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Abstract

In this paper, we tackle the reduction of rotation from an economic perspective. In a cost-benefit framework, we look at the impact of such a reduction on the forest economic value. We concentrate on a Douglas-fir plantation with rotation of 55 years and we wonder about the relevance to reduce to 40 years. We consider the role of climate change (through an increasing drought risk), the role of site fertility and temporal horizon. We also conduct sensitivity analysis on the discount rate and introduce fertilization overcost needed to sustain productivity in shorter rotation. We compare, from an economic point of view, three different adaptation strategies: absence of adaptation (i.e. sylviculture as usual), immediate adaptation and a delayed one. In our case study, the best option for the forest owner in terms of economic return is the absence of adaptation, after it is to delay the adaptation by one rotation and finally to adopt immediate adaptation. However, we also prove that such a trend should be reversed from a damage threshold. Then, with a loss of volume superior to 28% in case of drought event occurrence, an immediate adaptation allows a better economic return than the absence of adaptation. This result seems to suggest that the reduction of rotation may be an adaptation tool for vulnerable stands.

Key words: adaptation, climate change, cost-benefit analysis, drought, risk of decline, rotation, forest.

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1. Introduction

Climate change through increasing temperature, change in water regime and in disturbances regime will have an impact on various ecosystems in particular in the forest ecosystem. Indeed, due to the length of investment period and limited reversibility or plasticity of the decisions, forest seems to be of particular interest to analyse adaptation options. Forest managers are accustomed to consider the long-term implications of their decisions (Keenan 2012). However, many management actions are now responding to much shorter term economic or political imperatives. Some current management measures may continue to be suitable in responding to increasing pressures under climate change, while for other situations new measures will be required. Adaptation to climate change involves assessing, handling and controlling risks. Kolström *et al.* (2011) suggested that models are important to analyse risks, and that improved risk simulations are needed to assess the effectiveness of alternative management options in reducing disturbance impacts. This is precisely the aim of the present research.

As a forest planted today will come to maturity to be harvested in 30 to 100 years depending on the species, it will be exposed to future climatic hazards. However, the increase of CO_2 atmosphere concentration may continue during the coming century, the average temperature can increase from 1.1 to 6.4°C, the disturbances regime and the water regime may be modified (IPCC 2007). Productivity of forest ecosystems is severely constrained by water availability and extreme drought events may induce large-scale tree decline episodes in temperate forests. As a consequence of soil water deficit, tree growth is limited and individual tree survival may become problematic in case of extreme water depletion in soils (Bréda *et al.* 2006). Then, climate change should accentuate drought risk in forest and generate lower forest return (IPCC 2007).

In such a context, some adaptation actions are thus advocated to face increasing drought risk such as the reduction of rotation (Gottschalk 1995; Lindner *et al.* 2000; Spittlehouse and Stewart 2003). The rotation is the time from the establishment of a forest stand to its final felling. Indeed, reducing the rotation is considered as a win-win option, diminishing both the time of exposure to drought event and the vulnerability of trees. Consequently, owners wonder about the consideration of such an adaptation option, its implementation and the associated costs. Then, the question is: Is the reduction of rotation a management practice to consider adapting forest to future risk of dieback induced by drought event? And if yes, at which cost?

From a biological point of view, the reduction of rotation leads to some studies focusing essentially on the link between rotation and carbon storage (Liski *et al.* 2001; Kaipainen *et al.* 2004). Little attention has been paid to potential advantage to reduce rotation to improve tree resistance especially to drought events. Water availability is commonly limiting to Douglas-fir growth, more than energy limitations on growing season length (Littell *et al.* 2008). The sensitivity of Douglas-fir to summer water balance deficit indicates that increases in drought episodes will impair life history processes such as growth and mortality. Then, Douglas-fir plantations may suffer from a loss of productivity due to both a growth reduction and an increase of abnormal mortality. Only three Douglas-fir decline episodes have been reported in the international literature, two in the species' natural range and one in the Netherlands: two remained unexplained and the third one was related to frost damage (Carter *et al.* 1984; deKort 1993; Reich and van der Kamp 1993). However, Douglas-fir growth in its natural range is largely controlled by water and nutrient availability (Nigh 2006; Chen *et al.* 2010).

From an economic point of view, a forest economics literature focused on the impacts of risk on rotation. Thus, a stochastic forest stand value (Clarke and Reed 1989, 1990; Willassen 1998; Alvarez 2004; Chang 2005), stochastic timber price (Brazee and Mendelsohn 1988;

Thomson 1992; Insley 2002; Insley and Rollins 2005) or interest rate variability (Alvarez and Koskela 2003, 2005) lengthens the optimal rotation period. To the contrary, fire risk reduces the rotation compared to a deterministic situation, both theoretically (Reed 1984; Martell 1994; Amacher *et al.* 2005) and empirically (Kuuluvainen and Tahvonen 1999; Englin *et al.* 2000)[3]. This last result is thus discussed as regard to amenity values (Englin *et al.* 2000), change in fire risk over time (Stollery 2005) and risk aversion (Alvarez and Koskela 2006) among others. However, such literature only concentrates on fire risk which has different characteristics from drought risk. Indeed, a drought risk occurrence has a lower direct impact on a forest stand than fire but this impact increases over time. In addition, this literature does not focus on the impact of climate change on the risk, although it is well-known that climate change will impact negatively the intensity and severity of natural events, in particular drought event.

In this paper, our objective is to tackle the reduction of rotation to face risk of dieback induced by drought event from an economic perspective. In a cost-benefit framework, we look at the impact of such a reduction on the forest economic value. We focus on a Douglas-fir plantation with rotation of 55 years and we wonder about the economic relevance to reduce to 40 years as a strategy to reduce risk of dieback induced by drought event. We introduce climatic risk by soil water balance projection using climatic scenario, the increasing drought occurrence differing among temporal horizon (near or distant future) and depending on site fertility. We also conduct sensitivity analysis on the discount rate and introduce fertilization overcost, required to compensate higher nutrient exportation in shorter rotation especially on soils with low fertility. We compare, from an economic point of view, three different adaptation strategies: absence of adaptation, immediate adaptation and a delay one. We show that, for the forest owner and stand with limited vulnerability, the best option in terms of

[3] The interested reader may refer to the article of Newman (2002) in order to have a full overview of the literature on this topic.

economic return is the absence of adaptation, while the second is to delay the adaptation by one rotation and finally the third is to adopt immediate adaptation. However, we also demonstrate that such a trend depends on stand vulnerability, i.e. from a damage threshold. Then, if the loss of volume is superior to 28% in case of drought occurrence, an immediate adaptation dominates economically the absence of adaptation. This result suggests that reduction of rotation may be an adaptation tool for vulnerable stands.

The rest of the paper is organized as follows. Section 2 describes the materials and methods. Section 3 presents the results. Section 4 discusses the results and Section 5 concludes.

2. Materials and methods

We describe our procedure step by step following Hallegatte *et al.* (2010). The first step is to identify the options to compare, i.e. rotation of 55 years versus 40 years for Douglas-fir stand (Section 2.1). The second step consists in the description of the adaptation strategies considered in relation to the drought occurrence in the close and far future according to climatic scenarios down scaled to the studied region of production (Section 2.2), and the next subsection indicates the economic method (Section 2.3).

2.1 Case study

Currently, in France the Douglas-fir sylviculture consists in rotation of around 50 years. However, the Douglas-fir is known to be sensitive to soil water deficit leading to growth reduction (Aussenac *et al.* 1984; Aussenac and Granier 1988). Both water and nutrient availability are known to control Douglas-fir productivity in its natural range (Nigh 2006; Chen *et al.* 2010). In case of recurrent and/or severe drought events, the Douglas-fir decline has been reported in France, including cases of tree mortality (Sergent *et al.* 2012). In a context of climate change, leading to an increase probability of extreme drought events including in France (Najac *et al.* 2010), the risk for a forest stand to experience a drought event inducing decline is also increased. The option consisting in the reduction of rotation has been advocated as a way to reduce the probability to cope with the drought induced risk of decline. We explore here the economics of moving Douglas-fir rotation from 55 to 40 years in a context of increasing drought occurrence due to climate change.

Sylvicultural route, presented in Table 1, represents the costs and benefits associated to technical operations on the Douglas-fir stand depending on the rotation, 55 years or 40 years. We consider that the Douglas-fir stand is composed of plantation of 1100 stems/ha without natural regeneration. This plantation costs 1915€/ha whatever the rotation length. The difference is about the number of operations on the stand, their objective (maintenance, thinning, harvest) and the type of wood products to be sale.

Table 1. Sylvicultural operations and associated benefits as a function of the rotation length (€/ha)

Operations (year)	Benefits for high rotation (HR)	Benefits for short rotation (SR)
Initial costs	-1915	-1915
Maintenance (1)	-150	-350
Maintenance (2)	-200	-200
Maintenance (3)	-150	
Maintenance (4)		-200
Maintenance (5)	-200	
Maintenance (16)	-700	
Thinning (20)		2318
Thinning (22)	1344	
Thinning (25)		1676
Thinning (29)	1950	
Thinning (30)		2277

Harvest (40)		29878
Thinning (42)	7179	
Thinning (48)	5058	
Harvest (55)	38372	

Source: Institute for the Forest Development (IDF) and Société Forestière de la Caisse des Dépôts et Consignations (SFCDC).

These sylvicultural data are constructed following the same price curve. For instance, for the high rotation, the first thinning occurs at 22 years, 70m^3 are harvested representing 385 trees with a unit volume of 0.18m^3. The corresponding timber price is 19.2€/m^3 so that 19.2 x 70 = 1344€/ha. In the same way, for the short rotation, the first thinning occurs at 20 years, 92m^3 are collected, i.e. 341 trees with a unit volume of 0.27m^3. The corresponding timber price is 25.2€/m^3 so that 25.2 x 92 = 2318€/ha.

2.2 Definition of the adaptation strategies and the risk

We consider an even-aged monoculture Douglas-fir stand that has just been clear-cut, and in which natural regeneration is not present. The only source of risk that we consider is the risk of dieback induced by future drought events. This impact of drought occurrence evaluation required a two-step approach:

(1) The drought is quantified using a daily water balance model (Biljou©, Granier *et al.* 1999) from actual and future climate for a reference weather station (Dijon (Burgundy), INRA source, altitude: 211 m, rainfall: 663 mm, mean temperature: 10.2°C). The future climate for the study case resulted from the ARPEGE climatic model (version 4) developed by Météo France, associated with the greenhouse gas emissions scenario A1B of the GIEC. This scenario corresponds to an increase of the average temperature in France of around +2°C at

horizon 2050 and around +3.2°C at horizon 2100. In terms of rainfall, this scenario forecasts a decrease of around 25mm/year for the end of century (Brisson and Levrault 2011).

According to the CLIMATOR modelling protocol (ANR-006-VULN-007, Bréda *et al.* 2011), the soil water balance is calculated for a Douglas-fir stand with leaf area index of 6 and two types of soil properties are used, in order to test the interaction between climate change and buffering effect of soil retention properties. Then Biljou© water balance model is run for two types of soil differing by their soil extractable water (EW), a high one corresponding to a good site fertility (EW of 127 mm) and a low one illustrating a poorer site fertility (EW of 97 mm).

(2) In the framework of the project DRYADE (ANR-006-VULN-004), Douglas-fir dieback was demonstrated to be drought induced, radial growth and crown condition being impaired above a drought index threshold calculated by soil water balance as described above (Sergent *et al.* 2012). In the present work, the probabilities of drought induced risk of decline under future climate are calculated as the probability that the soil water deficit exceeds the intensity determined during the Douglas-fir decline in Burgundy after the dry years from 2003 to 2006. The probabilities are calculated for one climatic model, three time-slices, "recent past" or baseline (1970-2000), near future (2020-2059) and distant future (2070-2100), and three methods of climatic data downscaling (anomalies, whether type, dynamic quantile-quantile)[4].

We observe that probabilities are very dependent of methods of global to regional climate downscaling, which represent major part of the climatic uncertainty. To take into account the uncertainties due to climatic data downscaling at regional scale, we consider higher and lower probabilities for each time slice and for each soil extractable water, so that probabilities of drought induced risk of decline range as follows:

[4] The interested reader can find more details concerning the climatic models and the level of disintegration in the Green book of the CLIMATOR project coordinated by Brisson and Levrault (2011).

Table 2. Probability of drought occurrence for high fertility site

Horizon	Higher probability	Lower probability
1970-2000	p = 0.41	p = 0.32
2020-2059	p_h = 0.79	p_l = 0.44
2070-2100	a_h = 0.93	a_l = 0.68

Source : Authors' calculations.

Table 3. Probability of drought occurrence for low fertility site

Horizon	Higher probability	Lower probability
1970-2000	p = 0.51	p = 0.35
2020-2059	p_h = 0.83	p_l = 0.48
2070-2100	a_h = 0.93	a_l = 0.71

Source : Authors' calculations.

Probability p_h is the higher probability (depending on downscaling methods combinations) that a drought likely to induce Douglas-fir decline will occur before 2059 and a_h is the corresponding one for 2100 horizon. In the same way, p_l corresponds to the lower probability that such a drought will occur before 2059 and a_l before 2100. Finally, the probabilities p are calculated with observed climatic data (1970-2000), i.e. reflect the already experienced probability of drought suitable to induce decline in the studied region. These values ensure that the probability of drought occurrence will be severely increased under climate change.

Regarding the impacts of drought events on Douglas-fir, we assume that either there is a drought occurrence during the next rotation (with probability p) or during all the subsequent rotation (with probability a) or there is not (with 1-p, 1-a respectively). If the drought does not occur, the sylvicultural data are those presented in Table 1. The impact of drought on forest stand is difficult to estimate even if some information may be extracted from scientific knowledge to characterize this impact. First, the French Forest Health Service (Département de Santé des Forêts, DSF) did not report any Douglas-fir decline due to drought events on young trees, i.e. age below 20. Then, we assume that when the drought episode impacts Douglas-fir stands, it is after the first thinning, whatever the rotation length. Such an assumption is also consistent from an economic perspective because the first thinning corresponds to the first benefits. Second, it is observed that after the extreme drought event of 2003 in Burgundy, the loss of volume varied between 15 and 40% depending on the stand (Sergent *et al.* 2012), so that we assume a loss of 15%. To sum up, we assume that, with a drought occurrence, at each thinning or at final harvest, the volume and thus, the associated benefits are 15% lower than without risk. Table 4 presents the sylvicultural data in case of drought occurrence.

Table 4. Sylvicultural operations and associated benefits under drought occurrence as a function of the rotation length (€/ha)

Operations (year)	**Benefits for high rotation (HR)**	**Benefits for short rotation (SR)**
Initial costs	-1915	-1915
Maintenance (1)	-150	-350
Maintenance (2)	-200	-200
Maintenance (3)	-150	
Maintenance (4)		-200
Maintenance (5)	-200	
Maintenance (16)	-700	
Thinning (20)		2318
Thinning (22)	1344	
Thinning (25)		1424
Thinning (29)	1657	
Thinning (30)		1936
Harvest (40)		20915
Thinning (42)	6102	
Thinning (48)	4299	
Harvest (55)	32617	

Source: Authors' estimates.

Then, for the high rotation, if the drought occurs, as supposed after the first thinning, the harvested volume at the second thinning (year 29) is reduced by 15%, going from $67m^3$ without risk to $57m^3$ with risk, and thus the associated benefits are also reduced by 15%, dropping from 1950€/ha to 1344€/ha, as indicated in Table 4.

To face such a risk of drought induced decline, we consider that the owner may react in three different manners:

- Strategy 1 (S1): replanting now Douglas-fir with rotation of 55 years and keeping this management option for the subsequent rotations (no adaptation, sylviculture as usual).
- Strategy 2 (S2): planting now Douglas-fir with rotation of 40 years and keeping this management option for the subsequent rotations (immediate adaptation).
- Strategy 3 (S3): replanting now Douglas-fir with rotation of 55 years with view to shifting to shorter rotation of 40 years after the end of rotation (delay adaptation).

For none of these strategies the natural regeneration is tested like an option to adapt. We make the assumption that Douglas-fir stands are only renewed by plantation.

2.3 Economic method

The first step of the economic method consists in the calculation of the Net Present Value (NPV) of costs and benefits for one rotation. The NPV is the present value of positive payments minus the present value of negative payments made at different points in time (Klemperer 1996). The calculation is as follows:

$$NPV = \sum_{i=0}^{n} \frac{B_i - C_i}{(1+r)^i}$$

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

In a second step, the NPV allows to compute the Land Expectation Value (LEV), which is the sum of all NPVs. In general, this indicator is calculated as follows:

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

with B the benefits, C the costs and r the discount rate. The forest owner's objective is supposed to maximize the LEV. This criterion is well-suited to our analysis because the infinite discounting allows comparing management options associated to different temporal horizons (Morel and Terreaux 1995), as Douglas-fir with rotation of 55 years and 40 years.

3. Results

In our analysis, we assume a discount rate of 2%.

3.1 Analysis of the three strategies without risk

The Net Present Values without risk are calculated from Table 1 for high rotation: NPV(HR) = 16873€/ha, and for short rotation: NPV(SR) = 14735€/ha.

Using these NPV, the LEV of each strategy is then computed as follows:

$$LEV(S1) = NPV(HR) + \left(\frac{NPV(HR)}{(1+r)^{55}} \times \frac{(1+r)^{55}}{(1+r)^{55}-1}\right) = 25430€/ha \quad (1)$$

$$LEV(S2) = NPV(SR) + \left(\frac{NPV(SR)}{(1+r)^{40}} \times \frac{(1+r)^{40}}{(1+r)^{40}-1}\right) = 26933€/ha \quad (2)$$

$$LEV(S3) = NPV(HR) + \frac{LEV(S2)}{(1+r)^{55}} = 25936€/ha \quad (3)$$

Without drought event, the strategy 2 would allow the maximisation of LEV while the lowest LEV would be achieved thanks to the strategy 1, i.e. absence of adaptation. We also observe that an intermediary option could be to delay the reduction of rotation. Such an option gives more flexibility to the owner and allows observing the impact of climate change for again one more rotation before to adapt the sylvicultural practices. The differences between the three LEV are low, with the higher difference between strategy 2 and 1, i.e. 1503€/ha.

As drought event represents a threat for the Douglas-fir stand, especially in terms of extreme or recurrent soil water deficit, a risk of drought induced decline has to be included in the calculation for the future according to climate change scenario. In the following section, we introduce such a risk to quantify the economic loss for the forest owner.

3.2 Analysis of the three strategies under theoretical drought occurrence

The NPVs with risk of decline due to drought occurrence are calculated from Table 4 for high rotation: $NPV_{DR}(HR)$ = 14009€/ha and for short rotation: $NPV_{DR}(SR)$ = 10334€/ha. The impact of drought reduces considerably the NPV with a larger impact on the NPV of short rotation. Indeed, in case of short rotation, NPV is 14735€/ha without risk and 10334€/ha with risk, i.e. loss of 42%; while in case of high rotation, the NPV is 16873€/ha without risk and 14009€/ha with risk, corresponding to a decrease of 20%.

We then compute the LEV for each strategy:

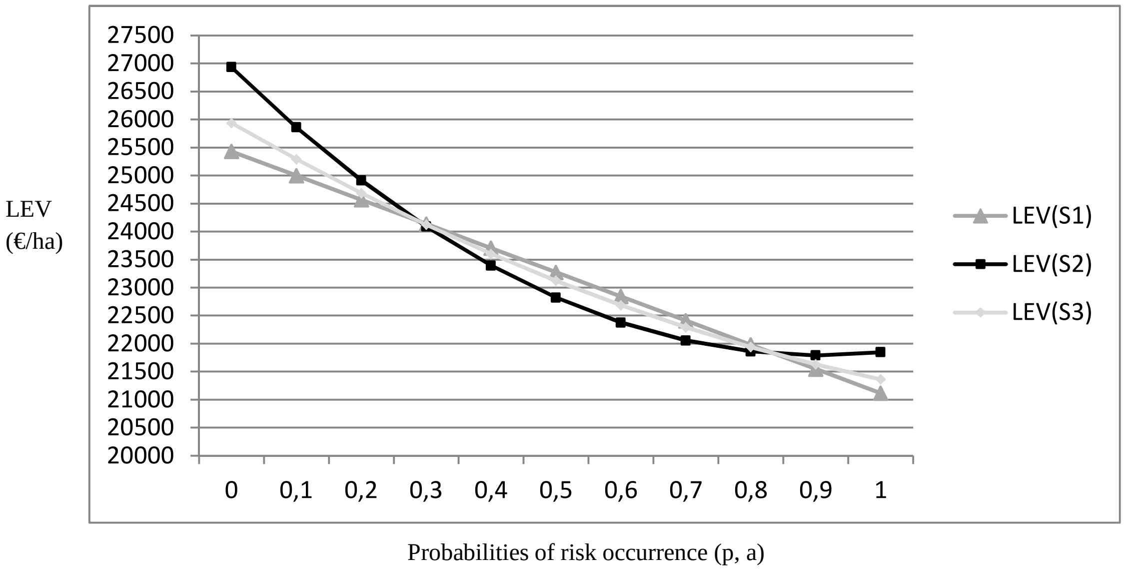
$$LEV(S1) = p\left(NPV_{DR}(HR) + \left[a\left(\frac{NPV_{DR}(HR)}{(1+r)^{55}} \times \frac{(1+r)^{55}}{(1+r)^{55}-1}\right) + (1-a)\left(\frac{NPV(HR)}{(1+r)^{55}} \times \frac{(1+r)^{55}}{(1+r)^{55}-1}\right)\right]\right) + (1-p)\left(NPV(HR) + \left[a\left(\frac{NPV_{DR}(HR)}{(1+r)^{55}} \times \frac{(1+r)^{55}}{(1+r)^{55}-1}\right) + (1-a)\left(\frac{NPV(HR)}{(1+r)^{55}} \times \frac{(1+r)^{55}}{(1+r)^{55}-1}\right)\right]\right) \quad (4)$$

$$LEV(S2) = p\left(NPV_{DR}(SR) + \left[a\left(\frac{NPV_{DR}(SR)}{(1+r)^{40}} \times \frac{(1+r)^{40}}{(1+r)^{40}-1}\right) + (1-a)\left(\frac{NPV(SR)}{(1+r)^{40}} \times \frac{(1+r)^{40}}{(1+r)^{40}-1}\right)\right]\right) + (1-p)\left(NPV(SR) + \left[a\left(\frac{NPV_{DR}(SR)}{(1+r)^{40}} \times \frac{(1+r)^{40}}{(1+r)^{40}-1}\right) + (1-a)\left(\frac{NPV(SR)}{(1+r)^{40}} \times \frac{(1+r)^{40}}{(1+r)^{40}-1}\right)\right]\right) \quad (5)$$

$$LEV(S3) = p\left(NPV_{DR}(HR) + \frac{LEV(S2)}{(1+r)^{55}}\right) + (1-p)\left(NPV(HR) + \frac{LEV(S2)}{(1+r)^{55}}\right) \quad (6)$$

All the LEV depend on p and a and, in order to compare these three different strategies, we made the simplifying assumption that p = a, i.e. the risk at horizon 2059 is as severe as the risk at horizon 2100. Then, it seems interesting to represent the LEV of all the strategies as in Figure 1 with in horizontal axis the values of probabilities (p and a) and in vertical one, the LEV.

Figure 1. A comparison of the three strategies' economic performance under theoretical probability of drought occurrence, p = a



We can observe that, under the simplifying assumption that the risk is constant over time, strategy 2 (immediate adaptation) dominates the two other ones for low and high probability levels. More precisely, for p,a < 0.29, strategy 2 dominates, for 0.29 < p,a < 0.84, strategy 1 (sylviculture as usual) dominates and for p,a > 0.84, strategy 2 dominates again. This result seems to suggest that strategy 3 (delay adaptation) is never preferable for the owner, i.e. s/he should adapt, now or in one rotation.

Recall that these conclusions are obtained under a simplifying assumption. Now, we look at what is happening under modelled impacts of drought events in the future.

3.3 Analysis of the three strategies under modelled drought impacts thanks to climatic scenarios

Now, we calculate the LEV of the three different strategies taking into account the probabilities of occurrence of future drought event as described in Tables 2 and 3 but also another parameter which is the fertilization costs (FC). Indeed, the reduction of rotation increases young wood exportation of higher nutrient content, then reduces the soil fertility that could impaired the sustainability of productivity and profitability, especially in case of low site fertility (Ranger and Turpault 1999; Sergent *et al.* 2012). Recent results in biogeochemical cycling in forest recommended compensating such nutrients exportation in poor site fertility by liming or fertilization to sustain long term productivity. To take into account this advice to sustain stand productivity, we introduce a fertilization cost of 250€/hectare at each new plantation (i.e. each 40 years) on the low soil extractable water. We consider that in case of high site fertility such overcost is not necessary.

Then, taking into account for fertilization costs does not modify the LEV of strategy 1 (due to independence with short rotation) but the LEV of strategy 2 and 3 in case of low fertility site become:

$$LEV_{FC}(S2) = p\left(NPV_{DR}(SR) + \left[a\left(\frac{NPV_{DR}(SR)-FC}{(1+r)^{40}} \times \frac{(1+r)^{40}}{(1+r)^{40}-1}\right) + (1-a)\left(\frac{NPV(SR)-FC}{(1+r)^{40}} \times \frac{(1+r)^{40}}{(1+r)^{40}-1}\right)\right]\right) + (1-p)\left(NPV(SR) + \left[a\left(\frac{NPV_{DR}(SR)-FC}{(1+r)^{40}} \times \frac{(1+r)^{40}}{(1+r)^{40}-1}\right) + (1-a)\left(\frac{NPV(SR)-FC}{(1+r)^{40}} \times \frac{(1+r)^{40}}{(1+r)^{40}-1}\right)\right]\right) \quad (7)$$

$$LEV_{FC}(S3) = p\left(NPV_{DR}(HR) + \frac{LEV_{FC}(S2)}{(1+r)^{55}}\right) + (1-p)\left(NPV(HR) + \frac{LEV_{FC}(S2)}{(1+r)^{55}}\right) \quad (8)$$

Table 5 presents the LEV of each strategy as a function of the site fertility (high versus low) and the probability of risk occurrence (higher versus lower). The LEV(S1) is obtained from equation (4), the LEV(S2) from equation (7) and the LEV(S3) comes from equation (8).

For example, the LEV(S1) in case of high fertility site and higher probabilities (p_h, a_h) is computed as follows:

$$LEV(S1) = p_h \left(NPV_{DR}(HR) + \left[a_h \left(\frac{NPV_{DR}(HR)}{(1+r)^{55}} \times \frac{(1+r)^{55}}{(1+r)^{55}-1} \right) + (1-a_h) \left(\frac{NPV(HR)}{(1+r)^{55}} \times \frac{(1+r)^{55}}{(1+r)^{55}-1} \right) \right] \right) + (1-p_h) \left(NPV(HR) + \left[a_h \left(\frac{NPV_{DR}(HR)}{(1+r)^{55}} \times \frac{(1+r)^{55}}{(1+r)^{55}-1} \right) + (1-a_h) \left(\frac{NPV(HR)}{(1+r)^{55}} \times \frac{(1+r)^{55}}{(1+r)^{55}-1} \right) \right] \right) = 21818\text{€/ha}$$

Table 5. LEV for each strategy function of the site fertility and the probability of risk occurrence (€/ha)

	High fertility		Low fertility	
	p_h, a_h	p_l, a_l	p_h, a_h	p_l, a_l
LEV(S1)	21818	23183	21703	23025
LEV(S2)	21594	22143	21402	21817
LEV(S3)	21877	23064	21698	22840

Several comments can be made on the basis of Table 5.

The best economic return. Table 5 lets appear that strategy 1 provides the best economic return as compared to the two other ones in most cases, except for high probabilities of drought event in high fertility site. This means that, on such stand with low vulnerability thanks to high soil extractable water, an absence of adaptation seems to be the best option for the forest owner from an economic point of view. In addition, it appears that strategy 2 of immediate adaptation would lead in any tested hypothesis of future climate to an economic loss as compared to strategy 1 in the studied region. Finally strategy 3 adopts an intermediary position, between no adaptation and an immediate one.

These results are calculated for a loss of volume of 15% in case of drought occurrence. However, as indicated before, a loss of volume ranging from 15 and 40% depending on stands was observed after the drought of 2003 in Burgundy (Sergent *et al.* 2012), so that the question is, given the forestry route and the real probabilities associated to drought occurrence, what is the amount of loss of volume necessary to decide the forest owner to adopt adaptation strategy (strategy 2 or 3)? We calculate that, if the loss of volume due to the occurrence of a drought event is superior to 28% of the standing volume, then strategy 2 is always the most economically profitable, after it is strategy 3 and finally strategy 1 being the least efficient. Consequently, for a loss of volume superior to 28%, the option consisting in no adaptation is not relevant. Whatever the loss of volume, strategy 3 never dominates the two other ones. Strategy 3 is always an intermediary option, dominating either strategy 1 (for a loss superior to 28%) or strategy 2 (for a loss of 15%). This result suggests that reduction of rotation may be an adaptation tool (1) in the most severe climatic scenario inducing a highly adverse water balance and/or (2) for vulnerable stands, i.e. those with high stock, low soil extractable water, with delay in thinning or with phytosanitary damages.

Sensitivity of Land Expectation Value to uncertainty sources. Our approach allows quantifying the respective contribution of the adaptation strategy, the uncertainty on the downscaled future climate and the site fertility on the economic criteria, the LEV.

We show that the LEV is first sensitive to climatic uncertainty. This means that for the same adaptation strategy and the same site fertility, a gap is observed between the LEV calculated with high probabilities (p_h, a_h) and low probabilities (p_l, a_l). For example, consider the strategy 1 and a high fertility, then the LEV associated to low probabilities is 21818€/ha and to high probabilities is 23183€/ha, i.e. a difference of 6.25%.

The economic criterion is in a second order sensitive to the adaptation strategy. Indeed, differences appeared between the LEV function of the strategy adopted. Consequently, for the same fertility and the same level of probabilities (high or low), we note a gap between the LEV of the different adaptation strategies. For example, consider a high fertility and high probabilities (p_h, a_h), if we compare strategy 1 and 2, we observe that LEV(S1) = 21818€/ha and that LEV(S2) = 21594€/ha, i.e. a difference of 1.03%.

The third order sensitivity concerns site fertility. The increase in drought occurrence in the studied region is such that the soil extractable water cannot mitigate significantly the risk of decline: the LEV is thus insensitive to site fertility. Then, for the same adaptation strategy and the same level of probabilities (high or low), the gap between the LEV obtained with high fertility and low fertility is very low, generally inferior to 1%. For instance, for strategy 1 and high probabilities (p_h, a_h), the LEV of high fertility is 21818€/ha and the one for low fertility is 21703€/ha, i.e. a difference of 0.53%.

Finally, these results are robust to the variation of discount rate. Indeed, we conduct sensitivity analysis on the discount rate of 2%. We find that with a discount rate of 1% or 3%, the results stay valid. This is of particular interest because it is rather complex to adopt a discount rate for forest projects (Calvet *et al.* 1997).

To sum up, climatic uncertainty at regional scale spreads into biophysical impact models, and then economic models, and thus cascading in the adaptation decision making process.

Parallel with existing results. Previous standard economic results suggested that reducing the rotation is an option to cope with fire risk (Reed 1984; Martell 1994; Amacher *et al.* 2005; Kuuluvainen and Tahvonen 1999; Englin *et al.* 2000). Is it also an efficient strategy to cope with drought induced risk of decline? Our results indicate that the answer depends on the value of the potential damage, i.e. on stand vulnerability and on probability of drought occurrence. Indeed, without risk we obtain that: LEV(S2) > LEV(S3) > LEV(S1) and with a risk corresponding to a potential damage of 15% of standing volume, we have : LEV(S1) > LEV(S3) > LEV(S2). In addition, with a risk of decline inducing a potential damage superior to 28%, then we have: LEV(S2) > LEV(S3) > LEV(S1). In summary, with a potential damage < 28%, it is not economically profitable to shorten the rotation from 55 to 40 years. But, with a potential damage superior to 28%, the calculation leads to advice to shorten rotation.

4. Discussion

We now discuss our results as regard to the chosen economic criteria, i.e. the Land Expectation Value and we introduce a public policy discussion.

4.1 Economic criteria

We consider the Land Expectation Value as economic criteria to compare the different adaptation strategies. This criterion is well-suited to compare sylvicultural options associated to different rotation (Morel and Terreaux 1995), as rotation of 55 years and 40 years in case of Douglas-fir management. However, with such a criterion, the forestry route is identical for each rotation. This means that each operation (thinning, maintenance, harvest) is implemented at the same date and for the same cost/benefit, during an infinite time period. Thus, this criterion does not allow the forest owner to react to the risk and to adapt her/his decision. In other words, if the stand suffers from a drought, the forest manager is considered to follow the forestry route up to the final harvest at 40 years or 55 years, depending on the management choice. But in practice, the forest owner could decide to harvest prematurely all the impacted trees (visually damaged or not). This limit represents a restriction when dealing with changing framework such as climate change, because in such a context the forest owner needs more flexibility and prioritizes reversible forestry route. That’s why other indicators are back on the scene such as the Net Present Value or the Internal Rate of Return. However, such indicators present higher limitations and are rarely retained (Fraysse *et al.* 1990; Morel and Terreaux 1995), suggesting that, nevertheless, the LEV is currently the well-suited economic indicator.

4.2 Public policy

Our results suggest that adaptation options are associated to economic losses for forest owners. Indeed, the reduction of rotation, certainly reduces the risk, but is costly for the forest owners and thus corresponds to a reduction in the forest value (i.e. the LEV). Along with this, in addition to private timber benefits, forests provide non-timber services such as biodiversity, recreation, carbon sequestration... which have a public dimension. These non-timber services may disappeared in case of risk occurrence, so that one can think that public authority may financially help forest owners for the implementation of some expensive adaptation options. This paper allows thinking about a potential mechanism of compensation for a reduction of the rotation. The reduction of the rotation may have a negative effect on the quantity of non-timber services provided but surely, it ensures a better and constant provision of such services over the time. Then, we can easily imagine that forest owners may be encourage to adopt the reduction of rotation in order to face climate change, by a compensation of their potential economic losses. The difference between the LEV of strategy 1 and 2, i.e. the financial losses incurred by the owners in case of immediate adaptation, may be an indicator of the value of this potential compensation for a forest owner who decides to adapt immediately. In the same way, the difference between the LEV of strategy 1 and 3, i.e. the financial losses incurred by the owners in case of a delay adaptation, may be an indicator of the value of this potential compensation for a forest owner who decides to delay the reduction of the rotation. For example, in Table 5, if we consider high fertility site and high probabilities of risk occurrence, we have: LEV(S1) > LEV(S3) > LEV(S2) => 23183€/ha > 23064€/ha > 22143€/ha. If the public authority wants to encourage owners to reduce the rotation, then it can compensate the expected loss: 23183 – 23064 = 119€/ha for an adaptation in one rotation, and 23183 – 22143 = 1040€/ha for an immediate adaptation.

Such compensations should encourage owners to adopt adaptation strategies which reduce the risk both on timber benefits and non-timber ones, ensuring a better and constant provision of timber and non-timber services over time.

5. Conclusion and perspectives

This paper analyses the reduction of rotation from 55 years to 40 years in the context of a Douglas-fir plantation as an option to cope with an increasing risk of tree dieback induced by drought events, thanks to a decrease of both exposure and tree vulnerability. From a forest management point of view, this is a win-win strategy. Now from an economic point of view, our results point out that the profitability for the forest owner of the three strategies of adaptation we tested (absence of adaptation, immediate adaptation and delay adaptation) is sensitive to the level of the potential damage in case of drought event occurrence. Then, if the loss in volume is superior to 28% of standing volume when drought event occurs, an immediate adaptation allows a highest Land Expectation Value than a delay one, which nevertheless remains economically more efficient than no adaptation at all. This threshold in terms of damage suggests that the reduction of rotation may be envisaged as an adaptation tool for vulnerable stands and if the more severe scenario of climate change occurs.

This paper presents some limitations. First, we do not consider some important expenses for the owners such as the initial purchase of the forest stand (or of the ground), the land tax, potential insurance premiums (civil liability, natural risks), expenses of guarding or management (expert, cooperative)… so that the Land Expectation Value that we calculated could be overestimated. However, as our objective is to compare the LEV of different scenarios our study stays relevant. Second, the uncertainties about the future climate arise from scenarios for the greenhouse gas and aerosol concentration (SRES scenarios), from choices in the climatic models and from the method for downscaling the climatic variables at the scale of the case study. For economic analysis, we proposed to explicitly include in the calculations the range of probabilities of climatic hazard occurrence. Indeed, we focus on one greenhouse gas emissions scenario A1B of IPCC and one climatic model (Arpège, Météo France), because we previously established that, at regional scale where adaptation takes place, the down-scaling uncertainty is far larger that the SRES hypothesis or the climatic model choice (Bréda *et al.* 2011). Third, we focus on a case study, a Douglas-fir plantation facing an increasing risk of dieback induced by drought events attributable to climate change, so that further researches are needed to generalize our conclusions at national scale and testing other adaptation options like natural regeneration instead of plantation, lowering stand leaf area index for a more "water saving" sylviculture or shorter rotation than 40 years.

The multidisciplinary approach developed here allows quantifying biological impacts of future drought events and evaluating economically several adaptation strategies to cope with risk of decline. Such approach requests close collaboration between economists of risks and the community of climatologists and ecologists studying biological impacts of climate change. As indicated by Yousefpour et al. (2012), "*Future studies should attempt to bridge the gap between comprehensive ecological models and economic models to assist forest decision makers […]*".

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References

Alvarez LHR (2004) Stochastic forest stand value and timber harvesting. SIAM Journal on Control and Optimization 42: 1972–1993

Alvarez LHR, Koskela E (2003) On forest rotation under interest rate variability. International Tax and Public Finance 10(4): 489-503

Alvarez LHR, Koskela E (2005) Wicksellian theory of forest rotation under interest rate variability. Journal of Economic Dynamics and Control 29(3): 29-545

Alvarez LHR, Koskela E (2006) Does risk aversion accelerates optimal forest rotation under uncertainty? Journal of Forest Economics 12: 171–184

Amacher GS, Malik AS, Haight RG (2005) Not Getting Burned: The Importance of Fire Prevention in Forest Management. Land Economics 81(2): 284-302

Aussenac G, Granier A (1988) Effects of thinning on water stress and growth in Douglas-Fir. Canadian Journal of Forest Research 18: 100-105

Aussenac G, Granier A, Ibrahim M (1984) Influence du dessèchement du sol sur le fonctionnement hydrique et la croissance du Douglas (*Pseudotsuga Menziesii* (Mirb.) Franco). Acta Oecologica 5: 241-253

Brazee RJ, Mendelsohn R (1988) Timber harvesting with fluctuating prices. Forest Science 34(2): 359-372

Bréda N, Granier A, Huc R, Dreyer E (2006) Temperate forest trees and stands under severe drought: a review of ecophysiological responses, adaptation processes and long-term consequences. Annals of Forest Science 63: 625-644

Bréda N, Bosc A, Badeau V (2011) Some aspects of climate change and forests in metropolitan France. The Green book of the CLIMATOR project. Climate change, agriculture and forests in France: simulations of the impacts on the main species Brisson N. & Levrault F. eds., ADEME, pp. 225-236

Brisson N, Levrault F (2011) Green book of the CLIMATOR project. Climate change, agriculture and forests in France: simulations of the impacts on the main species. ADEME Editions, March 2011, 334p. (On line version acceded 16th March 2012) http://www2.ademe.fr/servlet/getDoc?sort=-&cid=96&m=3&id=76705&ref=&nocache=yes&p1=111

Calvet P, Lemoine B, Peyron JL (1997) Taux d'actualisation et conduite sylvicole des peuplements forestiers: un exemple dans le cas du pin maritime en France. Canadian Journal of Forest Research 27: 1268–1275

Carter RE, Otchere-Boateng J, Klinka K (1984) Dieback of a 30-year-old Douglas-fir plantation in the Brittain River valley, British Columbia: symptoms and diagnosis. Forest Ecology and Management 7: 249-263

Chang FR (2005) On the elasticities of harvesting rules. Journal of Economic Dynamics and Control 29: 469–485

Chen PY, Welsh C, Hamann A (2010) Geographic variation in growth response of Douglas-fir to interannual climate variability and projected climate change. Global Change Biology 16: 3374-3385

Clarke HR, Reed WJ (1989) The tree-cutting problem in a stochastic environment. Journal of Economic Dynamics and Control 13: 569–595

Clarke HR, Reed WJ (1990) Harvest decisions and asset valuations for biological resources exhibiting size-dependent stochastic growth. International Economic Review 31: 147–169

de Kort I. (1993) Wood production and latewood percentage of Douglas-fir from different stands and vitality classes. Canadian Journal of Forest Research 23(7): 1480-1486

Englin J, Boxall P, Hauer G (2000) An Empirical Examination of Optimal Rotations in a Multiple-Use Forest in the Presence of Fire Risk. Journal of Agricultural and Resource Economics 25: 14-27

Fraysse J, Moreaux M, Terreaux JP (1990) Actualisation et gestion forestière. Cahiers d'Économie et de Sociologie rurales 15-16: 111-125

Gottschalk KW (1995) Using silviculture to improve health in northeastern conifer and eastern hardwood forests. *In* Forest health through silviculture. L.G. Eskew (compiler). U.S. Department of Agriculture Forest Service, Fort Collins, Colo. General Technical Report RM-267, 219–226

Granier A, Bréda N, Biron P, Villette S (1999) A lumped water balance model to evaluate duration and intensity of drought constraints in forest stands. Ecological Modelling 116: 269-283

Hallegatte S, Lecocq F, de Perthuis C (2010) Économie de l'adaptation au changement climatique. Rapport du Conseil Economique pour le Développement Durable (CEDD), février 2010

Insley M (2002) A real options approach to the valuation of a forestry investment. Journal of Environmental Economics and Management 44: 471-492

Insley MC, Rollins K (2005) On solving the multirotational timber harvesting problem with stochastic prices: a linear complementarity formulation. American Journal of Agricultural Economics 87: 735–755

IPCC (Intergovernmental Panel on Climate Change), 2007. Contribution to work groups I, II and III to the Fourth Assessment Report (AR4) of IPCC. Published under the direction of R.K. Pachauri and A. Reisinger. IPCC, Geneva, Swiss

Kaipainen T, Liski J, Pussinen A, Karjalainen T (2004) Managing carbon sinks by changing rotation length in European forests. Environmental Science and Policy 7: 205–219

Keenan RJ (2012) Adaptation of Forests and Forest Management to Climate Change: An Editorial. Forests 3: 75-82

Klemperer WD (1996) Forest resource economics and finance, McGraw-Hill Series in Forest Resources. McGraw-Hill, NewYork, 551p

Kolström M, Lindner M, Vilén T, Maroschek M, Seidl R, Lexer MJ, Netherer S, Kremer A, Delzon S, Barbati A *et al*. (2011) Reviewing the science and implementation of climate change adaptation measures in European forestry. Forests 2: 961–982.

Kuuluvainen T, Tahvonen O (1999) Testing the forest rotation model: evidence from panel data. Forest Science 45(4): 539-551

Lindner M, Lasch P, Erhard M (2000) Alternative forest management strategies under climate change: prospects for gap model applications in risk analyses. Silva Fennica 34: 101-111

Liski J, Pussinen A, Pingoud K, Mäkipää R, Karjalainen T (2001) Which rotation length is favourable for carbon sequestration? Canadian Journal of Forest Research 31: 2004-2013

Littell JS, Peterson DL, Tjoelker M (2008) Douglas-fir growth in mountain ecosystems : water limits tree growth from stand to region. Ecological Monographs 78: 349-368

Martell DL (1994) The Impact of Fire on Timber Supply in Ontario, Forestry Chronicle 70: 164-173

Morel M, Terreaux JP (1995) L'estimation de la valeur des forêts à travers un exemple : entre simplification abusive et complexité du réel. Revue Forestière Française XLVII – 2: 151-161

Najac J, Vidal JP, Martin E, Franchisteguy L, Soubeyroux JM (2010) Changes in drought characteristics in France during the 21st century. Geophysical Research Abstracts 12, EGU2010-8975

Newman DH (2002) Forestry’s golden rule and the development of the optimal forest rotation literature. Journal of Forest Economics 8: 5-27

Nigh GD (2006) Impact of climate, moisture regime, and nutrient regime on the productivity of Douglas-fir in coastal British Columbia, Canada. Climatic Change 76: 321–337

Ranger J, Turpault MP (1999) Input-output nutrient budgets as a diagnostic tool for sustainable forest management. Forest Ecology and Management 122: 139-154

Reed WJ (1984) The Effects of the Risk of Fire on the Optimal Rotation of Forest. Journal of Environmental Economics and Management 11(3): 1980-1990

Reich RW, van der Kamp BJ (1993) Frost, canker, and dieback of Douglas-fir in the central interior of British Columbia. Canadian Journal of Forest Research 23(3): 373-379

Sergent AS, Bréda N, Rozenberg P (2012) Douglas-fir is vulnerable to exceptional and recurrent drought episodes and recovers less well on less fertile sites. Annals of Forest Science, DOI 10.1007/s13595-012-0220-5

Spittlehouse DL, Stewart RB (2003) Adaptation to climate change in forest management. Journal of Ecosystems and Management 4: 1-11

Stollery KR (2005) Climate change and optimal rotation in a flammable forest. Natural Resource Modeling 18(1): 91-112

Thomson TA (1992) Optimal forest rotation when stumpage prices follow a diffusion process. Land Economics 68(3): 329-342

Willassen Y (1998) The stochastic rotation problem: a generalization of Faustmann’s formula to stochastic forest growth. Journal of Economic Dynamics and Control 22: 573–596

Yousefpour R, Jacobsen JB, Thorsen BJ, Meilby H, Hanewinkel M, Oehler K (2012) A review of decision-making approaches to handle uncertainty and risk in adaptive forest management under climate change. Annals of Forest Science 69(1): 1-15