Is diversification a good option to reduce drought-induced risk of forest decline? An economic approach focused on carbon accounting

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ABSTRACT

Extreme or recurrent drought events are the principal source of stress impairing forest health. They cause financial losses for forest owners and amenity losses for society. Most of the forested area in the Grand-Est region (France) is dominated by beech, which is projected to decline in the future due to repeated drought events driven by climate change. Beech forests need to adapt and diversification is a management option to reduce drought-induced risk of dieback. We studied two types of diversification that were analysed separately and jointly: Mixture of beech species with oak species and mixture of different tree diameter classes (*i.e.* uneven-aged forest), which is rarely considered as an adaptation strategy. We also considered two types of loss (financial, and in terms of carbon sequestration) under different recurrences of drought events, that are a consequence of climate change. We combined a forest growth simulator (MATHILDE) with a frequently used economic approach (*i.e.* land expectation value, henceforth LEV). The maximisation of the LEV criterion enabled identification of the best adaptation strategies in terms of timber revenue. We also analysed the impact of adaptation decisions on carbon sequestration by means of three different carbon-accounting methods (*i.e.* market value, shadow price and social cost of carbon). The results show that diversification reduces the loss in timber volume due to drought-induced risk and increases LEV, but reduces carbon storage. The trade-offs between the financial balance and the carbon balance, and the underlying question of the additivity (or not) of the two adaptation strategies are discussed.

Keywords: Drought; Adaptation; Climate change; Mixed forest; Economics; Carbon.

JEL codes: D01 (Microeconomic Behavior: Underlying Principles), Q23 (Forestry), Q54 (Climate, Natural Disasters and their Management, Global Warming), Q57 (Ecological Economics: Ecosystem Services; Biodiversity Conservation; Bioeconomics; Industrial Ecology).

I- INTRODUCTION

Drought is a natural phenomenon affecting forest productivity and health especially when its intensity is extreme. There exists much evidence of the link between drought intensity, crown condition and mortality in Europe (Seidl *et al.*, 2011) as well as globally (Allen *et al.*, 2010). These impacts result in economic losses for forest owners and amenities losses for society (*e.g.* reduced carbon sequestration). In France, the extreme drought events of 1976 and 2003 caused great damage (Bréda *et al.*, 2004; Bréda *et al.*, 2006). Severe droughts are thought to be rare phenomena, but their frequency might increase in the future as a consequence of climate change (IPCC, 2013).

While forests are expected to adapt naturally, spontaneous forest adaptation will not be fast enough in regard of the pace of changes. Consequently, climate-change-adapted forest management is required to cope with the increasing risk of drought-induced dieback (Spittlehouse and Stewart, 2003). Water-saving forest management can mitigate the intensity and duration of water shortage periods and their related damage; and therefore increase the trees' adaptive capacity to a changing climate (Bréda and Badeau, 2008).

Adapting forests also means maintaining the services they provide. One of them is carbon sequestration through photosynthesis, which is essential to mitigate climate change ("forests for adaptation", Locatelli *et al.*, 2010). The French government has made several commitments in this field, such as Paris agreements and carbon neutrality in 2050, and the forest sector is an essential lever to achieve these goals (Kolström *et al.*, 2011).

Management strategies can increase the resistance of forest ecosystems. Diversification is a management-based adaptation option. From an economic point of view, investing in a combination of different financial assets might reduce the risk (Markowitz, 1952). Diversifying forest stands can therefore lead to hedging from the climate fluctuations caused by climate change and its related extreme events.

In this paper, two types of diversification strategies are considered: The diversification of the composition, and that of the structure. The first one means shifting from monocultures to stands with two or more species. Mixing species can have positive effects such as favouring tree complementarity and increasing the stand productivity (Lebourgeois *et al.*, 2013; Forrester, 2014). However, it can also have adverse effects such as an increase in the competition for water resources (Grossiord *et al.,* 2014; Bonal *et al*., 2017). These positive or negative effects seem to be dependent on both the context (soil, climate…) and the species mix. The second diversification type consists of shifting from even-aged to uneven-aged silviculture, *i.e.* having different classes of tree diameter in a same stand. Jacobsen and Helles (2006) stated that the stability of forests granted by the continuous cover can lead to a better resilience to natural hazards.

In this context, a natural question is whether the diversification of forest stands is a good adaptation option to reduce drought-induced risk from an economic perspective. To answer this question, we analysed the economic costs and benefits of management-based adaptation strategies from a private forest owner's perspective, while considering the impact of these decisions on carbon storage. Few studies have tackled the issue of adaptation to climate change using a forest economics approach.

Drought-induced risk is often overlooked in economic analyses even though it is one of the most damageable disturbances for forests. To the best of our knowledge, only Bréda and Brunette (2019) and Brèteau-Amores *et al.* (2019) have investigated the adaptation to drought-induced risk. Moreover, composition diversification has rarely been analysed as a potential adaptation strategy (Yousefpour and Hanewinkel, 2014; Jönsson *et al.*, 2015) and never for structure diversification.

The objective of this paper was to test and compare different diversification strategies in terms of composition and structure as potential adaptation means for reducing drought-induced risk from an economic perspective. To do this, we focused on beech stands in the Grand-Est region, France. We used an individual-based model to simulate forest growth under two different scenarios of climate change, namely the representative concentration pathways (RCP) 4.5 and 8.5 (IPCC, 2013). More precisely, we tested two types of diversification that we analysed separately and then jointly: (i) Mixture of beech species with oak species and (ii) mixture of different tree diameter classes (*i.e.* uneven-aged forest). We also considered two types of loss due to drought-induced risk: A purely financial loss, and a loss in terms of carbon sequestration. The model predictions were used as inputs in the traditional forest economic approach based on land expectation value (LEV). The maximisation of the LEV criterion allowed us to identify the best adaptation strategies from a pure financial perspective and when considering a more holistic economic approach that also accounted for carbon storage. To account for the economic value of carbon sequestration, we considered three accounting methods, *i.e.* market value, shadow price and social cost of carbon. We tested whether (i) diversification is a good adaptation option to reduce drought-induced risk in terms of timber production and carbon storage; (ii) diversification and combining both diversification strategies lead to synergies; (iii) trade-offs between the financial balance and the carbon balance (adaptation *vs.* mitigation) are possible; (iv) carbon price has an impact on (i).

The rest of the paper is structured as follows. The material and the methods are presented in Section 2. Section 3 provides the main results. The results are discussed in Section 4, and Section 5 concludes.

II- MATERIAL AND METHODS

1. Study area: Grand-Est region and species of interest

The Grand-Est region is one of the most afforested in France with more than a third of its area covered by forests, of which 42% are privately owned[1]. Broadleaved species are the most abundant ones and they provide 64% of the commercial value of timber[1]. Among them, European beech (*Fagus sylvatica* L.), sessile oak (*Quercus petraea* Liebl.) and pedunculate oak (*Quercus robur* L.) are the three main species[1].

Repeated drought events are expected to cause a decline of beech productivity in the future (Charru *et al.*, 2010). Mixed stands are sometimes proposed as a suitable adaptation option. Beech and oak species are frequently co-occurring species as they have a number of common ecological requirements characteristics (Rameau *et al.*, 1989). Moreover, oak is more drought-tolerant than beech (Scharnweber *et al.*, 2011) and can increase drought resistance and resilience of beech due to inter-specific facilitation (Zapater *et al.*, 2011).

2. Methods

To compare composition and structure diversifications as potential adaptation strategies to reduce drought-induced risk, we defined ten management-based scenarios and simulated their forest growth. The model predictions were used as inputs to compute the land expectation value (LEV) for each scenario. All these elements are represented in Figure 1 and described in the following sub-sections.

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[1] Source: National Forest Inventory (IGN, 2019).

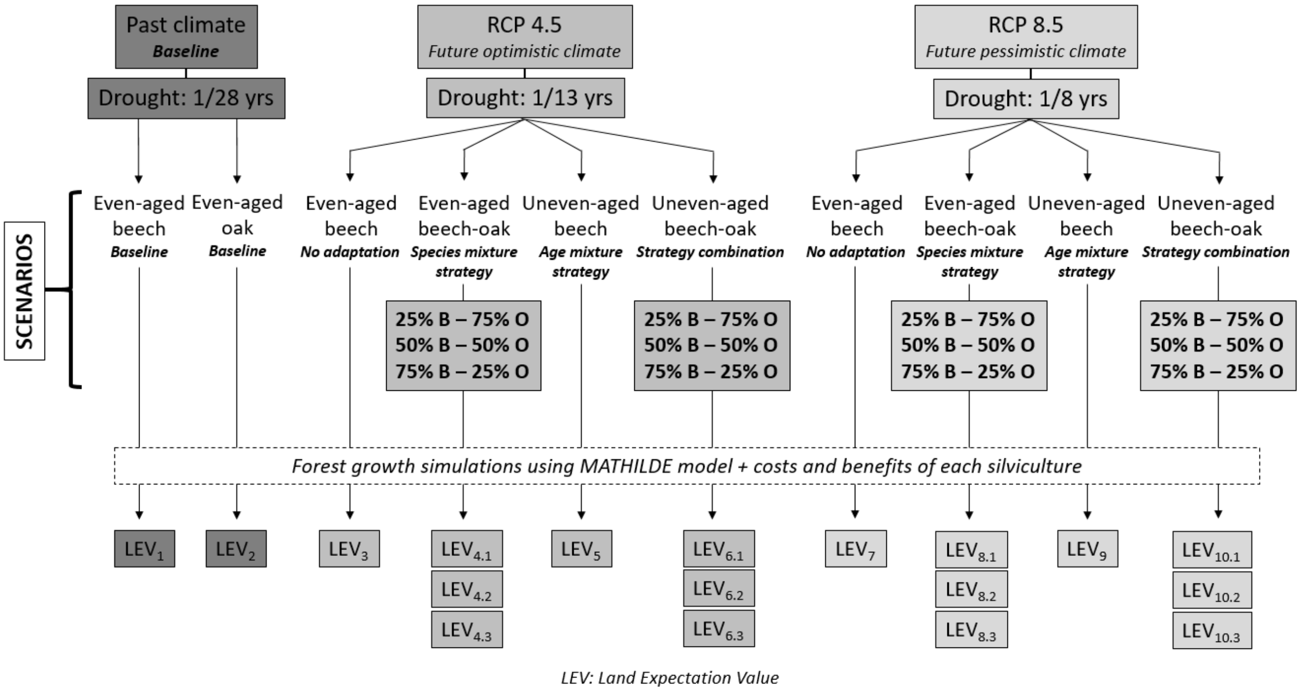

Figure 1: Schematic representation of the methodology: From scenario definition to economic evaluation.

2.1 Scenarios tested

The management scenarios were defined according to tree species and stand structures: Pure and even-aged beech/oak stand, pure and uneven-aged beech/oak stand, mixed and even-aged stand (with a respective ratio of beech to oak of 25:75, 50:50, or 75:25), mixed and uneven-aged stand (with the same ratios) (Figure 1).

These management scenarios were tested in conjunction with three climate scenarios: A reference climate, the RCP 4.5 and the RCP 8.5. All this resulted in a total of 18 scenarios: Two baseline scenarios in a reference climate plus eight scenarios in two different climate projections. The two baselines and the eight scenarios are summarized in Table 1. In addition, even-aged and uneven-aged oak stands were simulated in order to test the second hypothesis (synergies of the adaptation strategies).

To project drought occurrence, the growth model required the recurrence of drought events as input. These recurrences were defined from daily soil water deficit computed through a daily forest water balance model BILJOU© (Granier *et al.*, 1999). The computation of the most exceptional drought events (*i.e.* known in the reference period to induce beech dieback) yielded the respective recurrences of 28, 13, and 8 years interval. More details on the computation are provided in the Supplementary Material Section (A).

Code	**Scenario**
Baseline_B	Benchmark, current even-aged beech stand
Baseline_O	Benchmark, even-aged oak stand in current conditions
B_EA	Even-aged beech stand without adaptation
Mix25_EA	Even-aged mixed stand with a ratio 25:75 of beech and oak proportions
Mix50_EA	Even-aged mixed stand with a ratio 50:50 of beech and oak proportions
Mix75_EA	Even-aged mixed stand with a ratio 75:25 of beech and oak proportions
B_UA	Uneven-aged beech stand
Mix25_UA	Uneven-aged mixed stand with a ratio 25:75 of beech and oak proportions
Mix50_UA	Uneven-aged mixed stand with a ratio 50:50 of beech and oak proportions
Mix75_UA	Uneven-aged mixed stand with a ratio 75:25 of beech and oak proportions

Table 1: The different scenarios considered and their distinctive code.

2.2 Forest growth simulation

We used MATHILDE, a stochastic individual-based model, to simulate forest dynamics. The model is described in Fortin and Manso (2016) and Fortin *et al*. (2019).

Forest growth was simulated from inventory data. We created a fictive stand as an inventory data for each management scenario listed in Table 1. These fictive stands represented typical conditions in the Grand-Est region. MATHILDE tends to overestimate the mortality of young trees, and this leads to inconsistent simulations for even-aged stands younger than 30 years of age (Fortin and Manso, 2016). Therefore, the starting point for our simulations were 30-year-old even-aged stands with 2000 stems/ha. For uneven-aged stands, we assumed that they exhibited a balanced diameter distribution with 200 stems/ha. More details on the fictive stands are provided in the Supplementary Material Section (B). The simulation of tree growth for each stand is described below.

First, inventory data are loaded. Each inventory file contained the tree records of 10 plots of 400 m^2 each. Secondly, we used MATHILDE's built-in harvest algorithm to implement the management scenarios. The algorithm requires some bounds in terms of basal area. Whenever the upper bound is crossed, the harvesting is triggered and the trees are harvested until the lower bound is reached. The bounds were assumed to reproduce the management of even-aged and uneven-aged stands (see Table C.1 in the Supplementary Material Section). In the case of even-aged stands, the final cut was assumed to be carried out when either the dominant diameter reached 70 cm or the number of stems fell below 100 stems per hectare. The first condition is the one that normally applied without natural disturbances. The second condition is usually met when natural disturbances occur and the stand is deemed to be too depleted to recover. We enabled the recruitment of new trees in uneven-aged stands to keep the forest dynamics going, but not for even-aged stands in order to compute one rotation length at a time. These management scenarios were simulated under reference climate and RCPs 4.5 and 8.5 (Figure 1). Stochastic simulations in MATHILDE rely on the Monte Carlo technique. In this study, we computed 1000 realizations for each combination of climate and management scenario. The Monte Carlo technique provides a prediction of the stand evolution as well as the uncertainty associated with this prediction. Each realization represents the mean evolution of the 10 plots that compose the fictive stand.

Thirdly, MATHILDE is implemented in the CAPSIS platform (Dufour-Kowalski *et al.,* 2012), which contains a carbon accounting tool (CAT, Pichancourt *et al.*, 2018). Each realization of MATHILDE was processed through CAT in order to simulate the corresponding carbon balance. Basically, CAT turned the different realizations into carbon realizations, which were latter analysed in terms of economic benefits. More technical details on MATHILDE and CAT are provided in the Supplementary Material Section (D).

2.3 Economic analysis

2.3.1 Double-weighted land expectation value

We used the timber volume and carbon realizations from MATHILDE and CAT to perform an economic comparison of the adaptation strategies based on land expectation value (LEV).

The different scenarios listed in Figure 1 can be seen as an experimental design to assess the effect of different factors on the LEV. More precisely, it enables the following comparisons:

- LEV 1 *vs*. LEV 3 and LEV 1 *vs*. LEV 7: Effect of drought.

- LEV 3 *vs*. LEV 4 and LEV 7 *vs*. LEV 8: Effect of composition diversification strategy.

- LEV 3 *vs*. LEV 5 and LEV 7 *vs*. LEV 9: Effect of structure diversification strategy.

- LEV 3 *vs*. LEV 6 and LEV 7 *vs*. LEV 10: Effect of composition diversification combined with structure one.

In a deterministic setting, the LEV can be obtained from the one-single-rotation net present value (NPV) as follows:

$$LEV(T) = NPV(T)\left[\frac{(1+r)^T}{(1+r)^T - 1}\right] \; with \; NPV(T) = \sum_{t=1}^{T} \frac{B_t - C_t}{(1+r)^t} \tag{1}$$

Whereas in the context of Monte Carlo-based stochastic simulations (where *b* is the index of the realizations, so that *b* = 1, 2,..., *B*), the expectation of the NPV, as a function of a target rotation length *T*, can be estimated as follows:

$$\hat{E}[NPV(T)] = \frac{1}{B}\sum_{b=1}^{B} NPV\;(\min(H_b, T)) \tag{2}$$

where H_b is the date of the final harvest in realization b, which is at best equal to the target *T* or smaller than *T* in case of early harvest.

The expectation of LEV can then be approximated by the so-called double-weighted LEV as:

$$\hat{E}[LEV(T)] = \frac{1}{B}\sum_{b=1}^{B}\left[NPV\,(\min(H_b,T)) + \frac{\hat{E}[NPV(T)]}{(1+r)^{\min(H_b,T)}}\frac{(1+r)^{\bar{H}(T)}}{(1+r)^{\bar{H}(T)}-1}\right] \quad (3)$$

where $\bar{H}(T) = \sum_{b=1}^{B} \min(H_b,T)\,/B$. In fact, $\bar{H}(T)$ is the mean harvest age for a target rotation length *T*. If no early harvest was triggered off, then $\bar{H}(T) = T$. Otherwise, $\bar{H}(T) < T$. This double-weighted LEV is an approximation of LEV because (i) the true value of LEV is approximated by pooling all the realizations of a Monte Carlo simulation, and (ii) $\hat{E}[NPV(T)]$ is weighted by using the mean rotation length for all cases from the second rotation onwards, as opposed to the effective rotation length for every single outcome. This approximation simplifies greatly the computation of LEV by allowing a negligible approximation error.

In this setting, the forest owner is solely interested in maximizing the financial net return: The forest owner maximizes LEV with respect to *H(T)*. This setting assumes that the management remains the same over time. In equation (3), this assumption implies that the forest owner gets a certain gain on the first rotation and then from the second one the forest owner gets an expected gain based on an average rotation length $\bar{H}(T)$.

In the context of mitigation of climate change, we considered also carbon sequestration in our economic analysis in order to compare LEV maximization and carbon storage maximization. In this setting, the forest owner is also rewarded for provision of carbon services on a yearly basis. This subsidy depends on changes in carbon stocks. Therefore, the forest owner pays a tax when the forest stand is harvested. To compute the benefits from carbon sequestration, we considered the additional carbon stored in the standing timber, the soil and the wood products, and under three different carbon costs (detailed in Section II.2.3.2). We assumed also that the carbon sequestered in wood products is never released.

The financial net return provided only by timber production is denoted LEV_T and the one considering timber production and carbon sequestration LEV_{T+C}. LEV_T and LEV_{T+C} were maximized by computing their respective optimal stand age, N_T* and N_{T+C}*, at which the even-aged stand is clear-cut or at which the LEV equilibrium is reached for uneven-aged stand.

2.3.2 Carbon price scenarios

We considered three carbon costs, which are related to three different carbon accounting methods.

First, the market value of carbon is the current real carbon price. It results from the purchase of certified credits by a certification entity in order to offset carbon emissions. In our case, this implies a market or a label accounting for the carbon sequestered by forests and funding forest projects by the credits. In France, the low-carbon label[2] was created in 2018. It is based on voluntary participation by project leaders and funders (companies, local authorities). The project (afforestation, reforestation, conversion to enhance carbon sequestration) goes through an official certification process and accounts for the carbon it avoids or sequesters. The carbon price varies according to the different projects depending on funders' participation: After discussion with forestry experts of the label, it ranges from 5 to 50 EUR/tC with a majority of projects from 20 to 30 EUR/tC. We chose to use the average price of 28 EUR/tC.

Second, the shadow price of carbon is an estimate set according to the targeted level of emissions. It results from the optimal distribution of carbon emissions abatements across all economic sectors. It is the minimum cost to be paid by society to achieve the objective set (Quinet, 2019). In 2018, the French shadow price was 54 EUR/tC and this value was used in our analysis. To achieve the goal of carbon neutrality, this shadow price should increase to reach 775 EUR/tC by 2050.

Third, the social cost of carbon is also an estimate resulting from the equality between the marginal cost of CO_2 abatement (*i.e*. the costs of emissions reduction) and the marginal cost of damage (*i.e.* the benefit of future avoided damage due to this reduction). The social cost of carbon is "an estimate of

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[2] "Label Bas Carbone"

the total cost of damages generated by each ton of CO_2 that is spewed into the air" (Howard and Sterner, 2014). In our case study, it gives the total value of avoided damage caused by the flow of carbon to the atmosphere in the case of potential total deforestation. We chose to use the floor value of 125 USD/tC (about 110 EUR/tC) proposed by Van den Bergh and Botzen (2014).

III- RESULTS

1. Effect of drought recurrence on optimal rotation length, tree mortality, carbon sequestration and LEV

Table 2 shows the results of the optimisation of the rotation length taking into account only timber production (N_T*) and the one taking into account both objectives of timber production and carbon sequestration (N_{T+C}*), as well as results in terms of mortality and carbon sequestration.

Scenario		Optimal rotation length		Mortality		Carbon
		N_T*	N_{T+C}*	%	m^3	
PAST	Baseline_B	135	135	0.55	27	221
	Baseline_O	115	95	1.03	10	195
RCP 4.5	B_EA	125	125	0.62	26	189
	Mix25_EA	117	117	1.55	14	173
	Mix50_EA	117	117	1.71	14	170
	Mix75_EA	117	117	1.85	16	168
	B_UA	220	36	0.31	51	121
	Mix25_UA	220	220	0.87	25	99
	Mix50_UA	220	220	0.95	28	99
	Mix75_UA	220	220	1.04	31	96
RCP 8.5	B_EA	90	90	0.79	16	157
	Mix25_EA	160	160	1.32	21	121
	Mix50_EA	105	100	1.93	14	143
	Mix75_EA	150	150	1.28	23	123
	B_UA	220	36	0.41	37	109
	Mix25_UA	220	220	1.24	20	89
	Mix50_UA	220	220	1.31	23	88
	Mix75_UA	220	220	1.25	28	89

Table 2: Optimal rotation length considering the objective of timber production (N_T*) *and both economic objectives of timber production and carbon sequestration (*N_{T+C}*) *with a discount rate of 2% and a carbon price of 54 EUR/tC, average yearly mortality rate of trees in percentage (%) and the total mortality in cubic meters (*m^3*), and total carbon sequestrated in tons (aboveground, belowground and in wood products) for each scenario.*

First, beech (Baseline_B) has a greater optimal rotation length (N_T* and N_{T+C}*) than oak (Baseline_O) in current conditions. A greater recurrence of drought as induced by the RCP 4.5 and 8.5 causes a decrease of both optimal rotation lengths N_T* and N_{T+C}* in even-aged beech stand (B_EA) and even-aged mixed stand with a ratio beech-oak of 50:50 (Mix50_EA). On the other hand, it increases the optimal rotation length of even-aged mixed stand with a ratio beech-oak of 25:75 (Mix25_EA) and 75:25 (Mix75_EA). All uneven-aged stands (B_UA, Mix25_UA, Mix50_UA, and Mix75_UA) settle down at a common value of 220 years that corresponds to the end of the simulation, *i.e.* they are not affected by drought recurrence.

Second, oak has a greater average mortality rate than beech in current conditions, reversely regarding the total mortality in cubic meters. The more recurrent the drought induced by climate change, the higher the mortality rate and reversely for the total mortality of scenarios.

Third, oak stands sequestrate more than beech stands in current conditions. The greater recurrence of drought decreases carbon sequestration.

Fourth, Table 3 shows the percentage of gain and loss compared to the baseline (Baseline_B or B_EA). Oak provides a higher economic return than beech in current conditions. A greater recurrence of drought decreases LEV, except for Mix25_EA and B_UA from a carbon price of 54 EUR/tC.

Scenarios		LEV_T	LEV_{T+C}		
			28 EUR/tC	**54 EUR/tC**	**110 EUR/tC**
PAST	Baseline_B	-	-	-	-
	Baseline_O	251	244	241	234
RCP 4.5	B_EA	-	-	-	-
	Mix25_EA	31	31	30	30
	Mix50_EA	40	39	39	37
	Mix75_EA	38	38	37	36
	B_UA	32	27	42	226
	Mix25_UA	290	274	259	232
	Mix50_UA	210	197	186	164
	Mix75_UA	92	84	77	64
RCP 8.5	B_EA	-	-	-	-
	Mix25_EA	177	141	115	75
	Mix50_EA	5	-1	-4	-3
	Mix75_EA	-5	-17	-26	-39
	B_UA	94	69	93	289
	Mix25_UA	480	405	351	266
	Mix50_UA	360	300	257	190
	Mix75_UA	179	143	117	76

Table 3: Variation of LEV considering only timber production (T) or with carbon sequestration (C) for a carbon price of 28 EUR/tC, 54 EUR/tC, 110 EUR/tC of each scenario compared to the baseline of beech (Baseline_B or B_EA) in percentage, for RCP 4.5 and RCP 8.5[3]*.*

2. Effect of diversification and combined diversification on optimal rotation length, tree mortality, carbon sequestration and LEV

First, in Table 2, the scenarios of composition diversification (Mix25/50/75_EA) have a lower optimal rotation length compared to the no-adaptation scenario (B_EA), whereas the scenarios of structure diversification (B_UA) and combined diversification (Mix25/50/75_UA) have a higher one than the baseline in the more optimistic climate scenario (RCP 4.5). In the more pessimistic climate scenario (RCP 8.5), adaptation provides a higher optimal rotation length than the baseline.

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[3] We performed a classical sensitivity analysis to evaluate the impact of changes in the discount rate on each scenario analysed. The results of the analysis are provided in the Supplementary Material Section (E).

Second, the scenario of structure diversification has a lower average mortality rate than the baseline, whereas the scenarios of composition and combined diversification have a higher one. Regarding the total mortality, it is more heterogeneous. Both mortality parameter increase with the proportion of beech mainly in RCP 4.5.

Third, no adaptation scenario provides a better carbon sequestration than the baseline and the worst case is the combination of strategies.

Fourth, in Table 3, the best economic return is provided by uneven-aged mixed stand with a ratio beech-oak of 25:75 (Mix25_UA), except in RCP 8.5 with a carbon price of 110 EUR/tC (B_UA). The scenario of combined diversification still provides the best economic return than the scenarios of composition and structure (except the case mentioned before) diversifications.

3. Effect of carbon price on optimal rotation length and LEV

First, in Table 2, considering one of the two or both objectives does not affect optimal rotation length of beech. While LEV_{T+C} is higher than LEV_T, $N_{T+C}*$ is less than or equal to N_T*: Considering one of the two or both objectives does not affect optimal rotation length of scenarios, except for B_UA, and Mix50_EA in the more severe climate scenario (RCP 8.5) for which $N_{T+C}*$ is lower than N_T*.

Second, in Table 3, the higher the carbon price, the higher the LEV but the lower the percentage of gain. The carbon price has more impact on the economic return of structure diversification than the other strategies: Under a price of 110 EUR/tC, B_UA is the best scenario in RCP 8.5 and the second best in the small-temperature increment scenario (RCP 4.5). In RCP 4.5, adaptation is always a good strategy, while it can be the worst option, *i.e.* maladaptation in RCP 8.5. More precisely, integrating a carbon price increases the number of maladaptation scenario (Mix75_EA only, then with Mix50_EA).

IV- DISCUSSION

1. Diversification is a good adaptation option to reduce drought-induced risk from an economic perspective

Results vary according to drought recurrence and the related climate scenario, the discount rate, the forest economic objectives, and the carbon price (Tables 2 and 3). The heterogeneity of the results can be explained by the fact that mixtures introduce new interactions, but not necessarily additive ones. This illustrates the fact that the diversified stand's productivity compared to monocultures is unclear (Mina *et al.*, 2018).

However, considering the more optimistic climate scenario (RCP 4.5), diversification increases LEV. Regarding the more pessimistic one (RCP 8.5), there is a risk of maladaptation and thus a decrease of LEV compared to the no-adaptation option. The results corroborate our first hypothesis for structure diversification and combined diversification. This is in line with Müller *et al*. (2019) showing uneven-aged stands as more cost-effective than even-aged ones and papers proposing to combine different strategies, among which species mixture to cope with storm risk (Jönsson *et al.*, 2015). On the other hand, composition diversification is still unclear. Only even-aged mixed stands with a ratio beech-oak of 25:75 (Mix25_EA) seem to be a good adaptation option among the three scenarios of composition diversification tested. Optimising species proportions according to forest management objectives before analysing them and instead of fixing them should improve future studies. Moreover, testing different species in mixtures and optimising also the number of species in the stand could be included as well.

2. Diversification and combining both diversification strategies lead to synergies

From an economic perspective, the combination of different strategies can be more beneficial for the forest owner than each strategy separately, *i.e.* synergies between adaptation strategies can appear.

We tested this hypothesis through the Pretzsch and Schütze framework (2009). The framework and the resulted tables are provided in the Supplementary Material Section (F).

Diversifying the stand and combining both diversification strategies can lead to synergies on timber volume, which are emphasized by a greater recurrence of drought: From 28% in RCP 4.5 to 85% of scenarios in RCP 8.5 show synergies. Some synergies appear as well as on LEV depending on the discount rate (from 14% for 1% to 100% for 4%). Indeed, complementarity can occur between beech and oak (Zapater *et al.*, 2011) and in tree structure (Jucker *et al.*, 2015) resulting in a higher water uptake thanks to different vertical rooting pattern among species (Zapater *et al.*, 2011). The results corroborate our second hypothesis.

3. Financial balance *vs*. carbon balance

Diversification decreases carbon sequestration (Table 2), contrary to the results of Kirby and Potvin (2007) and Lange *et al.* (2015). Adaptation to drought-induced risk will be in conflict with mitigation of climate change. Our result does not allow validating whether trade-offs between the financial balance and the carbon balance are possible or not: The third hypothesis is rejected. It would be interesting to study further different strategies and their trade-offs between adaptation and mitigation of climate change. For this, we need also to integrate different climate change-related risks in our analysis (*i.e*. multi-risks analysis).

4. Valorising carbon decreases the optimal rotation length and increases LEV

The optimal rotation length considering only timber production (N_T*) is ever more than or equal to the optimal one considering both objectives of timber production with carbon sequestration (N_{T+C}*). This result is not in line with the common literature (Van Kooten *et al*., 1995; Pajot, 2011) showing generally an increase of rotation length when carbon services are taken into account in addition to timber production and it does not allow integrating carbon payment as suggested by Brèteau-Amores *et al.* (2019). However, Akao (2011) explains that rotation lengths can become shorter when the forest function of sequestering atmospheric carbon is more important than the one of postponing sequestered carbon release. Moreover, Akao mentioned also that the shorter case is likely to occur when the harvested wood products store the sequestered carbon for many years, which is our case. Therefore, optimising only timber production integrates yet optimal carbon services. In addition, valorising carbon can decrease the rotation length at the same time, which is in line with adaptation recommendations (Spittlehouse and Stewart, 2003).

Integrating carbon value increases also the value of forest stand (LEV), even more when adaptation is applied. This shows the importance to consider carbon in our analysis and corroborates the fourth hypothesis. While we integrated the carbon stored in wood products in addition to the remaining aboveground and belowground carbon in forest stand, the carbon price has little impact on the scenario providing the best economic return. Mixed forests will generate a mixed supply: Integrating future use of wood products with different lifetimes may improve our analysis, in order to consider at the same time the effect of the timber production of forest owners with the economic consequences on the downstream of the wood chain through different wood products. Moreover, timber market currently fluctuates and climate change will enhance this fluctuation (Favero *et al.*, 2018): An extension of our study could be to include different trajectories of timber and carbon prices as well.

5. Limits and perspectives of the study

The management is driven by basal area and dominant tree diameter in the model, which are the commonly used criteria in forest management. Nevertheless, there was no possibility to maintain the diversity, *i.e.* the proportions of each species and each tree diameter class. A consequence of the first point was the increasing proportion of beech, as it actually occurs in forest stand (Von Lüpke, 1998).

The LEV of the adapted stands can thus be higher than estimated. However, this under-estimation can be counterbalanced by the under-estimation of drought effect.

The drought-induced dieback was modelled as a probability of direct overmortality, which does not include the post-drought effects (Power *et al.*, 1995). Moreover, on the computation of drought recurrences, we assumed that the future climate regardless of the RCP will result in the same water balance whatever the structure and the composition of stands, which is not correct. The different vertical rooting pattern of beech and oak (Zapater *et al.*, 2011) and the different leaf area index (LAI) between mixed and pure stands (Jonard *et al*., 2011) lead to different water uptake in the soil. All these elements should be included in further studies, which require more investigation on mixed stands' ecology.

While diversification can be a good adaptation strategy, the known-how is also important: The implementation of these silviculture treatments lacks currently management knowledge and skills and thus requires more investigation as well. In addition, we studied two types of diversification. Another one can be to introduce genetic variability with different provenances of species (Lefèvre *et al*., 2014).

V- CONCLUSION

Drought extreme events, increasing mortality, result in losses of timber production and carbon sequestration. We showed that optimizing rotation length considering only timber production valorises both timber and carbon services. One of the originalities of this study was to integrate structure diversification, as an adaptation strategy, in addition to composition one. Another one was the combination of stochastic simulations with a frequently used economics approach: Our study included uncertainty of forest owners' revenues related to forest growth and carbon sequestration, under two climate scenarios. Diversification (composition and structure) can be a good option to reduce drought-induced risk and leads to some synergies in terms of timber productivity (timber volume) and economic value (timber production with or without carbon valorisation). The heterogeneity of our results showed the importance to consider different criteria, climate scenarios, and different ecosystem services. Integrating other species on this analysis to test different types of diversification and other ecosystem services like partitioning between blue and green water should improve this analysis. Further studies should also investigate different strategies with their trade-offs between adaptation and mitigation of climate change in a multi-risks analysis. Finally, to be efficient, adaptation need to be connected to the entire forest sector. Mixed forests will generate a mixed supply: Impact on wood chain sector should be investigated as well.

ACKNOWLEDGEMENTS

This work was performed in partnership with Cyril Vitu and Stéphane Asaël from the CRPF of Grand-Est region. The authors gratefully acknowledge the suggestions of Marielle Brunette, Eric Lacombe and the help of Aurélien Barthélémy and Jacques Becquey. The UMR BETA and SILVA are supported by a grant overseen by the French National Research Agency (ANR) as part of the “Investissements d'Avenir” program (ANR-ll-LABX-0002-01, Lab of Excellence ARBRE). The first author benefits from a PhD grant supported by the Meta-Programme ACCAF of INRAE, the INRAE department EcoSocio and the Grand-Est region.

SUPPLEMENTARY MATERIAL

A. Drought recurrences definition

The recurrences of drought events were defined from daily soil water content computed through BILJOU©.

Water balance calculations have been performed for a representative beech stand of Grand-Est region with a medium site fertility (*i.e.* available soil water content of 100 mm and leaf area index of 5.5) and for the reference climate, RCP 4.5 and RCP 8.5 (data from ARPEGE model).

We assumed that the same water balance results from future climate regardless the RCP and regardless to stand composition and structure.

B. Creation of fictive stands

We created a fictive stand for each management scenario. More precisely, mixed stand of beech and oak has the same density as in monoculture: The introduced species substitutes a part of the current species in the stand (25, 50 or 75%).

Concerning diversification by structure, the stand is defined as a homogeneous uneven-aged one according to the structure triangle in the French forest management. It corresponds to a share of stand basal area by three different diameter classes. In our study, stands are composed of roughly 30% of trees with a DBH of 17.5 – 27.5 cm, 45% of trees with a DBH of 27.5 – 47.5 cm, and 25% of trees with a DBH of more than 47.5 cm.

C. Simulation of forest management

MATHILDE's built-in harvest algorithm requires some bounds in terms of basal area to implement the management scenarios. The bounds are shown in the following table:

Management scenario	Stand age (yrs)	Bounds (m^2ha^{-1})
Even-aged beech	0-50	[14, 18]
	50-70	[18, 22]
	70 until final cut	[22, 26]
Even-aged oak	0-50	[14, 18]
	50 until final cut	[18, 22]
Even-aged mixed stand	0-50	[14, 18]
	50 until final cut	[18, 22]
Uneven-aged beech	n/a	[14, 18]
Uneven-aged oak	n/a	[12, 16]
Uneven-aged mixed stand	n/a	[12, 16]

Table C.1: Basal area bounds (m²/ha) that were used in the different management scenarios (source: CRPF). The bounds are age dependent for even-aged management scenarios. n/a: not applicable.

D. MATHILDE and CAT

MATHILDE is a distance-independent individual-based model that simulates forest dynamics (Fortin and Manso, 2016). MATHILDE is fitted to data from a large network of permanent plots measured over the 1958-2007 period. It is designed to simulate even-aged and uneven-aged stands as well as pure and mixed stands of beech and sessile oak in Northern France. More precisely, it predicts tree mortality, the diameter increment of survivors and the recruitment of new trees over five-year growth periods. The model is composed of different sub-models, which are illustrated on Figure D.1.

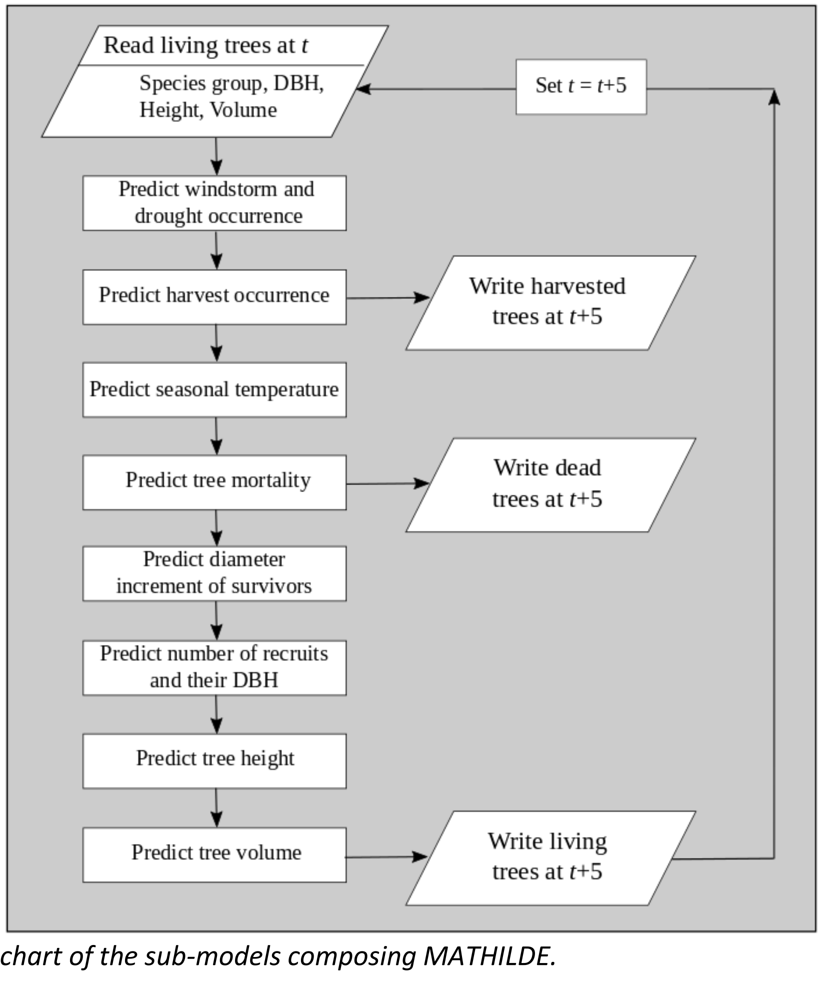

Figure D.1: Flowchart of the sub-models composing MATHILDE.

The climate sub-model is fitted to data from SAFRAN model over the 1959-2012 period. It predicts the mean seasonal temperature over a period, depending on the initial year of the period and the occurrence of drought during the period. The growing season temperature is controlled by a parameter driving its increase. This parameter depends on the given climate scenario and changes when a drought occurs during the period.

The mortality sub-model encompasses many explanatory variables such as tree species, diameter at breast height (DBH, 1.3 m in height), basal area of trees with DBH larger than the subject tree as well as the occurrence of drought, windstorm and harvesting (Manso *et al.*, 2015a). The effects of drought and windstorm are the average of those observed over the last 60 years.

The diameter-increment sub-model predicts the increment of a given tree over a period (Manso *et al.*, 2015b). The explanatory variables are tree species, DBH, basal area of trees with DBH larger than the subject tree, plot basal area, harvest occurrence, and mean seasonal temperature during the time interval.

The sub-model of tree recruitment predicts the number of trees that cross the threshold of 7.5 cm for each species. The explanatory variables are the all-species basal area as well as the basal area of the species. In addition to the aforementioned sub-models, MATHILDE also includes a model of height-diameter relationships (Fortin *et al.* 2019).

MATHILDE is designed to simulated forest growth from inventory data in a stochastic manner using the Monte Carlo technique. This method provides a prediction of the stand evolution as well as the uncertainty associated with this prediction. Confidence interval bounds are derived using the percentile rank method (Efron and Tibshirani, 1993). The model implements an algorithm that triggers the harvesting based on plot basal area and a target dominant diameter, *i.e.* the mean diameter of the 100 thickest trees per hectare. Once the harvesting is triggered, a sub-model of tree harvest predicts the probability that an individual tree is harvested (see Manso *et al*. 2018).

MATHILDE is implemented in the CAPSIS platform (Dufour-Kowalski *et al.,* 2012), which contains a carbon accounting tool (CAT, Pichancourt *et al.*, 2018). CAT allows for the representation of complex emission life cycles inherent to managed forests. It takes into account the main issues related to carbon accounting tools, such as the numerous uncertainties, risk of carbon leakage and double counting. The assessment of the carbon balance is also supported by built-in Monte Carlo error propagation methods. In addition to the IPCC standards, CAT also provides estimates of

(i) cumulative material and energy substitution, that is the greenhouse gas emissions avoided when a harvested wood product (HWP) replaces an alternative product;
(ii) cumulative fossil fuel carbon emissions during the life cycle of the different HWP;
(iii) the accumulation of non-degradable HWP at solid waste disposal site (SWDS), and
(iv) cumulative methane (CH4) emissions caused by the degradation of HWP at SWDS. By default (semi-aerobic conditions), CAT assumes that 25% of the carbon emitted from the SWDS is methane. The non-degradable part of carbon that accumulates at a SWDS is assumed to be permanently sequestered.

Simulations are run by default under global warming potential factors of the fifth assessment report on climate change (IPCC, 2013). Results are exported in carbon units with the probability level of the confidence intervals equal to 0.95 by default.

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E. Land expectation value and sensitivity analysis of discount rate

We performed a sensitivity analysis of discount rate. The results are presented in Table E.1 and are ranked by their economic return (LEV) for each climate scenario. The detailed gain and loss compared to the baseline (Baseline_B and B_EA) are provided in Table E.2.

T	**0.01**	**0.02**	**0.03**	**0.04**
PAST	Baseline_O	Baseline_O	Baseline_O	Baseline_O
	Baseline_B	Baseline_B	Baseline_B	Baseline_B
RCP 4.5	Mix25_UA	Mix25_UA	Mix25_UA	Mix75_EA
	Mix50_UA	Mix50_UA	Mix50_UA	Mix50_EA
	B_EA	Mix75_UA	Mix50_EA	Mix25_EA
	Mix75_UA	Mix50_EA	Mix75_EA	Mix25_UA
	B_UA	Mix75_EA	Mix25_EA	Mix50_UA
	Mix50_EA	B_UA	Mix75_UA	Mix75_UA
	Mix75_EA	Mix25_EA	B_UA	B_UA
	Mix25_EA	B_EA	B_EA	B_EA
RCP 8.5	Mix25_UA	Mix25_UA	Mix25_UA	Mix25_EA
	Mix50_UA	Mix50_UA	Mix50_UA	Mix25_UA
	Mix75_EA	Mix75_UA	Mix25_EA	Mix50_UA
	Mix50_EA	Mix25_EA	Mix75_UA	Mix75_UA
	B_EA	B_UA	B_UA	B_UA
	Mix75_UA	Mix50_EA	Mix50_EA	Mix50_EA
	B_UA	B_EA	B_EA	B_EA
	Mix25_EA	Mix75_EA	Mix75_EA	Mix75_EA

T+C_28	**0.01**	**0.02**	**0.03**	**0.04**
PAST	Baseline_O	Baseline_O	Baseline_O	Baseline_O
	Baseline_B	Baseline_B	Baseline_B	Baseline_B
RCP 4.5	Mix25_UA	Mix25_UA	Mix25_UA	Mix50_EA
	Mix50_UA	Mix50_UA	Mix50_UA	Mix75_EA
	B_EA	Mix75_UA	Mix50_EA	Mix25_EA
	Mix75_UA	Mix50_EA	Mix75_EA	Mix25_UA
	B_UA	Mix75_EA	Mix25_EA	Mix50_UA
	Mix50_EA	Mix25_EA	Mix75_UA	Mix75_UA
	Mix75_EA	B_UA	B_UA	B_UA
	Mix25_EA	B_EA	B_EA	B_EA
RCP 8.5	Mix25_UA	Mix25_UA	Mix25_UA	Mix25_EA
	Mix50_UA	Mix50_UA	Mix50_UA	Mix25_UA
	Mix50_EA	Mix75_UA	Mix25_EA	Mix50_UA
	B_EA	Mix25_EA	Mix75_UA	Mix75_UA
	Mix75_EA	B_UA	B_UA	B_UA
	Mix75_UA	B_EA	B_EA	B_EA
	B_UA	Mix50_EA	Mix50_EA	Mix50_EA
	Mix25_EA	Mix75_EA	Mix75_EA	Mix75_EA

T+C_54	**0.01**	**0.02**	**0.03**	**0.04**
PAST	Baseline_O	Baseline_O	Baseline_O	Baseline_O
	Baseline_B	Baseline_B	Baseline_B	Baseline_B
RCP 4.5	Mix25_UA	Mix25_UA	Mix25_UA	Mix50_EA
	Mix50_UA	Mix50_UA	Mix50_UA	Mix75_EA
	B_EA	Mix75_UA	Mix50_EA	Mix25_EA
	B_UA	B_UA	Mix75_EA	Mix25_UA
	Mix75_UA	Mix50_EA	Mix25_EA	Mix50_UA
	Mix50_EA	Mix75_EA	Mix75_UA	Mix75_UA
	Mix75_EA	Mix25_EA	B_UA	B_UA
	Mix25_EA	B_EA	B_EA	B_EA
RCP 8.5	Mix25_UA	Mix25_UA	Mix25_UA	Mix25_EA
	Mix50_UA	Mix50_UA	Mix50_UA	Mix25_UA
	B_UA	Mix75_UA	Mix25_EA	Mix50_UA
	B_EA	Mix25_EA	Mix75_UA	Mix75_UA
	Mix50_EA	B_UA	B_UA	B_UA
	Mix75_EA	B_EA	B_EA	B_EA
	Mix75_UA	Mix50_EA	Mix50_EA	Mix50_EA
	Mix25_EA	Mix75_EA	Mix75_EA	Mix75_EA

T+C_110	**0.01**	**0.02**	**0.03**	**0.04**
PAST	Baseline_O	Baseline_O	Baseline_O	Baseline_O
	Baseline_B	Baseline_B	Baseline_B	Baseline_B
RCP 4.5	B_UA	Mix25_UA	Mix25_UA	Mix50_EA
	Mix25_UA	B_UA	B_UA	Mix75_EA
	Mix50_UA	Mix50_UA	Mix50_UA	Mix25_EA
	B_EA	Mix75_UA	Mix50_EA	Mix25_UA
	Mix75_UA	Mix50_EA	Mix75_EA	B_UA
	Mix50_EA	Mix75_EA	Mix25_EA	Mix50_UA
	Mix75_EA	Mix25_EA	Mix75_UA	Mix75_UA
	Mix25_EA	B_EA	B_EA	B_EA
RCP 8.5	B_UA	B_UA	Mix25_UA	Mix25_EA
	Mix25_UA	Mix25_UA	B_UA	Mix25_UA
	Mix50_UA	Mix50_UA	Mix50_UA	B_UA
	B_EA	Mix75_UA	Mix25_EA	Mix50_UA
	Mix50_EA	Mix25_EA	Mix75_UA	Mix75_UA
	Mix75_EA	B_EA	Mix50_EA	B_EA
	Mix75_UA	Mix50_EA	B_EA	Mix50_EA
	Mix25_EA	Mix75_EA	Mix75_EA	Mix75_EA

Table E.1: Scenarios code ranked by their economic return for each climate scenario (past, RCP 4.5 and RCP 8.5) and for four discount rates (1%, 2%, 3%, and 4%). The four tables correspond to LEV considering only timber production (T) (top left) or with carbon sequestration (T+C) for a carbon price of 28 EUR/tC *(top right), 54 EUR/tC (bottom left), and 110 EUR/tC (bottom right). Each management scenario is related to a colour.*

T	**Scenarios**	**0.01**	**0.02**	**0.03**	**0.04**
PAST	Baseline_B	-	-	-	-
	Baseline_O	211	251	317	376
RCP 4.5	B_EA	-	-	-	-
	Mix25_EA	-83	31	349	1202
	Mix50_EA	-79	40	374	1285
	Mix75_EA	-81	38	372	1287
	B_UA	-54	32	154	349
	Mix25_UA	73	290	622	1157
	Mix50_UA	20	210	483	920
	Mix75_UA	-40	92	271	552
RCP 8.5	B_EA	-	-	-	-
	Mix25_EA	-33	177	643	1691
	Mix50_EA	7	5	3	2
	Mix75_EA	12	-5	-17	-24
	B_UA	-22	94	222	391
	Mix25_UA	230	480	823	1283
	Mix50_UA	110	360	646	1026
	Mix75_UA	-7	179	369	612

T+C_28	**Scenarios**	**0.01**	**0.02**	**0.03**	**0.04**
PAST	Baseline_B	-	-	-	-
	Baseline_O	205	244	313	362
RCP 4.5	B_EA	-	-	-	-
	Mix25_EA	-78	31	337	1075
	Mix50_EA	-76	39	365	1150
	Mix75_EA	-76	38	359	1133
	B_UA	-54	27	144	304
	Mix25_UA	77	274	595	1030
	Mix50_UA	21	197	461	818
	Mix75_UA	-40	84	257	486
RCP 8.5	B_EA	-	-	-	-
	Mix25_EA	-41	141	549	1468
	Mix50_EA	1	-1	-2	-3
	Mix75_EA	-2	-17	-27	-33
	B_UA	-32	69	181	330
	Mix25_UA	195	405	706	1111
	Mix50_UA	82	300	552	886
	Mix75_UA	-19	143	309	523

T+C_54	**Scenarios**	**0.01**	**0.02**	**0.03**	**0.04**
PAST	Baseline_B	-	-	-	-
	Baseline_O	199	241	308	350
RCP 4.5	B_EA	-	-	-	-
	Mix25_EA	-74	30	326	953
	Mix50_EA	-72	39	353	1020
	Mix75_EA	-72	37	347	1004
	B_UA	-16	42	146	271
	Mix25_UA	79	259	571	910
	Mix50_UA	20	186	442	720
	Mix75_UA	-40	77	245	424
RCP 8.5	B_EA	-	-	-	-
	Mix25_EA	-48	115	481	1312
	Mix50_EA	-3	-4	-4	-1
	Mix75_EA	-13	-26	-35	-40
	B_UA	39	93	178	313
	Mix25_UA	170	351	622	991
	Mix50_UA	63	257	483	788
	Mix75_UA	-28	117	266	461

T+C_110	**Scenarios**	**0.01**	**0.02**	**0.03**	**0.04**
PAST	Baseline_B	-	-	-	-
	Baseline_O	186	234	284	322
RCP 4.5	B_EA	-	-	-	-
	Mix25_EA	-65	30	259	767
	Mix50_EA	-64	37	281	820
	Mix75_EA	-64	36	276	808
	B_UA	96	226	403	647
	Mix25_UA	79	232	453	725
	Mix50_UA	15	164	346	569
	Mix75_UA	-43	64	184	328
RCP 8.5	B_EA	-	-	-	-
	Mix25_EA	-57	75	374	1009
	Mix50_EA	-5	-3	0	0
	Mix75_EA	-29	-39	-38	-39
	B_UA	180	289	461	700
	Mix25_UA	138	266	488	757
	Mix50_UA	40	190	375	598
	Mix75_UA	-41	76	199	341

Table E.2: Variation of LEV (in percentage terms) of each scenario compared to the baseline of beech (Baseline_B or B_EA), for RCP 4.5 and RCP 8.5 and for four discount rates (1%, 2%, 3%, and 4%). The four tables correspond to LEV considering only timber production (T) (top left) or with carbon sequestration (T+C) for a carbon price of 28 EUR/tC (top right), 54 EUR/tC (bottom left), and 110 EUR/tC (bottom right).

F. Synergy analysis of adaptation strategies

First, the overyielding is defined as a higher observed parameter P_{mix} in the mixed stand than the expected parameter $\widehat{P_{mix}}$ (Pretzsch and Schütze, 2009), *i.e*.

$$P_{mix} > \widehat{P_{mix}} \leftrightarrow P_{mix} > q_1.P_1 + q_2.P_2$$

where q_1 and q_2 are the respective mixing proportions of species 1 and species 2, and P_1 and P_2 the respective parameter of species 1 and species 2 in monoculture.

Then, a transgressive overyielding of the mixed stand can be observed, when the observed parameter P_{mix} is higher than the parameter of both species in monoculture (P_1 and P_2) (Pretzsch and Schütze, 2009), *i.e*.

$$P_{mix} > P_1 \ and \ P_{mix} > P_2$$

The tested parameters were the total volume harvested and the land expectation value. The results are presented in Tables F.1 and F.2. An overyielding is represented by a coefficient of 1 and a transgressive overyielding by a coefficient of 1+. An absence of overyielding is represented by a coefficient of 0.

Scenario		0.01	0.02	0.03	0.04
RCP 4.5	B_EA	-	-	-	-
	Mix25_EA	0	0	0	1
	Mix50_EA	0	0	1+	1+
	Mix75_EA	0	0	1+	1+
	B_UA	0	0	1+	1+
	Mix25_UA	0	1	0	0
	Mix50_UA	0	1	0	0
	Mix75_UA	0	0	0	0
RCP 8.5	B_EA	-	-	-	-
	Mix25_EA	1+	1+	1+	1+
	Mix50_EA	1+	1+	1+	0
	Mix75_EA	1+	1+	1+	1+
	B_UA	0	0	0	0
	Mix25_UA	0	1	1	1
	Mix50_UA	0	1	1	1
	Mix75_UA	0	1	1	1

Table F.1: Results of the tested synergy of mixed stands in total volume harvested characterised by overyielding (coefficient 1) or transgressive overyielding (coefficient 1+) or absence (coefficient 0) for each scenario and considering four discount rates (1%, 2%, 3%, and 4%).

		0.01				**0.02**				**0.03**				**0.04**			
Scenario		**T**	**28**	**54**	**110**	**T**	**28**	**54**	**110**	**T**	**28**	**54**	**110**	**T**	**28**	**54**	**110**
RCP 4.5	B_EA	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Mix25_EA	0	0	0	0	0	0	0	0	1	1	1	0	1+	1+	1+	1+
	Mix50_EA	0	0	0	0	0	0	0	0	1	1	1	1	1+	1+	1+	1+
	Mix75_EA	0	0	0	0	0	0	0	0	1	1	1	1	1+	1+	1+	1+
	B_UA	0	0	0	0	0	0	0	1	1	1	1	1+	1	1	1	1+
	Mix25_UA	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
	Mix50_UA	0	0	0	0	1	1	0	0	1	1	1	1	1	1	1	1
	Mix75_UA	0	0	0	0	0	0	0	0	1	1	1	0	1	1	1	0
RCP 8.5	B_EA	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Mix25_EA	0	0	0	0	0	0	0	0	1+	1+	1+	1+	1+	1+	1+	1+
	Mix50_EA	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Mix75_EA	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	B_UA	0	0	0	1	0	0	0	1	1	1	1	1+	1	1	1	1+
	Mix25_UA	0	0	0	0	1	1	1	0	1	1	1	1	1	1	1	1
	Mix50_UA	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
	Mix75_UA	0	0	0	0	0	0	0	0	1	1	1	0	1	1	1	0

Table F.2: Results of the tested synergy of mixed stand on LEV considering only timber production (T) or with carbon sequestration for a carbon price of 28 EUR/tC, 54 EUR/tC, and 110 EUR/tC, characterised by overyielding (coefficient 1) or transgressive overyielding (coefficient 1+) or absence (coefficient 0) for each scenario and considering four discount rates (1%, 2%, 3%, and 4%).

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