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► **To cite this version:**

Sandrine Brèteau-Amores, Marielle Brunette, Hendrik Davi. An Economic Comparison of Adaptation Strategies Towards a Drought-induced Risk of Forest Decline. *Ecological Economics*, 2019, 164, pp.106294. 10.1016/j.ecolecon.2019.04.006 . hal-02159597

**HAL Id: hal-02159597**

**<https://hal.science/hal-02159597>**

Submitted on 25 Oct 2021

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

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February 1, 2019

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6 Drought is a source of stress that affects forest growth, resulting in financial losses for forest  
7 owners and amenity losses for society. Due to climate change, such natural events will be more  
8 frequent and intense in the future. In this context, the objective of this paper is to compare, from  
9 an economic perspective, different forest adaptation strategies towards a drought-induced risk  
10 of decline. For that purpose, we focused on a case study of a beech forest in Burgundy (France)  
11 and we studied several adaptation options: density reduction, reduction of the rotation length,  
12 and substitution with Douglas-fir. We also considered two levels of drought risk (intermediate  
13 and low soil water capacity) and two climate scenarii from the IPCC (RCP 4.5 and RCP 8.5).  
14 We combined a process-based forest-growth simulator (CASTANEA) with a traditional forest  
15 economics approach. The results showed that adaptation provided the best economic return  
16 in most of the scenarii considered. Combining strategies appears as a relevant way to adapt  
17 forests in view of a drought-induced risk of forest decline. We also demonstrated the importance  
18 of considering two disciplinary fields. Beneficial scenarii in an ecological perspective were not  
19 necessarily beneficial in an economic one and vice versa.

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

# 21 1 Introduction

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

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

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

39 In the literature, few studies have tackled the question of adaptation to climate change using  
40 a forest economics approach. They performed a cost-benefit analysis through the maximization of  
41 the net present value (NPV) or Faustmann's land expectation value (LEV). In this context, several  
42 strategies are then analyzed. Hanewinkel et al. (2010) and Brunette et al. (2014) studied the shift  
43 to better-adapted species. The first paper deals with a shift from Norway spruce to European beech  
44 in Germany, while the second one deals with a change from Norway spruce to Douglas-fir in France.

45 Whereas in Germany, adaptation seems to correspond to financial loss, in France it seems that  
46 conversion to Douglas-fir may be a source of profit for the forest owner. The species mixture is  
47 analyzed in Yousefpour and Hanewinkel (2014) with the question of admixing beech into a Norway  
48 spruce stand. They found that the best solution in economic terms is to establish beech regeneration  
49 in 46% of the Norway spruce area. Bréda and Brunette (2014) focused on the reduction of rotation  
50 length for Douglas-fir in France as a potential adaptation strategy towards a drought-induced risk  
51 of forest decline. They showed that adaptation is always preferable in economic terms for the forest  
52 owner.

53 This short literature review reveals that past articles always focused on one strategy at a time.  
54 They never compared different strategies or analyzed combinations of them. An exception is proba-  
55 bly the study of Jönsson et al. (2015), which compares different adaptation strategies against storms.  
56 However, the methodology is different and based on the impact of adaptive forest management on  
57 productivity and sensitivity to storms. Another observation is that only one article deals with the  
58 drought-induced risk of forest decline (Bréda and Brunette, 2014). Finally, climate scenarii are  
59 rarely considered.

60 The objective of this paper is to carry out an economic comparison of different adaptation  
61 strategies to fight against the drought-induced risk of forest decline. For that purpose, we adopted an  
62 original approach that combines CASTANEA, a process-based forest-growth model, with a classical  
63 forest economic analysis. CASTANEA is a mechanistic model for simulating the functioning of the  
64 main managed European tree species (Davi et al., 2005; Dufrêne et al., 2005). The model simulates  
65 the main stocks of the forest ecosystem (carbon, water, nitrogen) aboveground and belowground, at  
66 time steps ranging from half an hour to a century. Only a mechanistic model can precisely simulate  
67 forest growth in reaction to drought and climate change, as well as the impact in terms of carbon  
68 sequestration. CASTANEA was chosen because it is the only model that simulates both carbon

69 sequestration (Davi et al., 2006) and tree growth (Davi et al., 2009), while integrating the risk of  
70 mortality related to water stress (Davi and Cailleret, 2017) and that takes the specificity of each  
71 species into account, contrary to global models. We simulated forest stands according to different  
72 adaptation strategies (density reduction, reduction of rotation length and species shift) under two  
73 climate scenarii from the IPCC (RCP 4.5 and 8.5) and for two levels of drought risk related to a  
74 variation in soil water capacity (intermediate and high). We then used the outputs of CASTANEA  
75 to provide an economic comparison of the adaptation strategies. We performed a classical forest  
76 economics analysis based on Faustmann's formula and Hartman's formula. Faustmann's LEV takes  
77 the costs and the benefits from wood harvesting into account, whereas Hartman's LEV also considers  
78 the benefits from amenities, in our case, carbon sequestration. The maximization of these criteria  
79 showed that adaptation provided the best economic return, as opposed to the baseline or the "do-  
80 nothing" scenario. Indeed, substitution with Douglas-fir combined with a reduced initial density and  
81 a reduction of the rotation length was the best strategy under both levels of drought risk and both  
82 climate scenarii. From an economic perspective, the combination of different strategies was therefore  
83 more beneficial for the forest owner than each strategy separately (synergy vs. additionality). These  
84 results are discussed with regard to the financial balance and the carbon balance.

85 The rest of the paper is structured as follows. The material and the methods are presented in  
86 Section 1. Section 2 provides the results. The results are discussed in Section 3, and Section 4  
87 concludes.

## 88 **2 Material and methods**

### 89 **2.1 Some definitions**

#### 90 **2.1.1 Characterization of drought and risk**

91 According to the IPCC (2002), drought is defined as "a phenomenon that occurs when precipitation  
92 is significantly below normal recorded levels and that causes significant hydrological imbalances that  
93 are detrimental to systems of land resources production". More precisely, from the ecophysiological  
94 point of view, drought is a reduction of the soil water reserve sufficiently severe to prevent the optimal  
95 functioning of trees due to insufficient precipitation, high temperature and large water uptake by  
96 trees. The definitions of drought vary greatly from country to country, but the literature identifies  
97 four different types of drought, including the edaphic (or agronomic) drought that is particularly of  
98 interest to us since it refers to the soil and to the impacts on living beings.

99 The precipitation regime is the first determinant in the development of a state of drought. It  
100 results from a pluviometric drought, which is a prolonged rainfall deficit compared to the mean or  
101 median (that is the normal state). However, drought also depends on the evapotranspiration level  
102 that is closely related to the temperature and atmospheric drought. The estimation of the water  
103 balance makes it possible to define the conditions under which precipitation distribution, soil water  
104 reserves and losses by evapotranspiration or drainage induce a negative effect on trees, referred to  
105 as water stress. According to Lebourgeois et al. (2005), water stress is the most important concept  
106 for the forest manager since water is the determinant of good stand health. We use the available  
107 water content (AWC) to illustrate this water stress.

108 According to Crichton (1999), drought risk can be described in terms of three components: the  
109 hazard, the stand exposure to the hazard and the stand's vulnerability. The hazard is characterized  
110 by its intensity (i.e., the magnitude of the phenomenon), its severity (linked to the duration of

111 the phenomenon), and its frequency (i.e., the probability of damage). Exposure is the level or the  
112 conditions at which the stand may be in contact with the hazard. It is a function of the geographical  
113 location and the physical context, which can limit or accentuate the hazard (e.g., compact and  
114 shallow soils). Vulnerability refers to the internal characteristics of the stand, influenced by species  
115 ecology, soil characteristics or stand density. It shows the extent to which the stand is likely to  
116 suffer from damage related to the hazard. Consequently, it takes the sensitivity of individuals to  
117 the effects of a hazard into account, as well as their ability to resist, adapt to them, and to return  
118 to the baseline situation (i.e., resilience) (UNEO, 2007). A hazard (which is only a natural process)  
119 becomes a natural risk only when there is an interaction between the hazard and the population,  
120 goods and activities affected (Veyret et al., 2013). The natural risk therefore implies the perception  
121 of this hazard by the population and, subsequently, its management (for cohabitation with the  
122 danger) (Veyret et al., 2013). Adaptation strategies will consequently play a role on vulnerability  
123 through the implementation of a water-saving silviculture.

124 The impacts of drought may be classified as biological or socio-economic. Four categories of bio-  
125 logical impacts can be distinguished: accommodation through changes in physiological functioning  
126 (Bréda and Badeau, 2008; Matesanz and Valladares, 2014), in phenology or in tree growth (Solberg,  
127 2004; Matesanz and Valladares, 2014); genetic adaptation (de Miguel et al., 2012); and migration  
128 and tree mortality (Spiecker et al., 2004; Galiano et al., 2011, 2012). The biological impacts begin  
129 at the tree level, which results in impacts at the stand level, which, in turn, results in impacts at the  
130 ecosystem level. Thus, at the stand level, loss of growth proportional to drought intensity induces  
131 loss of productivity, whereas at the ecosystem level, drought reduces most of the biological cycles  
132 that affect the functions of the forest and that lead to a loss of ecosystem services, mainly wood  
133 production and carbon sequestration (Maroschek et al., 2009). In terms of socio-economic impacts,  
134 drought generates financial losses linked to the current value of felled timber resulting from the loss



135 of marketability, a decrease in future stand value, the additional cost of forest restoration, and the  
136 loss of hunting and other regular income (Birot and Gollier, 2001). In addition, drought is also  
137 linked to the loss of carbon sequestration, which generates financial and social losses, as well as the  
138 loss of other amenities such as recreation (Thürig et al., 2005).

139 These impacts should be intensified in the near future due to climate change. Indeed, climate  
140 change is a global phenomenon due to an anthropogenic cause: the increase in the atmospheric  
141 concentration of greenhouse gases, the most important of which is carbon dioxide ( $CO_2$ ) (IPCC,  
142 2013). Climate will thus evolve towards an increase in average temperature, an escalation in the  
143 differences between wet and dry regions, a decrease in water availability, and an increase in the  
144 frequency and the intensity of extreme events such as severe drought (Spiecker, 2003). However,  
145 increasing  $CO_2$  can also limit the drought effect by increasing the water use efficiency of plants  
146 (Davi et al., 2006; Keenan et al., 2013).

### 147 **2.1.2 Adaptation strategies**

148 In order to try to limit the increasing impacts of drought, several adaptation strategies can be  
149 identified. We chose to test two main adaptation strategies according to their importance in the  
150 literature and according to the classification of soft and hard adaptation strategies<sup>1</sup> given by the  
151 World Bank (2010): (1) the reduction of rotation length (soft adaptation); and (2) species substi-  
152 tution from beech to Douglas-fir (hard adaptation). These two strategies are analyzed separately  
153 as well as jointly, and in combination with a third strategy, density reduction (soft adaptation).

154 First, the reduction of rotation length reduces the time of exposure to a drought event and the  
155 vulnerability of trees due to aging (Spiecker, 2003; Bréda and Peiffer, 2014). Young and old trees  
156 are the most vulnerable to drought (Archaux and Wolters, 2006): special attention must therefore

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<sup>1</sup>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.

157 be paid to the establishment of young trees and to avoiding long rotations.

158       Second, the introduction of drought-tolerant species and origins reduces the aerial carbon bal-  
159 ance, while using the same forest area (Keskitalo, 2011; FAO, 2011). Moreover, it would be preferable  
160 to introduce so-called transitional species or varieties, i.e., species able to thrive in both the current  
161 and projected future climate (e.g., pine, Douglas-fir, robinia).

162       Third, the reduction of the leaf area and, therefore, of the stand density, improves the resistance  
163 of forest stands to the lack of water (Archaux and Wolters, 2006; Bréda and Badeau, 2008), re-  
164 duces the intensity and duration of water deficits, and increases water availability (Spiecker, 2003).  
165 This results in an increase in initial planting space (Spiecker, 2003) and more intensive and ear-  
166 lier thinning (Spiecker, 2003; Keskitalo, 2011) in order to stabilize and thus protect stands (i.e.,  
167 to have a continuous forest cover and to protect it from all hazards) (Spiecker, 2003; Bernier and  
168 Schoene, 2009), to take advantage of  $CO_2$  fertilization to maximize and accelerate growth (Bernier  
169 and Schoene, 2009), to increase resistance and resilience to future damage (Kerhoulas et al., 2013),  
170 and to stimulate the growth of trees remaining after a drought (Kerhoulas et al., 2013).

## 171 **2.2 Case study**

### 172 **2.2.1 Case study area: Burgundy region**

173 Burgundy is a rural region and one of the major forest regions in France in terms of afforestation  
174 (30% afforestation rate), which has increased over the last 30 years. It has a great geographic  
175 (from valleys to mountains) and geological diversity. Its contrasted climate is of the Atlantic type  
176 with rainfall spread out throughout the year, ranging from 600 mm (Loire valley) to 1,500-1,800  
177 mm (Morvan peaks), average temperatures between 9.5 and 11.5°C, events of snow and frost, as  
178 well as frequent late frosts in May. However, biotic (pests and pathogens such as canker and  
179 bark beetle) and abiotic factors (e.g., late frosts, repeated water deficits, soil compaction due to

180 forest mechanization) threaten the health of forests. Burgundy forests are characterized by private  
181 property (68% according to the IGN, the French National Forest Inventory), a primary function  
182 of production, and a dominance of deciduous trees except in the Morvan. Indeed, beech and oak  
183 represent 90% of the forest areas. However, these two species are sensitive to summer water deficit  
184 and many beech diebacks can be observed, which may be amplified by a weakly dynamic silviculture.  
185 This is why, during the turnover of Burgundy stands, deciduous forests gradually shift to forests  
186 with more productive and valuable species such as Douglas-fir in order to anticipate future climate  
187 changes and to thus avoid financial losses and to respond to the growing demand for wood, with  
188 a more dynamic silviculture. Beech and Douglas-fir also produce commercially highly-valued wood  
189 in Burgundy, i.e., their annual production is 221,000  $m^3$  and 898,000  $m^3$ , respectively, in private  
190 forests.

### 191 **2.2.2 Species of interest**

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

203 increase in neighboring interactions and in the diversity of tree species (Chakraborty et al., 2017).

204 Overall, distribution in France is limited by temperature for Mediterranean species and by  
205 water supply for northern species as well as deciduous species (beech, oak) and conifers (Douglas-  
206 fir, spruce, fir). This is why the hydric constraints in the northern half of France cast doubts on the  
207 existence and the production of these latter species, particularly beech that has had many diebacks  
208 on superficial soils with low water reserves. Substitution with a species that is more productive  
209 under a dry climate and more valuable, such as Douglas-fir, seems to be a better economic solution,  
210 as suggested by Latte et al. (2015) for the regeneration of old beech stands. In addition, with the  
211 interest of the French public authorities (e.g., the National Forest Fund in France during the period  
212 1946-2000) and some professionals (builders, wood producers, furniture industries) in the rapid  
213 growth, the lower cost of production and maintenance, and the standardized sawing techniques of  
214 conifers (pine, fir), the demand would be based on an accelerated national production of conifers.  
215 Since two-thirds of the French forest is composed of deciduous trees, the transition could be backed  
216 by a less water-consuming silvicultural system, which is linked to the subject of our study.

217 A native of western North America, Douglas-fir (*Pseudotsuga menziesii* Mirb.) is an introduced  
218 species valued by forest managers for its rapid growth and the quality of its wood (Ronch et al.,  
219 2016). It appears to be able to provide significant wood production under a relatively dry climate  
220 (Eilman and Rigling, 2012; Ronch et al., 2016). However, despite all these qualities, Douglas-fir  
221 is more sensitive to high temperatures due to its high leaf area (i.e., strong transpiration) than  
222 to droughts. This explains the damage reported in France after the drought in 2003 (because of  
223 its combination with a heat wave), in particular in the Burgundy region (Sergent et al., 2014).  
224 Moreover, although Douglas-fir is described by some authors as a drought-resistant species (Eilman  
225 and Rigling, 2012), it does not seem to be well-adapted to the range and accumulation of intense  
226 and recurrent episodes of drought after a severe one, which could be explained by a lack of resilience,

227 e.g., after the drought in 2003 (Sergent et al., 2014).

228 Beech and Douglas-fir are both mesophilous species, i.e., species that grow in habitats that are  
229 neither extremely dry nor extremely humid (ONF, 1999). They prefer mountainous areas due to  
230 their high requirement for atmospheric moisture, although they are present in the plain. They  
231 are therefore sensitive to heat. Douglas-fir and beech have the same skewed and moderately deep  
232 rooting, but with different transpiration control during drought (ONF, 1999). Indeed, beech has a  
233 higher midday soil water potential and, consequently, a higher sensitivity to drought compared to  
234 Douglas-fir (ONF, 1999; Pierangelo and Dumas, 2012). In addition, deciduous trees have a higher  
235 demand for available water content than conifers (ONF, 1999): beech therefore consumes more water  
236 reserves than Douglas-fir in summer. However, edaphic drought can be aggravated by the existence  
237 of a high evaporation demand. Finally, Bréda and Badeau (2008) confirmed that the development  
238 of beech is dependent on water balance and drought, whereas for species such as Douglas-fir, their  
239 development is mainly related to temperature, supporting our suggestion to substitute beech with  
240 Douglas-fir.

### 241 **2.2.3 Study scenarii**

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

250 With respect to the uncertainty of future climate, the consequences of the two extreme climate  
 251 scenarii from the IPCC were analyzed: RCP 4.5 and RCP 8.5 (IPCC, 2013). RCP 4.5 represents  
 252 the most optimistic scenario, and RCP 8.5 represents the most pessimistic one (higher temperature,  
 253 higher  $CO_2$  concentration, etc.). All of these elements result in [(2 baselines + 7 scenarii  $\times$  2  
 254 drought risks)  $\times$  2 climates], which is equal to 32 scenarii. The two baselines and the seven scenarii  
 255 are summarized in Table 1.

Table 1: The different scenarii considered with their code

Code	Scenario
Baseline_B	Benchmark, current beech stand
Baseline_D	Benchmark, Douglas-fir in current conditions
B_NA	Beech stand without adaptation
B_DR1	Beech stand with a reduced rotation length
B_DR2	Beech stand with 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

256 The scenario is indicated by the following code for the benchmark (AWC of 150 mm): Base-  
 257 line\_Species (B for beech or D for Douglas-fir). The scenario is indicated by the following code for  
 258 both levels of drought risk (AWC of 100 mm and 50 mm): Species (B for beech or D for Douglas-  
 259 fir)\_Silviculture (NA for no adaptation, DR for density/rotation reduction and S for substitution).  
 260 Scenarii for beech were composed of a classical path (Baseline\_B and B\_NA) and three dynamic  
 261 ones (B\_DR1, B\_DR2 and B\_DR3) representing the silviculture of the density/rotation reduction  
 262 strategy. Simulations for Douglas-fir were composed of a classical path (Baseline\_D and D\_S)  
 263 representing the silviculture of the substitution strategy plus two dynamic ones (D\_S+DR1 and  
 264 D\_S+DR2) in order to test the combination of the two strategies.

## 265 **2.3 Methods**

266 To compare the adaptation options to deal with the drought-induced risk of forest decline, we first  
267 simulated forest growth with different silvicultural treatments according to these different adaptation  
268 strategies, the three different levels of water content and the two climate scenarii. The simulations  
269 were run with the CASTANEA model. The economic approach was then applied to the outcome of  
270 the simulations.

### 271 **2.3.1 Simulation of forest growth and silvicultural treatments**

272 CASTANEA requires three different files as inputs: the inventory file, the species file and the  
273 weather file. First, the inventory file contains all the trees with their characteristics related to  
274 the simulated stand. Through R software, soil characteristics (height, stone content, etc.) that are  
275 directly linked to the AWC and characteristics of the managed stand (tree diameter, LAI, etc.) make  
276 it possible to generate the list of all the trees according to these parameters. Second, the species file  
277 contains all the species-specific parameters that control the energy budget, growth (photosynthesis,  
278 respiration), carbon allocation and water consumption (see Table S1 in Supplementary Material).  
279 Third, the weather file contains the climatic characteristics of the studied site (global radiation, air  
280 temperature, relative air humidity, wind speed, precipitation). These georeferenced data for current  
281 and future climates (RCP 4.5 and RCP 8.5) came from the Meteo France network for four different  
282 SAFRAN points of 8×8 km (3202, 3710, 4303, 5121), chosen to represent the variety of climates in  
283 Burgundy. All of the results for each scenario are then taken from the average of the four SAFRAN  
284 points (see Figure S1 in Supplementary Material).

285 CASTANEA simulates photosynthesis and respiration to estimate net primary production. The  
286 carbon is then allocated to six compartments following the allocation rules described in Davi et al.  
287 (2009) and Davi and Cailleret (2017): large roots, fine roots, reserves, leaves, branches and trunks.

288 Biomass growth in the trunk is converted into volume growth from the density of the wood at the  
 289 end of the year. This makes it possible to estimate growth in ring width and volume on an annual  
 290 basis.

291 The annual output data were the volume of wood, the mortality rate, and the carbon seques-  
 292 trated into the forest stand. Risk of mortality by carbon starvation and hydraulic failure was  
 293 assessed according to Davi and Cailleret (2017). For this purpose, we simulated Non-Structural  
 294 Carbohydrates ([NSC]) and midday leaf water potential. Hydraulic failure is computed when the  
 295 midday leaf water potential drops below the P50 of the species (leaf water potentials below which  
 296 50% of conductivity loss occurs). The threshold of mortality on [NSC] is estimated by fitting the  
 297 threshold to minimize the difference among simulated and measured annual mortality rates between  
 298 2000 and 2015 once the hydraulics failure was computed. The mortality measurements were taken  
 299 from the French National Inventory on Burgundy.

300 The CASTANEA model simulated the forest growth of a stand of one hectare through different  
 301 silvicultural paths starting from a 125-year-old beech forest in Burgundy from 2000 to 2100. The  
 302 silvicultural paths arise from the CRPF (Regional Center for Privately-Owned Forests) of Burgundy  
 303 for both species. Table 2 presents the different characteristics of each silvicultural path.

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

304 The seven silvicultural paths were simulated through three different AWC (50, 100 and 150 mm)

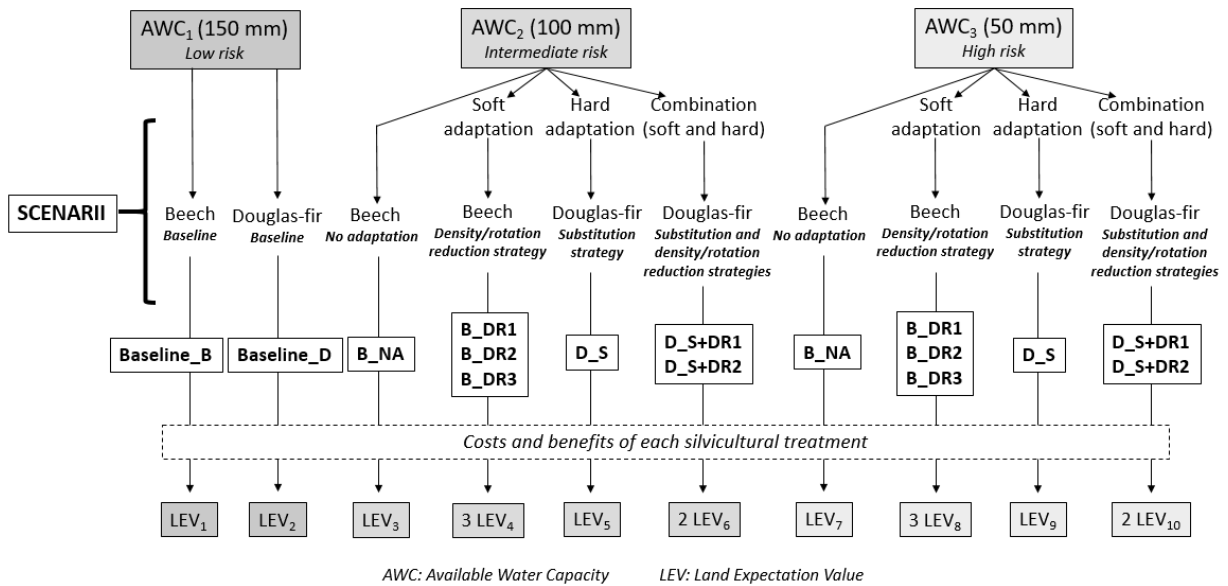


305 that characterized the drought effect and two different IPCC scenarii (RCP 4.5 and RCP 8.5) that  
 306 characterized the climate effect.

### 307 2.3.2 Economic approach

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

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



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

- 313 • (LEV 1 with LEV 3) and (LEV 1 with LEV 7): effect of drought.
- 314 • (LEV 3 with LEV 4) and (LEV 7 with LEV 8): effect of density/rotation reduction strategy.
- 315 • (LEV 1 with LEV 2) and (LEV 3 with LEV 5) and (LEV 7 with LEV 9): effect of species  
 316 substitution strategy.

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

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

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

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

324 It is assumed here that the forest owner has a single objective: to maximize the LEV. The infinite  
325 horizon used by this criterion makes it possible to compare management options associated with  
326 different temporal horizons, assuming that the silvicultural path was identical for each subsequent  
327 rotation after the first one. In other words, each silvicultural operation (thinning, maintenance,  
328 harvest) was implemented at the same age and for the same cost or benefit an infinite number of  
329 times. This may be seen as a limit of this criterion. However, other existing ones present greater  
330 limitations and are rarely adopted (Frayse et al., 1990; Morel and Terreaux, 1995). Faustmann's  
331 LEV takes the costs and the benefits from wood harvesting into account. After discussion with  
332 forestry experts, a discount rate  $r$  of 3% was decided. A sensitivity analysis on this parameter was  
333 performed and is presented in Section 4.2.

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

338 For that purpose, we also calculated Hartman's LEV, which makes it possible to take the benefits  
339 from wood harvesting and from amenities as well (Hartman, 1976), in our case, carbon sequestration

340 (see Couture and Reynaud (2011) for a short review of studies using Hartman's framework with  
 341 carbon storage). The Hartman model was applied as follows:

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

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

345 The discount rate  $r$  was also 3% for beech and Douglas-fir in order to be able to compare the LEVs.  
 346 To calculate the benefits from carbon sequestration, we considered the additional sequestration of  
 347 the standing wood and we chose the social cost of carbon of 44 EUR/T (Watkiss and Downing,  
 348 2008). The social cost of carbon is "an estimate of the total cost of damages done by each ton of  
 349  $CO_2$  that is spewed into the air" (Howard and Sterner, 2014). It therefore gives the total value  
 350 of avoided damage caused by the flow of carbon to the atmosphere in the case of potential total  
 351 deforestation.

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

Table 3: Stand density (number of trees per ha), 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	12524	249	12457

### 3 Results

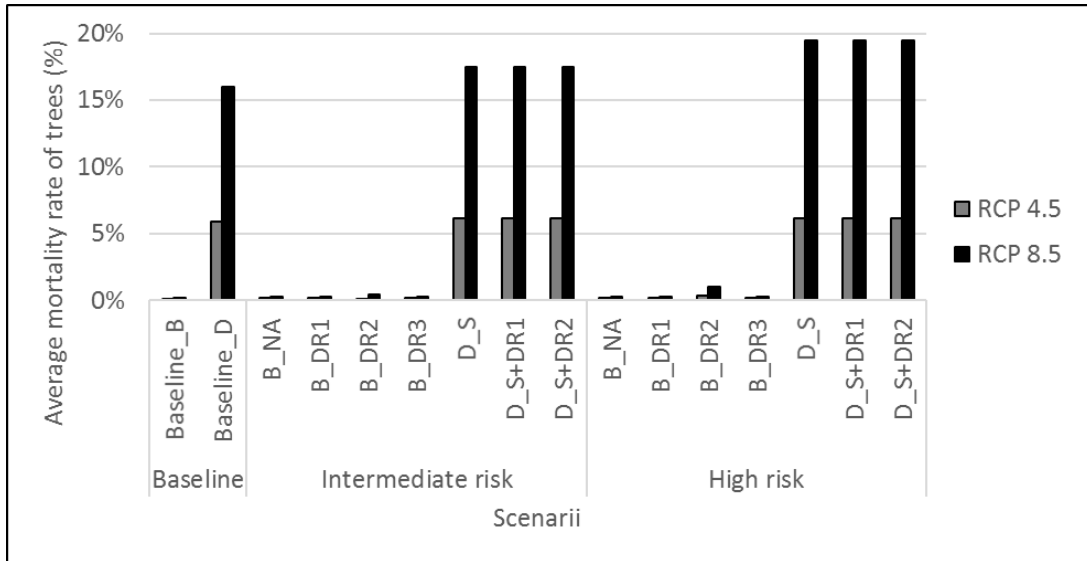
#### 3.1 Forest growth and mortality

Figures 2 and 3 show the results of the simulations of the forest stand per scenario and per RCP, in terms of growth (volume increment of wood in cubic meters per hectare) and mortality (in percentage terms), respectively. Mortality was taken into account in the calculation of the 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 the mortality. There is no difference between scenarii when considering the same tree species. Climate has a negative effect on mortality: Scenarii 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 scenarii). Drought has a negative effect for all the scenarii: They present lower growth in a high risk than in an intermediate risk. Climate has a slightly positive effect on Douglas-fir:

Figure 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)



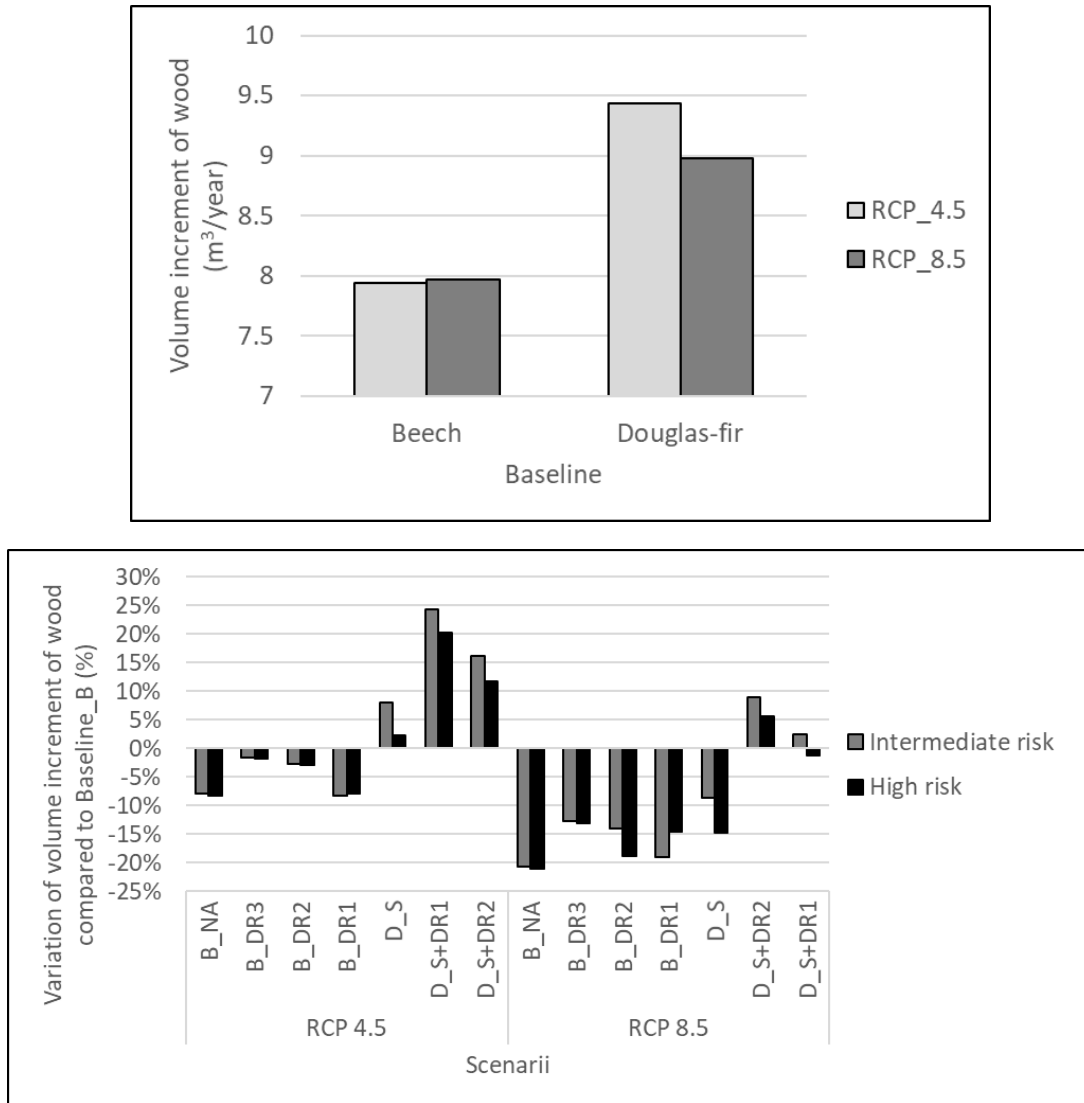
368 Scenarii have a higher growth in RCP 8.5 than in RCP 4.5, which can be explained by the  $CO_2$   
 369 fertilization (higher  $CO_2$  concentration in RCP 8.5 than in RCP 4.5). There is no climate effect for  
 370 beech and for the baseline of both tree species. Considering only beech, growth decreases with the  
 371 reduction of stand density (5000, 3000 and 1000 trees/ha for B\_DR1, B\_DR2 and B\_DR3 respec-  
 372 tively). Combinations of different strategies (D\_S+DR1 and D\_S+DR2) have the best growth,  
 373 unlike non-adaptation (B\_NA), which is below the baseline.

374

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

376 First, the scenarii with Douglas-fir showed the highest volume increment of wood, whereas  
 377 they had the highest mortality rates. More precisely, the two scenarii that combined two strategies  
 378 (D\_S+DR1 and D\_S+DR2) were the best ones, showing a higher growth in the more severe climate  
 379 scenario (RCP 8.5) than in the small-temperature increment scenario (RCP 4.5). All these elements  
 380 corroborate the literature describing Douglas-fir as a high productive species in dry climates (Eilman  
 381 and Rigling, 2012; Ronch et al., 2016).

Figure 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



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

386 These two points demonstrate different sensitivities to drought and climate change. Indeed,  
 387 beech reacts and is thus more sensitive to drought (precipitation effect) than to climate (temperature

388 effect) (Latte et al., 2015; Chakraborty et al., 2017), and the contrary for Douglas-fir (Sergent et al.,  
389 2014).

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

### 394 **3.2 Economic comparison**

395 The resulting variations in LEVs compared to the baseline of beech (Baseline\_B) are presented in  
396 Table 4. The range of values of Faustmann's LEV is from -983 to 4,916 EUR/ha and from -866  
397 to 4,717 EUR/ha for the RCP 4.5 and 8.5, respectively. In terms of implementation of adaptation  
398 strategies, scenarii with a positive variation of LEVs compared to the baseline represent the benefit  
399 of adaptation for forest owners: B\_DR1, B\_DR2 and D\_S+DR2. In contrast, scenarii with a  
400 negative variation of LEVs compared to the baseline represent the potential cost of adaptation for  
401 forest owners: B\_DR3, D\_S and D\_S+DR1.

402 Concerning the baseline, maintaining the current beech stand was more profitable than substi-  
403 tuting it with Douglas-fir. Table 4 reveals that a substitution strategy combined with that of a  
404 density reduction (D\_S+DR2) provides the best economic return, regardless of the level of drought  
405 risk and the climate scenario. In a second step, the density reduction of beech then provides the  
406 best economic return with the scenario B\_DR2, followed by the scenario B\_DR1. Note that the  
407 two other scenarii with Douglas-fir (D\_S and D\_S+DR1) are the worst options from an economic  
408 perspective, regardless of the level of drought risk and the climate scenario.

409 Based on Table 4, we can say that costs and benefits of adaptation strategies are clearly not  
410 additive, but synergies between adaptation strategies appear to be. For example, for an intermediate

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%

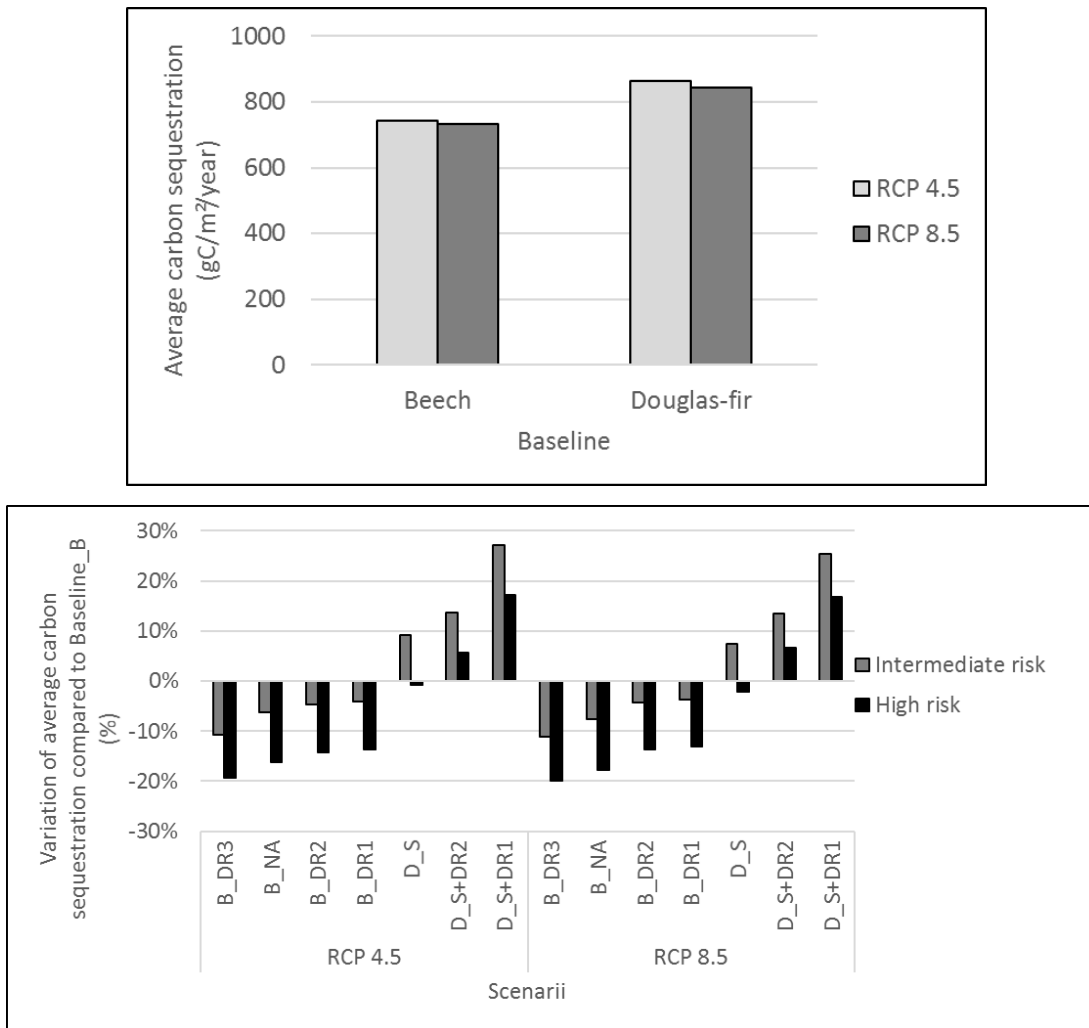
411 level of risk, considering only the reduction of the initial rotation length of the beech stand (B\_DR1)  
412 allows a financial benefit (+79%), applying a first reduction of initial density (B\_DR2) as well  
413 (+82%). However, a more intense density reduction (B\_DR3) generates loss (-3%) due to the  
414 beech characteristics (shadow species). The same comment applied for high risk. In the same vein,  
415 implementing substitution alone (D\_S) corresponds to financial loss (-67%), and adding a reduction  
416 of rotation length (D\_S+DR1) increases the previous loss (-111%). However, combining the three  
417 strategies (substitution with a reduction of rotation length and stand density, D\_S+DR2) makes  
418 it possible to generate the highest benefits (+216%). This observation is also true for high risk.  
419 Following these observations, it appears that the reduction of rotation length and density reduction  
420 are complementary.



421 **3.3 Carbon sequestration**

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

Figure 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



424 Recall that mortality was considered in the calculation of the volume. We can see that Douglas-  
 425 fir presents a higher carbon sequestration than beech (baseline and scenarii). Drought has a negative  
 426 effect for all the scenarii. They present lower carbon sequestration under a high risk than under an

427 intermediate risk. Climate does not affect carbon sequestration (baseline and scenarii). Considering  
 428 only beech, carbon sequestration decreases with the reduction of stand density (5000, 3000 and  
 429 1000 trees/ha for B\_DR1, B\_DR2 and B\_DR3, respectively). Scenario D\_S+DR1 that combines  
 430 different strategies has the best carbon sequestration, in contrast to scenario B\_DR3 (reduced  
 431 density and rotation length), which is the worst one and below the baseline.

432 In terms of economic perspective, the resulting variations in LEVs compared to the baseline of  
 433 beech (Baseline\_B) are presented in Table 5. The range of Hartman's LEV is from -230 to 5,672  
 434 EUR/ha and from -969 to 5,378 EUR/ha for the RCP 4.5 and 8.5, respectively. The same results  
 435 are observed when considering Hartman's LEV: the scenario D\_S+DR2 provides the best economic  
 436 return, regardless of the climate and the level of drought risk.

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%

## 437 4 Discussion

### 438 4.1 Adaptation in an economic perspective

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

448 However, two economic results were unexpected. First, despite its low quality and, as a result,  
449 value, the reduced initial density and rotation length scenario B\_DR2 provides the second best  
450 return. Indeed, while Douglas-fir can be more interesting (as described above), beech is the natural  
451 species of this stand. This implies that the regeneration of a beech stand was natural (seeds from  
452 old trees) and thus without costs, unlike for a Douglas-fir stand obtained artificially (plantation)  
453 involving plantation costs. Forest owners may perceive these high plantation costs (compared to the  
454 natural regeneration of beech) as a brake to adaptation. It may be interesting then to encourage  
455 them to shift to better-adapted tree species. A way to incite them to choose adaptation may be  
456 the subsidization of plantation by the public authorities. Indeed, in a context of international  
457 negotiation to limit climate change, forests have to play a role and public authorities have an  
458 interest in adapting them. In France, forests are privately owned, so incentives to encourage owners  
459 to adapt, such as subsidization, may be required. On the other hand, the forest sector should adapt

460 to these silvicultural changes and it is likely that the government may also have a role to play.

461       Second, while the scenarii D\_S+DR1 and D\_S+DR2 were the best ones in terms of growth  
462 (from an ecological point of view), they presented contrasted economic results. Indeed, scenario  
463 D\_S+DR2 provides the best economic return, and scenario D\_S+DR1 the worst one. This coin-  
464 cides with the objective of scenario D\_S+DR2 that was to reduce plantation costs by starting with  
465 660 trees/ha (instead of 1660 trees/ha for the other scenario as a way to meet industrial demand).  
466 This result also proves the importance of having an interdisciplinary vision. Bringing together the  
467 two fields leads to the emergence of a consensual and more relevant solution, scenario D\_S+DR2. In  
468 addition, in terms of wood quality, the implementation of scenario D\_S+DR2 is only possible with  
469 a "deciduous filler". In our case, it would be an addition of beech (which regenerates naturally) at  
470 the understory to avoid branched Douglas-fir and to thus obtain wood of good quality. This beech  
471 filler can also offer additional benefits such as the production of firewood.

472       Whether we consider scenario D\_S+DR2 or scenario B\_DR2, they both showed the success  
473 of combining different strategies. This agrees with the idea of Jönsson et al. (2015), who promote  
474 a portfolio of adaptation strategies to reduce the risk of damage. This result also supports the  
475 recommendation of the World Bank (2010) to combine soft and hard adaptation. This idea to  
476 combine strategies should be more widespread among forest owners. Indeed, adaptive management  
477 is part of the category of "no regret" or "win-win" strategies: reducing stand density makes it  
478 possible to save water in the soil in both scenarii and money as well in scenario D\_S+DR2 under  
479 (or not) a drought risk. However, the lack of relevant information is seen as a brake to adaptation  
480 (Yousefpour and Hanewinkel, 2015; Sousa-Silva et al., 2016). Forest owners are reluctant to adapt  
481 due to a large uncertainty concerning the impact of the implemented adaptation strategies. In this  
482 sense, the combination of strategies offers flexibility to the owners in addition to adaptive capacity.  
483 The reduction of the rotation length increases the flexibility of forest management, thus reducing

484 the decision horizon, particularly in scenario D\_S+DR2, which has the shortest rotation length.

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

## 487 **4.2 Carbon consideration**

488 Figure 4 showed that when considering scenarii of beech and those of Douglas-fir separately, the  
489 higher the initial stand density was, the more carbon that was sequestered. This does not coincide  
490 with drought adaptation strategies. That is why the combination of two strategies through the best  
491 scenario (D\_S+DR2) is a good trade-off between adaptation and mitigation of climate change.

492 Hartman's LEV gives the highest values compared to Faustmann's LEV. Without taking carbon  
493 sequestration into account, we underestimate the value of the forest stand. However, Hartman's  
494 LEVs present the most extreme values and, consequently, the greatest variation of values in the most  
495 severe climate scenario (RCP 8.5). This criterion therefore takes all of the externalities of carbon  
496 sequestration linked to the implied silviculture into account. These results prove the importance  
497 of taking carbon sequestration into account, mainly in the context of climate change, and not just  
498 wood production to compute the profitability.

499 This approach leads to an initial consideration of carbon in these analyses. Many debates exist  
500 about carbon accounting. That is why this step can be developed in further studies. Indeed, it  
501 would be interesting to know how positive externalities from carbon sequestration can be managed  
502 in reality. Amenities can generate carbon credits, which can result in a payment to forest owners  
503 for the total sequestered carbon or the annual increment of sequestered carbon of the past year  
504 (Dwivedi et al., 2012). A payment implies thinking about the way in which to provide it (Guitart  
505 and Rodriguez, 2010) - at the final harvest or as a revenue each year. We can take the future use of  
506 wood products with different lifetimes into account, as well as the carbon stored in these products.

507 This suggests that wood quality has to be integrated into our study. For example, firewood directly  
508 re-emits sequestered carbon, whereas carbon in a wooden table has a longer lifetime. With this  
509 approach in mind, the individual negative effect of the wood production of forest owners should  
510 be considered at the same time as the economic consequences for society, along with the social  
511 contribution through different wood products.

512 Finally, on the whole, adaptation makes society as well as the economy more resilient to haz-  
513 ards (Konkin and Hopkins, 2009), which refers to the "forests for adaptation" of Locatelli et al.  
514 (2010). However, the implementation of effective adaptation measures depends on the availabil-  
515 ity of human resources and skills (Maroschek et al., 2009). Adaptive management is part of the  
516 "no regret", reversible and non-technical strategies and the ones that reduce the decision horizon  
517 due to its flexibility with respect to the evolution of climate change and its beneficial investments,  
518 even in the absence of drought risk (Courbaud et al., 2010). Adaptive management is thus part  
519 of the adaptation measures to climate change and also contributes to its mitigation by increasing  
520 the carbon-sink capacity, for example (Kolström et al., 2011). The FAO (2011) emphasizes that  
521 "effective management of global forests not only reduces the risk of damage from potential disasters,  
522 but also has the potential to mitigate and adapt to climate change".

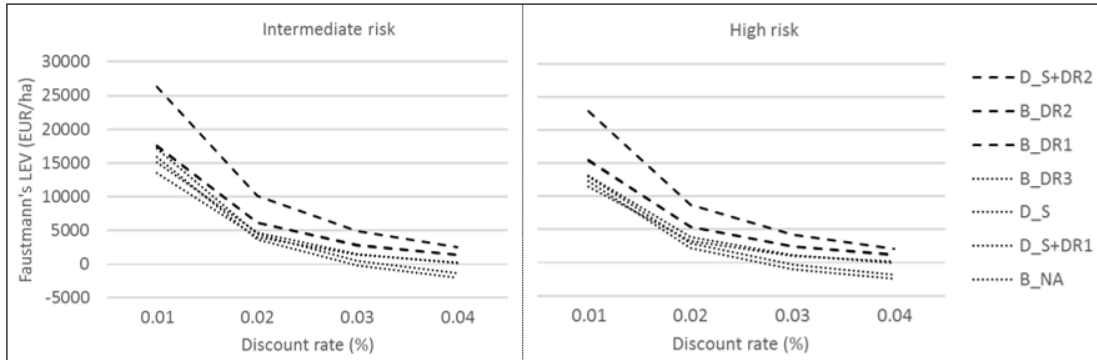
### 523 **4.3 Sensitivity analysis**

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

527 In Fig. 5, Faustmann's LEV of scenario D\_S+DR2 is the highest, regardless of the discount  
528 rate for both risks. The second one is scenario B\_DR2 since the discount rate for an intermediate  
529 risk is 1.5%, regardless of the discount rate for the high one. The order between scenarii does not

530 change since the discount rate is 3.5%.

Figure 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)



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

#### 533 4.4 Limits and perspective

534 The CASTANEA model was used for the first time for the purpose of forest management. A good  
535 reaction of volume increment was observed after a thinning, i.e., a boost of growth because of  
536 the increase in growing space and water resources in the first years. However, drought generates  
537 effects on growth for the year of the event and for one or more years after (Power et al., 1995;  
538 Rouault et al., 2006). These post-drought effects are taken into account in the model through  
539 the effect of Non-Structural Carbon on growth, but they are still not properly evaluated. Three  
540 adaptation strategies (density/rotation reduction and species substitution) were chosen as the most  
541 relevant and mentioned in the literature, but also on the basis of their technical feasibility with  
542 the CASTANEA model and in Burgundy. Indeed, substitution of beech stands with Douglas-fir  
543 has already been tested in the Morvan. The architecture of the CASTANEA model (inventory  
544 file for one species growing at the same age) did not make it possible to compute intraspecific

545 (uneven-aged forests) and interspecific (mixture of species) stands, which explains why this well-  
546 documented measure was not studied here. Indeed, many studies have proved the effectiveness  
547 of mixed stands in terms of biodiversity objectives to reduce drought risk (FAO, 2011; Keskitalo,  
548 2011). Mixtures make it possible to diversify wood production instead of opposing the different  
549 uses, with, in general, conifers providing lumber wood and deciduous trees providing energy wood.  
550 Therefore, to investigate this strategy, we need to more extensively study mixed stands and the  
551 (aboveground and underground) interactions between species (competition and symbiosis) in order  
552 to be able to model them. Nonetheless, while all forest services must be taken into account in order  
553 to preserve the multifunctionality of forests, mixture strategy probably requires taking trade-offs  
554 between adaptation to drought and biodiversity objectives into account, which may be conflicting.

555 Another potential limitation of this study is that our model considers a fixed wood price grid  
556 depending on tree diameter. First, the wood price varies with the tree diameter but also fluctuates  
557 with the supply, which are two parameters affected by climate change (see Section 3.1), and such  
558 variations are not considered in our study. Second, the wood price increases together with the  
559 diversity of wood uses and the substitution effect of fossil fuels. More and more uses are being  
560 discovered for Douglas-fir wood, and its growing demand is not considered in this paper.

## 561 **5 Conclusion**

562 The productivity of forests is severely limited by water availability in the soil. We observed that  
563 drought induces extensive tree decline due to impacts over several years that result in high socio-  
564 economic losses, which will then be accentuated by climate change. Moreover, the literature de-  
565 scribes the drought hazard at different levels, but without spatial analysis, as is the case for storms  
566 and especially fire hazard (monitoring, prevention by creating transects). Indeed, a mapping based  
567 on synthetic water deficit indices would be interesting to "spatialize" the estimation of available



568 water reserves at any given time.

569 Our study shows that the adaptation of beech stands in Burgundy is needed to fight against  
570 drought-induced decline. Adaptation is costly for forest owners. Therefore, in order to consider  
571 adaptation to drought in forest management, the forest owner needs to analyze exposure to drought,  
572 to assess potential impacts, and to evaluate the adaptive capacity of both the forest stand and  
573 the management system. In addition to this, an important question was how to select suitable  
574 measures from the multitude of adaptation options. On the basis of growth and carbon sequestration  
575 simulations by the CASTANEA model, substitution of beech stands with Douglas-fir, combined with  
576 a reduction of the initial stand density and a reduction of the rotation length, provides the best  
577 economic return, regardless of the climate and the level of drought risk. Our paper is the first to  
578 compare different adaptation strategies to face the drought-induced risk of forest decline, and the  
579 synergy of both strategies provided a robust result. We also showed that adaptation is not always  
580 as economically beneficial as ecologically and, consequently, trade-offs between objectives may exist  
581 (Johnston and Withey, 2017).

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

588 In the aim of promoting the best strategy to be combined with drought risk for decision-making,  
589 we showed the importance of the interconnection between different fields (ecology and economics),  
590 to take the multifunctionality of forests (wood production and carbon sequestration in this case),  
591 the need for general information about silvicultural treatments, and the collaboration between dif-

592 ferent sectors (forest managers and researchers) into account. In addition, since drought increases  
593 vulnerability to secondary attacks (pests and pathogens), current challenges for disturbance mod-  
594 eling would include carrying out multiple-risk analyses in dynamic ecosystem models for decision  
595 support in forest management.

## 596 **Acknowledgments**

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

## 604 References

- 605 F. Archaux and V. Wolters. Impact of summer drought on forest biodiversity: What do we know?  
606 Annals of Forest Science, 63(6):645–652, 2006.
- 607 World Bank. Economics of adaptation to climate change: Social synthesis report. 2010.
- 608 P. Bernier and D. Schoene. Adapting forests and their management to climate change: An overview.  
609 Unasylva, 60(231-232):5–11, 2009.
- 610 Y. Birot and C. Gollier. Risk assessment, management and sharing in forestry, with special emphasis  
611 on wind storms. 14th Convocation of Academies of Engineering and Technological Sciences, 2001.
- 612 N. Bréda and V. Badeau. Forest tree responses to extreme drought and some biotic events: Towards  
613 a selection according to hazard tolerance? Comptes Rendus Geoscience, 340(9-10):651–662, 2008.
- 614 N. Bréda and M. Brunette. Are 40 years better than 55 ? An analysis of the reduction of forest  
615 rotation to face drought event. Cahiers du LEF, 2014-03, 2014.
- 616 N. Bréda and M. Peiffer. Vulnerability to forest decline in a context of climate changes: New  
617 prospects about an old question in forest ecology. Annals of Forest Science, 71(6):627–631, 2014.
- 618 M. Brunette, S. Costa, and F. Lecocq. Economics of species change subject to risk of climate change  
619 and increasing information: A (quasi-) option value analysis. Annals of Forest Science, 71(2):  
620 279–290, 2014.
- 621 T. Chakraborty, S. Saha, A. Matzarakis, and A. Reif. Influence of multiple biotic and abiotic factors  
622 on the crown die-back of European beech trees at their drought limit. Flora, 229:58–70, 2017.
- 623 M. Charru, I. Seynave, F. Morneau, and J.D. Bontemps. Recent changes in forest productivity: An

624 analysis of National Forest Inventory data for common beech (*Fagus sylvatica* L.) in north-eastern  
625 France. Forest Ecology and Management, 260(5):864–874, 2010.

626 B. Courbaud, G. Kunstler, X. Morin, and T. Cordonnier. Quel futur pour les services écosystémiques  
627 de la forêt alpine dans un contexte de changement climatique? Revue de Géographie Alpine, 98  
628 (4), 2010.

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

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

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

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

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

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

643 H. Davi, C. Barbaroux, C. Francois, and E. Dufrêne. The fundamental role of reserves and hy-  
644 draulic constraints in predicting LAI and carbon allocation in forests. Agricultural and Forest  
645 Meteorology, 149(2):349–361, 2009.

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

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

652 P. Dwivedi, R. Bailis, A. Stainback, and D.R. Carter. Impact of payments for carbon sequestered  
653 in wood products and avoided carbon emissions on the profitability of NIPF landowners in the  
654 US South. Ecological Economics, 78:63–69, 2012.

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

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

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

662 J. Fraysse, M. Moreaux, and J.P. Terreaux. Actualisation et gestion forestière. Cahiers d’Economie  
663 et de Sociologie Rurales, 15–16:111–125, 1990.

664 L. Galiano, J. Martínez-Vilalta, and F. Lloret. Carbon reserves and canopy defoliation determine  
665 the recovery of Scots pine 4 yr after a drought episode. New Phytologist, 190(3):750–759, 2011.

666 L. Galiano, J. Martínez-Vilalta, S. Sabaté, and F. Lloret. Determinants of drought effects on crown

667 condition and their relationship with depletion of carbon reserves in a Mediterranean holm oak  
668 forest. Tree Physiology, 32(4):478–489, 2012.

669 V. Godreau. Les stations à hêtre des plateaux de Bourgogne. Tome II, Conseil Régional de Bour-  
670 gogne, 1992.

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

673 M. Hanewinkel, S. Hummel, and D.A. Cullmann. Modelling and economic evaluation of forest  
674 biome shifts under climate change in southwest Germany. Forest Ecology and Management, 259  
675 (4):710–719, 2010.

676 R. Hartman. The harvesting decision when a standing forest has value. Economic Inquiry, 14(1):  
677 52–58, 1976.

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

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

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

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

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

686 A.M. Jönsson, F. Lagergren, and B. Smith. Forest management facing climate change - An ecosystem  
687 model analysis of adaptation strategies. Mitigation and Adaptation Strategies for Global Change,  
688 20(2):201–220, 2015.

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

692 L.P. Kerhoulas, T.E. Kolb, M.D. Hurteau, and G.W. Koch. Managing climate change adaptation  
693 in forests: A case study from the US southwest. Journal of Applied Ecology, 50(6):1311–1320,  
694 2013.

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

697 M. Kolström, M. Lindner, T. Vilén, M. Maroschek, R. Seidl, M.J. Lexer, S. Netherer, A. Kremer,  
698 S. Delzon, A. Barbati, M. Marchetti, and P. Corona. Reviewing the science and implementation  
699 of climate change adaptation measures in European forestry. Forests, 2(4):961–982, 2011.

700 D. Konkin and K. Hopkins. Learning to deal with climate change and catastrophic forest distur-  
701 bances. Unasylva, 60(231/232):17–23, 2009.

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

705 F. Lebourgeois, N. Bréda, E. Ulrich, and A. Granier. Climate-tree-growth relationships of European  
706 beech (*Fagus sylvatica* L.) in the French Permanent Plot Network (RENECOFOR). Trees, 19  
707 (4):385–401, 2005.

708 B. Locatelli, M. Brockhaus, A. Buck, and I. Thompson. Forests and Adaptation to Climate Change:  
709 Challenges and Opportunities, volume 25 of IUFRO World Series. IUFRO, 2010. ISBN 978-3-  
710 901347-93-1.

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

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

715 M. Morel and J.P. Terreaux. L'estimation de la valeur des forêts à travers un exemple: Entre  
716 simplification abusive et complexité du réel. Revue Forestière Française, 47(2):151–161, 1995.

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

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

720 S. Power, M.R. Ashmore, and K.A. Ling. Recent trends in beech tree health in southern Britain  
721 and the influence of soil type. Water, Air, and Soil Pollution, 85(3):1293–1298, 1995.

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

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

728 A.S. Sergent, P. Rozenberg, and N. Bréda. Douglas-fir is vulnerable to exceptional and recurrent  
729 drought episodes and recovers less well on less fertile sites. Annals of Forest Science, 71(6):  
730 697–708, 2014.

731 S. Solberg. Summer drought: A driver for crown condition and mortality of Norway spruce in  
732 Norway. Forest Pathology, 34(2):93–104, 2004.



733 R. Sousa-Silva, Q. Ponette, K. Verheyen, A. Van Herzele, and B. Muys. Adaptation of forest  
734 management to climate change as perceived by forest owners and managers in Belgium. Forest  
735 Ecosystems, 3(1):22, 2016.

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

738 H. Spiecker, J. Hansen, E. Klimo, J. Skovsgaard, H. Sterba, and K. von Teuffel. Norway spruce con-  
739 version: Options and consequences. Research report 18, S. Brill, Leiden, Boston, Koln, European  
740 Forest Institute, 2004.

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

743 E. Thürig, T. Palosuo, J. Bucher, and E. Kaufmann. The impact of windthrow on carbon seques-  
744 tration in Switzerland: A model-based assessment. Forest Ecology and Management, 210(1):  
745 337–350, 2005.

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

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

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

752 R. Yousefpour and M. Hanewinkel. Balancing decisions for adaptive and multipurpose conversion  
753 of Norway spruce (*Picea abies* L. Karst) monocultures in the black forest area of Germany. Forest  
754 Science, 60(1):73–84, 2014.

755 R. Yousefpour and M. Hanewinkel. Forestry professionals' perceptions of climate change, impacts  
756 and adaptation strategies for forests in south-west Germany. Climatic Change, 130(2):273–286,  
757 2015.

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

# Appendices

760

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

762

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

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

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

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

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

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

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

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

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

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

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

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



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

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

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

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