	256	12600	522	87	469

BEECH_D_50	RCP 4.5					RCP 8.5				
Operations (tree age)	Wood	Benefit W	Carbon	C wood	Benefit C	Wood	Benefit W	Carbon	C wood	Benefit C
Maintenance (17)	31	-2085	496	0	0	31	-2085	496	0	0
Thinning 1 (25)	82	263	471	35	187	74	233	384	34	181
Thinning 2 (30)	51	210	561	14	75	50	170	550	13	68
Thinning 3 (35)	61	445	691	15	79	55	400	584	14	73
Thinning 4 (40)	74	490	711	16	84	69	400	624	14	73
Thinning 5 (46)	100	680	667	15	81	87	500	524	12	64
Thinning 6 (52)	109	750	505	13	70	87	725	612	13	68
Thinning 7 (58)	117	1186	610	14	77	116	1120	585	14	73
Thinning 8 (66)	138	1582	597	18	99	130	1351	588	16	86
Thinning 9 (74)	160	2040	653	19	103	138	2080	604	19	104
Harvest (90)	243	11950	428	82	445	248	12200	486	84	455

DOUGLAS_C_100	RCP 4.5					RCP 8.5				
Operations (tree age)	Wood	Benefit W	Carbon	C wood	Benefit C	Wood	Benefit W	Carbon	C wood	Benefit C
Maintenance (16)	45	-3640	402	0	0	45	-3640	402	0	0
Thinning 1 (22)	83	220	464	11	61	84	250	310	13	69
Thinning 2 (29)	81	352	397	11	61	93	312	383	10	54
Thinning 3 (42)	132	4185	492	24	129	116	3420	440	19	105
Thinning 4 (48)	168	1870	367	9	47	138	2365	303	11	59
Harvest (55)	132	9240	409	34	182	171	11970	469	44	236

DOUGLAS_C_50	RCP 4.5					RCP 8.5				
Operations (tree age)	Wood	Benefit W	Carbon	C wood	Benefit C	Wood	Benefit W	Carbon	C wood	Benefit C
Maintenance (16)	39	-3640	319	0	0	39	-3640	319	0	0
Thinning 1 (22)	68	175	391	9	48	65	185	217	9	51
Thinning 2 (29)	65	280	348	9	48	70	240	333	8	41
Thinning 3 (42)	105	3240	424	18	100	89	2520	362	14	77
Thinning 4 (48)	131	1485	318	7	37	101	1815	239	8	46
Harvest (55)	105	7350	372	27	145	131	9170	467	33	181