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Composition diversification vs. structure diversification: How to conciliate timber production and carbon sequestration objectives under drought and windstorm risks in forest ecosystems

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ABSTRACT

Forests provide ecosystem services such as timber production and carbon sequestration. However, forests are sensitive to climate change, and financial and amenity losses are expected for forest owners and society, respectively. The forests in the Grand-Est region, France, are dominated by European beech, for which a decline is anticipated due to repeated drought events induced by climate change. These forest ecosystems are also threatened by windstorm events. Beech forests need to adapt and diversification can decrease drought and windstorm risks. In this context, the objective of the paper was to compare different forest adaptation strategies from an economic perspective with the objective of reducing drought- and windstorm-induced risks of dieback. For this purpose, we studied two types of diversification that we analysed separately and jointly: Mixing beech with oak and diversifying stand structure (*i.e.* from an even-aged to an uneven-aged forest). We also considered two types of loss (financial, and in terms of carbon sequestration) under different recurrences of drought and windstorm risks. We combined a forest growth simulator with a forest economic approach through the computation of land expectation value (LEV). Maximizing the LEV criterion made it possible to identify the best adaptation strategies in economic terms. The results show that diversification increases timber production and LEV, but reduces carbon storage. The two risks as well as the adaptation strategies show some synergies. Finally, trade-offs between the financial balance and the carbon balance (*i.e.* adaptation *vs*. mitigation) are possible.

Keywords: Forest; Drought; Windstorm; Adaptation; Climate change; Mixture; Economics; Multi-risks; Carbon.

JEL codes: 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 major disturbance affecting forest health worldwide (Zierl, 2004; Allen *et al.*, 2010). In Europe, trees are suffering from severe droughts occurring especially in early summer (Bréda and Badeau, 2008), which result in a decrease of biomass production and in an increase of tree mortality (Seidl *et al.*, 2011). Drought-induced damage implies economic losses for forest owners, as well as a loss of amenities for society, such as carbon sequestration. These impacts could become even more important in the future as the frequency, duration and intensity of extreme natural events might increase with climate change (Dale *et al*., 2001).

Forest stands can be affected by several hazards during the same rotation. In France, droughts and windstorms are the two main damaging abiotic risks (Roualt *et al*., 2006; Bonnesoeur *et al*., 2013) affecting the overall carbon sequestration capacity of forests (Thurig *et al.*, 2013). Like droughts, severe windstorms also affect forest health, damaging forest stands especially in winter and late autumn (Valinger and Fridman, 2011). Given that forest ecosystems play a major role in climate change mitigation through carbon sequestration, there is growing concern about how this mitigation capacity can be maintained as risks increase (Locatelli *et al.*, 2010; Kolström *et al.*, 2011). In this context, investigating the cumulative impact of several extreme events on forest stands can provide further insight into potential adaptation strategies.

The pace of changes induced by climate change being too fast for a natural and spontaneous forest adaptation, a way to cope with these increasing risks is to apply a well-suited management (Spittlehouse and Stewart, 2003). Several strategies can maintain forest ecosystems' resilience through silvicultural management (Spittlehouse and Stewart, 2003) such as reducing the rotation length or decreasing stand density. Adaptation implies new management costs and benefits for forest owners (Kolström *et al.*, 2011) and thus it must be suitable for all major disturbances. Diversification can be an adaptation option, developing more stable forest stands to hedge from climate fluctuations and disturbances due to climate change. Diversification has a broad meaning and it can apply to different components. In this paper, we considered the diversification could apply to stand composition or stand structure. The first one means shifting from monocultures to mixed stands with two or more species. This can lead to complementarity in tree structure *i.e.* "canopy packing" (Jucker *et al.*, 2015) which in turn, can increase tree resistance to damage (Lebourgeois *et al*., 2013; Jactel *et al.*, 2017). Different vertical rooting patterns among species can result in a higher water uptake (Zapater *et al.*, 2011) and a greater wind resistance of the stand (Mason and Valinger, 2013). Mixing species can also increase forest productivity (Forrester, 2014) and other ecosystem services (Duncker *et al.*, 2012) such as carbon sequestration (Kirby and Potvin, 2007; Lange *et al.*, 2015). However, it can increase tree competition for water resources (Bonal *et al*., 2017) leading to lower soil moisture availability (Grossiord *et al*., 2014). The structural diversification means shifting from even-aged to uneven-aged silviculture, *i.e.* having different diameter classes in a same stand, leading to a better stability of the uneven-aged stand structure (Hanewinkel *et al*., 2014). This implies a better resilience to natural hazard (Jacobsen and Helles, 2006), since the understorey trees allow faster recovery after disturbance (Stanturf *et al*., 2007). However, uneven-aged silviculture can increase vulnerability since the successive thinnings can reduce the stabilizing effect of crown contact that normally takes place in even-aged stands (Mason and Valinger, 2013).

In this context, the question is whether diversification of forest stand is a good adaptation option to reduce drought- and windstorm-induced risks of forest dieback from an economic standpoint. We propose an analysis of the economics costs and benefits of adaptation provided by timber production and carbon storage from private owners' perspective. In the literature, few studies have dealt with forest adaptation to climate change using an economic approach. To the best of our knowledge, only Bréda and Brunette (2019) and Brèteau-Amores *et al*. (2019; 2020) have tackled the issue of forest adaptation to drought-induced risks. Although, some studies have investigated the impacts of windstorm damage on forests (Brunette *et al.*, 2015; Rakotoarison and Loisel, 2017), only a few of them have dealt with forest adaptation against windstorm risk (Jönsson *et al.,* 2015; Müller *et al.*, 2019). Moreover, few studies have considered carbon loss in addition to economic loss (Yousefpour and Hanewinkel, 2014; Brèteau-Amores *et al.*, 2019; Müller *et al.*, 2019; Brèteau-Amores *et al.*, 2020). Montagné-Huck and Brunette (2018) showed that dealing with multiple hazards was addressed in other disciplines, but not using an economic approach: Only Petucco and Andrés-Domenech (2018) combined windstorm with another natural risk (pests). However, they studied these two risks independently, *i.e.* without interaction, which was also point out by Montagné-Huck and Brunette (2018). To the best of our knowledge, there is no study combining drought and windstorm risks.

The objective of this paper was to test and then to compare composition and structure diversifications as potential adaptation strategies aiming at reducing drought- and windstorm-induced risks of forest dieback from an economic perspective. For this purpose, 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 a pure financial loss and a loss in terms of carbon sequestration. The model predictions were used as inputs in the computation of land expectation value. The maximisation of the criterion allowed us to identify the best adaptation strategy. 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 strategy to reduce drought- and windstorm-induced risks; (ii) considering both risks impacts the results and recommendations compared to investigating each risk separately; (iii) diversifying the stand and combining both strategies lead to synergies; (iv) carbon price has an impact on (i).

II- MATERIAL AND METHODS

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

The Grand-Est region is one of the most afforested region in France, with 42% of private forests[1]. Forests cover more than a third of the region with a majority of broadleaved species[1]. Among them, European beech (*Fagus sylvatica* L.), sessile oak (*Quercus petraea* Liebl.) and pedunculate oak (*Quercus robur* L.) are economically important since they provide 40% of the total timber resource[1].

Drought and windstorm occurrences are major causes of tree mortality in Grand-Est region (Roualt *et al*., 2006; Bonnesoeur *et al*., 2013). Extreme drought episodes in 1976 and 2003 caused a great deal of damage the same year as well as in the following years after the drought (Bréda *et al*., 2004). The 2003 drought caused more damage than that of 1976 due to the heat wave that simultaneously occurred when water shortage induced stomatal control and loss of canopy refreshment (Bréda *et al*., 2006). The radial growth of beech is sensitive to edaphic drought: Beech productivity is projected to decline or its range to be restricted in the future due to repeated droughts such as in 2003 (Lebourgeois *et al.*, 2005; Charru *et al.*, 2010). Severe windstorms have also occurred in the region with major consequences on the forest sector. The Grand-Est was the first producer of high quality beech timber before the huge windstorms Lothar and Martin in 1999 (Bonnesoeur *et al.*, 2013): They devastated some 176 Mm^3 of roundwood, equivalent to three times the French annual timber harvest (MAP and IFN, 2006).

Diversifying stands can be an option to adapt beech to these risks, as recommended in the French windstorm crisis management plan for the forest sector (created in 2018). The success of this strategy depends on whether the additional species have an impact on the severity of water shortage

[1] Source: IGN.

constraints (Metz *et al.*, 2016). Admixing beech with deep-rooting species (*i.e.* taking up water in deeper soil layers) such as oak (Zapater *et al*., 2013) or silver fir (Magh *et al.*, 2018) can reduce the drought stress, because of the asynchronous stress reaction pattern of beech and oak (Zapater *et al*., 2011; Pretzsch *et al.*, 2013). More resistant than beech, oak can reduce windstorm damage at the stand level (Mason and Valinger, 2013). Moreover, mixed forests of beech and oak are common in Europe (Pretzsch *et al*., 2013) and represent more than 10% of French mixed forests (Morneau *et al*., 2008).

There are two major oak species in France: Sessile and pedunculate oak. The first one is more resistant to soil water shortage and supports more competition than the latter (Rameau *et al.*, 1989; Sevrin, 1997). However, sessile oak can be more subject to game herbivory, which may result in higher management costs due to the need of fencing to ensure regeneration success (Sevrin, 1997).

2. Methods

We defined six management-based scenarios and simulated their forest growth. The model predictions were used as inputs to compute land expectation value (LEV) for each scenario. Figure 1 maps all these elements, which are described in the following sub-sections.

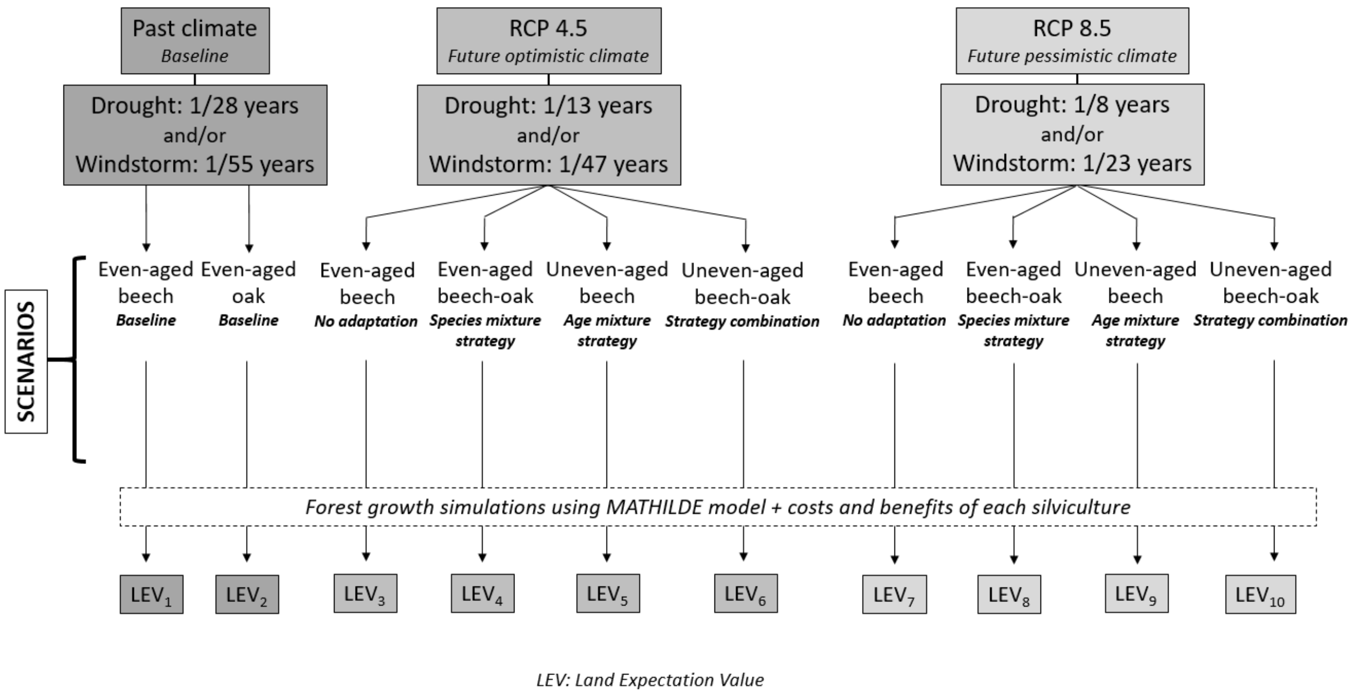

Figure 1: Schematic representation of the methodology: From scenario definition to economic evaluation.

2.1 Scenarios tested

The scenarios were defined according to tree species and stand structure: Pure and even-aged beech/oak stand, pure and uneven-aged beech stand, mixed and uneven-/even-aged stand with a ratio 50:50 of beech to oak (Figure 1). Two baselines were simulated under past climate and four scenarios were simulated and tested under future climate composed by the RCP 4.5 and the RCP 8.5 (IPCC, 2013), which are summarized in Table 1. In addition to these scenarios, even-aged and uneven-aged oak stands were also simulated in order to test the third hypothesis (synergies of the adaptation strategies).

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
Mix50_EA	Even-aged mixed stand with a ratio 50:50 of beech to oak
B_UA	Uneven-aged beech stand
Mix50_UA	Uneven-aged mixed stand with a ratio 50:50 of beech to oak

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

The recurrence of drought and windstorm events are considered as exogenous variables in our simulations. Following the methodology in Brèteau-Amores *et al*. (2020), we used the same drought recurrence. They computed the most exceptional drought events, *i.e.* known in the reference period to induce beech dieback, through a daily forest water balance model BILJOU© (Granier *et al*., 1999) under reference climate, RCP 4.5 and RCP 8.5. The drought recurrences of these three climate scenarios were estimated at 28, 13, and 8 years respectively. Concerning windstorm occurrence, we computed the most exceptional events, *i.e.* inducing damage similar to that of Lothar 1999 windstorm, from Météo France data for the three climate scenarios. The respective recurrences were 55, 47, and 23 years. More details on the computation of windstorm recurrences are provided in the Supplementary Material Section (A).

Roualt *et al*. (2006) showed that windstorm could increase tree vulnerability to drought. The impact of windstorms depending on soil moisture, the consequence of drought (*i.e.* developing root system to uptake water in deeper layer of soil) can provide a better root anchorage and limit the amount of windthrow (Stocker, 1976). Although these two papers show some degree of correlation between the effects of the two risks, there is no clear ecological link between the occurrence of drought and windstorm risks. Consequently, we considered and tested drought and windstorm occurrences independently: In other words, the occurrence of a windstorm does not increase the likelihood of a drought and reversely. In order to test the risks separately and jointly, we simulated the management scenarios under drought risk and/or windstorm risk.

All of these elements resulted in [2 baselines in past climate + (4 scenarios × 2 RCP x (drought risk + windstorm risk + drought and windstorm risks)], which yielded a total of 26 scenarios tested.

2.2 Forest growth simulation and economic analysis

We applied the same methodology as in the paper of Brèteau-Amores *et al*. (2020) from forest growth simulation to the economic analysis. More precisely, we used MATHILDE (Fortin and Manso, 2016), a distance-independent individual-based model, to simulate forest dynamics under past climate, RCP 4.5 and RCP 8.5. Forest growth was simulated using representative fictive stands, created by Brèteau-Amores *et al*. (2020), for each management scenario listed in Table 1. We simulated stands from 30 years of age, because MATHILDE is known to overestimate the mortality of young trees, which leads to inconsistent simulations for even-aged stands younger than 30 years (Fortin and Manso, 2016). Each inventory file contained the tree records of 10 plots of 400 m^2 each. Simulations of scenarios are based on basal area criteria corresponding to the type of management that is currently applied with reference to the silviculture guide. MATHILDE is meant to simulate forest growth in a stochastic fashion based on the Monte Carlo technique. It also uses a built-in harvest algorithm to implement the management scenarios. We computed 1000 realizations for each scenario. Each realization represented the mean evolution of the 10 plots that compose the fictive stand. Each growth realization was processed through a carbon accounting tool (CAT, Pichancourt *et al*., 2018) in order to simulate the corresponding carbon balance. The different realizations of forest growth and carbon balance were then analysed in terms of economic benefits. More technical details on MATHILDE and CAT are provided in the Supplementary Material Section (B).

We performed an economic comparison of the adaptation strategies based on Hartman's land expectation value (LEV). The experimental design allowed to the following comparisons based on Figure 1:

• LEV 1 *vs*. LEV 3 and LEV 1 *vs*. LEV 7: Effect of drought and/or windstorm.

• 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.

Hartman's model makes it possible to consider simultaneously the benefits from harvested timber and from amenities provision, applied here for only one amenity that is carbon sequestration. In France, the final harvest is usually carried out when the trees have reached a particular target diameter or when the density is getting to low. These features are part of the built-in algorithm in MATHILDE. Given that the growth is different in each realization, this implied that the final cut can be triggered before the theoretical cutting-age *T*. For instance, if the growth was much faster than expected, the trees then reach their target diameter sooner. Likewise, if the stand was heavily damaged by a windstorm, a low stem density can trigger the final harvest.

To account for this variable rotation length, we used the adapted formula of Hartman's LEV by Brèteau-Amores *et al.* (2020). In this context of Monte Carlo-based stochastic simulations, the expectation of net present value (NPV) was estimated as follows:

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

where *b* is the index of the realizations (so that *b* = 1, 2,…, *B*), *T* the target rotation length, 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 was then approximated by the so-called double-weighted LEV. The latter allows pooling all the realizations of a Monte Carlo simulation and is weighted by using the mean rotation length for all cases from the second rotation onwards as follows:

$$\hat{E}[LEV(T)] = \frac{1}{B}\sum_{b=1}^{B}\left[NPV\ (\min(H_b, T)) + \frac{\hat{E}[NPV(T)]}{(1+r)^{\min(H_b,T)}}\frac{(1+r)^{\bar{H}(T)}}{(1+r)^{\bar{H}(T)}-1}\right] \tag{2}$$

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, $\bar{H}(T) < T$.

In this setup, the forest owner maximizes the double-weighted LEV with respect to *H(T)*, *i.e.* the forest owner is interested in maximizing the financial net return obtained from timber production and carbon sequestration. The infinite horizon used by this criterion allows comparing management strategies associated with different rotation lengths. It is assumed that the management remains the same over time. This 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 the mean rotation length $\overline{H}(T)$ (eq. 2). The carbon service is rewarded each year depending on changes in carbon stocks. Therefore, harvesting implies that the forest owner pays a tax. These carbon benefits were computed considering the additional carbon stored in the standing timber, the soil and the wood products, without release of the carbon stored in wood products. We used the three carbon costs of 28, 54 and 110 EUR/tC (Brèteau-Amores *et al.*, 2020). They correspond respectively to the average market price coming from certified credits by the French low-carbon label[2], the current French shadow price and the floor value of the social cost. We also considered a null carbon price corresponding to neglected carbon services. Finally, we optimised LEV in the way to compute the optimal stand age at which the even-aged stand is clear-cut or at which the LEV equilibrium is reached for uneven-aged stand.

III- RESULTS

1. Effect of drought and/or windstorm recurrence on timber volume, tree mortality, carbon sequestration and LEV

Table 2 shows the results of the total harvested timber volume, including timber from the thinnings and the final cut for even-aged stands, the total carbon sequestrated in the aboveground, the belowground and in wood products, and in terms of mortality.

First, the total harvested timber volume is higher in beech stand (Baseline_B) than in oak stand (Baseline_O) in current conditions. We can observe the negative effect of drought and/or windstorm risks on the total harvested timber volume, when comparing the baseline (Baseline_B) to the no-adaptation scenario (B_EA). The greater recurrence of drought and/or windstorm as induced between the more optimistic climate scenario (RCP 4.5) and the more pessimistic one (RCP 8.5) decreases this timber volume. This decrease is higher for scenarios in RCP 8.5 than in RCP 4.5, and when combining drought and windstorm than considering both risks separately.

Second, beech stand captures more carbon than oak stand in current conditions. Comparing Baseline_B and B_EA, we can see that drought and/or windstorm risks decrease carbon sequestration. The greater the recurrence of drought and/or windstorm, the higher the decrease of carbon stored. This decrease is higher in RCP 8.5 than in RCP 4.5. Most scenarios under drought risk or under windstorm risk sequestrate more carbon than scenarios under both risks.

Third, the total volume of dead wood is lower in oak stand than in beech stand in current conditions and reversely considering the average mortality rate. We can observe that drought and/or windstorm increase the average mortality rate (except for drought in RCP 4.5) and decrease the total volume of dead wood, comparing Baseline_B and B_EA. The greater recurrence of drought and/or windstorm increases the average mortality rate of the scenarios. It increases also their total volume of dead wood, but not for scenarios under drought risk. This increase is higher in RCP 8.5 than in RCP 4.5, and when combining drought and windstorm than considering both risks separately.

[2] "Label Bas Carbone".

Scenarios			Volume	Carbon	Mortality	
					m^3	%
PAST		Baseline_B	652	219	47	0.69
		Baseline_O	500	194	20	1.13
RCP 4.5	Drought (D)	B_EA	534	189	26	0.62
		Mix50_EA	477	170	14	1.71
		B_UA	703	121	51	0.31
		Mix50_UA	615	99	28	0.95
	Storm (S)	B_EA	528	191	38	0.69
		Mix50_EA	476	169	23	1.72
		B_UA	677	119	68	0.21
		Mix50_UA	602	98	43	0.96
	D+S	B_EA	496	191	45	0.81
		Mix50_EA	453	167	28	1.94
		B_UA	655	119	96	0.42
		Mix50_UA	589	98	56	1.2
RCP 8.5	Drought (D)	B_EA	329	157	16	0.79
		Mix50_EA	360	143	14	1.93
		B_UA	544	109	37	0.41
		Mix50_UA	464	88	23	1.31
	Storm (S)	B_EA	332	155	28	0.75
		Mix50_EA	346	112	54	1.7
		B_UA	502	105	86	0.43
		Mix50_UA	602	98	43	0.96
	D+S	B_EA	304	154	31	1
		Mix50_EA	331	122	56	2.09
		B_UA	479	105	109	0.58
		Mix50_UA	435	85	57	1.28

Legend	
Gain	100%+
	75-100%
	50-75%
	25-50%
	0-25%
Loss	25-0%
	50-25%
	75-50%

Table 2: Total harvested timber volume (thinnings and final cut) in cubic meters, total carbon sequestrated in tons (aboveground, belowground and in wood products), and average yearly mortality rate of trees in percentage (%) and the total mortality in cubic meters (m^3) for each scenario. The colour represents the gain (in blue) or the loss (in red) compared to the baseline (Baseline_B, in white).

Table 3 shows the results of the economic analysis considering four carbon prices for a discount rate of 2% and 3%. As classically done, we performed a sensitivity analysis to evaluate the impact of changes in the discount rate on each scenario analysed. The full table of this analysis is provided in the Supplementary Material Section (C).

Oak stand provides a higher LEV than beech stand in current conditions. Comparing Baseline_B and B_EA, we can see the negative effect of drought and/or windstorm on LEV. The greater recurrence of drought decreases scenarios' LEV, contrary to the recurrence of windstorm that increases scenarios' LEV except for uneven-aged beech stand (B_UA) for low carbon prices (0 and 28 EUR/tC). The greater recurrence of both risks decreases scenarios' LEV for most scenarios.

		Carbon price	0		28		54		110	
		Discount rate	0.02	0.03	0.02	0.03	0.02	0.03	0.02	0.03
PAST		Baseline_B	1670	509	1729	525	1784	542	1902	600
		Baseline_O	6289	2283	6405	2329	6522	2371	6774	2462
RCP 4.5	Drought (D)	B_EA	1259	404	1316	420	1369	435	1484	528
		Mix50_EA	1762	1931	1832	1952	1898	1971	2039	2013
		B_UA	1664	1025	1668	1025	1945	1072	4837	2657
		Mix50_UA	3904	2355	3907	2355	3910	2356	3916	2357
	Storm (S)	B_EA	1170	374	1221	388	1268	401	1371	484
		Mix50_EA	1799	1964	1862	1984	1925	2003	2059	2043
		B_UA	1633	1009	1636	1010	1946	1073	4842	2660
		Mix50_UA	3856	2333	3859	2334	3862	2334	3868	2335
	D+S	B_EA	1182	381	1240	397	1295	413	1412	490
		Mix50_EA	1723	1892	1789	1911	1850	1930	1981	1969
		B_UA	1585	987	1588	987	1986	1095	4919	2702
		Mix50_UA	3758	2286	3761	2286	3764	2286	3770	2287
RCP 8.5	Drought (D)	B_EA	789	304	907	348	1017	389	1253	477
		Mix50_EA	831	313	902	340	976	374	1221	479
		B_UA	1531	978	1532	978	1960	1081	4868	2674
		Mix50_UA	3630	2267	3631	2268	3632	2268	3634	2268
	Storm (S)	B_EA	711	269	791	300	872	330	1046	400
		Mix50_EA	2184	2256	2187	2256	2190	2257	2197	2258
		B_UA	1462	942	1463	943	1983	1093	4914	2699
		Mix50_UA	3935	2377	3938	2377	3941	2377	3947	2378
	D+S	B_EA	717	274	817	312	910	346	1111	421
		Mix50_EA	2125	2224	2132	2226	2138	2228	2152	2231
		B_UA	1398	910	1399	910	2020	1113	4995	2743
		Mix50_UA	3495	2198	3496	2198	3497	2198	3499	2199

Legend	
Gain	100%+
	75-100%
	50-75%
	25-50%
	0-25%
Loss	25-0%
	50-25%
	75-50%

Table 3: Land expectation value in EUR/ha of each scenario for four carbon prices (0, 28, 54 and 110 EUR/tC) and two discount rates (2% and 3%). The colour represents the gain (in blue) or the loss (in red) compared to the baseline (Baseline_B, in white).

2. <u>Effect of adaptation strategies on timber volume, tree mortality, carbon sequestration and LEV</u>

First, the scenario of structure diversification (B_UA) and the one of combined diversification (Mix50_UA) increase the total harvested timber volume compared to the baseline (B_EA) (Table 2). The scenario of composition diversification (Mix50_EA) increases the total harvested timber volume as well in the more severe climate scenario (RCP 8.5), but decreases it in the small-temperature increment scenario (RCP 4.5) compared to B_EA.

Second, the three adaptation scenarios sequestrate less carbon than B_EA (Table 2). The scenario of composition diversification was the least bad scenario and the scenario of combined diversification was the worst one.

Third, only the scenario of structure diversification decreases the average mortality rate compared to the no-adaptation scenario (B_EA) (Table 2). Concerning the total volume of dead wood, the scenario of combined diversification has a positive effect in RCP 4.5 and under only drought risk in RCP 8.5 compared to B_EA. The scenario of structure diversification and the one of combined diversification increase the total volume of dead wood.

Fourth, the three adaptation scenarios provide a higher LEV than B_EA, except for the scenario of composition diversification under drought risk in RCP 8.5 (*i.e.* maladaptation case) (Table 3).

3. Effect of carbon price and discount rate on LEV

In Table 3, the higher the carbon price, the higher the LEV, but the lower the percentage of gain compared to the baseline (B_EA). The higher the discount rate, the lower the LEV. The strategy providing the best economic return depends on these two criteria. Moreover, for a carbon price between 0 and 54 EUR/tC, the scenario of combined diversification is the best strategy, whereas the scenario of composition diversification is the best one under drought and windstorm risks in the more pessimistic climate scenario (RCP 8.5) for a discount rate of 3%. For a carbon price of 110 EUR/tC, the scenario of structure diversification provides the best economic return.

IV- DISCUSSION

1. Diversification can be a good adaptation strategy to reduce drought- and windstorm-induced risks from an economic perspective

Drought and windstorm risks decrease the total harvested timber volume and carbon sequestration, and increase the average mortality rate (Table 2). Both risks have positive and negative effects on LEV (Table 3). These impacts are counterbalanced by adaptation that increases timber production applying a structure (B_UA) or combined (Mix50_UA) diversification and decreases mortality with structure or composition (Mix50_EA) diversification. This is in line with the results showing the positive effect of diversification on forest productivity (Forrester, 2014; Dănescu *et al.*, 2016) and resistance to drought and windstorm (Lebourgeois *et al*., 2013; Mason and Valinger, 2013; Zapater *et al*., 2013; Hanewinkel *et al*., 2014). All adaptation strategies increase the LEV, a result that corroborates our first hypothesis. However, they all show reduced carbon sequestration, which is contrary to the results of Kirby and Potvin (2007) and Lange *et al.* (2015), but in line with those of Brèteau-Amores *et al.* (2020). Nonetheless, trade-offs may be found between the financial balance and the carbon balance, *i.e*. between adaptation and mitigation to climate change, depending on the weight of the following parameters. On the one hand, composition diversification leads to a higher sequestration than the two other strategies, but it provides the best economic return only for a discount rate of 3% in the more pessimistic climate scenario (RCP 8.5). On the other hand, combined diversification provides the best economic return in the more optimistic climate scenario (RCP 4.5), but it is the worst option in terms of carbon sequestration. In between, structure diversification requires a high carbon price to provide the best economic return.

2. Considering both risks impacts the results and recommendations compared to investigating each risk separately

In Table 2, we observe that combining drought and windstorm risks has a greater impact than each risk separately on forest growth and/or carbon sequestration. The combination of both risks can result in multiplicative effect for mortality, but not for timber production and carbon sequestration. More precisely, the average mortality rate of uneven-aged beech stand (B_UA) doubles under drought and windstorm risks in the small-increment temperature scenario (RCP 4.5) for a carbon price of 54 and

110 EUR/tC. In the more severe climate scenario (RCP 8.5), the total volume of dead wood of mixed stands (Mix50_EA/_UA) and B_UA for a carbon price of 0 and 28 EUR/tC doubles or more. This can be explained by the linkage function on which the MATHILDE mortality submodel is based: A windstorm and a drought occurring in the same time interval will cause more mortality than two events occurring in two separate intervals. However, this greater impact on forest growth and/or carbon sequestration does not imply a greater impact on LEV (Table 3).

Another interesting result is that of RCP 4.5 when considering one or two risks: It has no impact on the strategy providing the best economic return (Table 3). In RCP 8.5, the effect of composition diversification (Mix50_EA) is unclear considering only drought risk and can be the worst option (*i.e.* maladaptation). However, composition diversification is a good adaptation strategy under windstorm risk, and even can be the best strategy under both risks. This corroborates the second hypothesis and shows the importance to take into account several risks on this analysis under different climate scenarios. Diversification can also have co-benefits to cope with other disturbances, which should be tested in an economic approach. For example, diversification may have a positive impact to fight against insect pests (Griess and Knoke, 2011; Jactel *et al*., 2017), but it may be not the case when considering this risk with drought and windstorm risks in such analysis.

3. Diversifying the stand as well as combining both strategies lead to synergies

Synergies between adaptation strategies can appear from an economic perspective, implying that the combination of different strategies can be more beneficial for the forest owner than each strategy separately. We tested this hypothesis through the Pretzsch and Schütze framework (2009). The framework and the resulted tables are provided in the Supplementary Material Section (D).

Tables D.1 and D.2 present the results of the tested presence or absence of synergy for each adaptation strategies in terms of total harvested timber volume and LEV respectively. Table D.1 shows that diversifying the stand and combining both strategies can lead to synergies on the total harvested timber volume, which are emphasized by a lower carbon price and a greater recurrence of drought and/or windstorm: From 50% (110 EUR/tC) to 75% (0 EUR/tC) of scenarios in the more optimistic climate scenario (RCP 4.5) show synergies and from 77 to 100% of scenarios in the more pessimistic climate scenario (RCP 8.5). Table D.2 shows that some synergies appear as well as on LEV depending on the discount rate: From 5% (1%) to 100% (4%) in RCP 4.5 and from 8% to 88% in RCP 8.5. These results, corroborating our third hypothesis, can be explain by the complementarity and asynchrony between beech and oak in the resource uptake (Zapater *et al*., 2011) and in tree structure (Jucker *et al*., 2015). Loreau and de Mazancourt (2008; 2013) showed that the more species are asynchronic, the more the stand is stable in time. However, we can observe that synergies are not equal between RCP 4.5 and RCP 8.5, which suggest that asynchrony in need of resources may change with climate change.

As in the paper of Knoke and Seifert (2008), mixed stands (Mix50_EA/_UA) show a higher economic return than pure stands (B_EA/_UA) in RCP 4.5 with a carbon price of 0 and 28 EUR/tC and under windstorm and combined risks in RCP 8.5 with a carbon price between 0 and 54 EUR/tC. Higher LEV from uneven-aged stands (B_UA and Mix50_UA) than even-aged stands (B_EA and Mix50_EA) is observed for a carbon price of 110 EUR/tC, for a carbon price of 54 EUR/tC with a discount rate of 2% in RCP 4.5, and under drought in RCP 8.5. This result is confirmed by Müller *et al*. (2019). Our results show that there is no general pattern as in the literature: The question of the correct combination and mixture is still raised (Mina *et al.*, 2018).

4. Valorising carbon increases forest value

Introducing a carbon price leads to increase LEV (Table 3) showing the importance to consider timber production with the provision of carbon services. Our results show also that the strategy providing the best economic return can depend on carbon price: Structure diversification was the best option under a carbon price of 110 EUR/tC regardless the other parameters. The results corroborate our fourth hypothesis.

Mixed stands may provide other co-benefits such as a higher biodiversity due to a diversified habitat. The complementary vertical rooting patterns between beech and oak (Mason and Valinger, 2013) may also increase the protection to soil erosion due to a better anchorage. An extension of this study can be to integrate these other ecosystem services into the modelling.

CONCLUSION

Severe droughts and windstorms affect forest growth and carbon sequestration. One of the originality of our study was to investigate from an economic perspective these two risks at the same time with independent recurrences but with linked damage. We showed a higher impact on timber production, mortality and carbon sequestration when the two risks were considered jointly instead of separately. Diversification (composition and structure) can be a good strategy to reduce drought- and windstorm-induced risk and leads to some synergies in terms of timber productivity and economic value. More precisely, diversifying only the stand structure or combined with composition diversification increases timber production. Diversifying the stand structure or the composition tends to decrease mortality. Diversification increases LEV, but decreases carbon storage: Trade-offs can be found between the financial balance and the carbon balance depending on the carbon price, the discount rate and the climate scenario considered. The heterogeneity of our results showed the importance to consider different criteria, climate scenarios, and different ecosystem services. Integrating other species or provenances on this analysis to test different diversifications, as well as integrating other ecosystem services and other risks should improve this analysis.

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SUPPLEMENTARY MATERIAL

A. Windstorm frequencies computation

To compute windstorm frequencies, we used daily meteorological data from Météo France for the past climate, the RCP 4.5 and the RCP 8.5. Because severe windstorms occur during autumn and winter (Valinger and Fridman, 2011), we considered the maximum daily wind gust at 10 m from September to February for 20 SAFRAN points. We randomly selected these points within the Grand-Est region to integrate spatial variability: 12413; 13127; 13240;1 3251; 13405; 13829;1 4124; 14243; 14252; 14522; 14544; 14846; 14964; 15097; 15125; 15256; 15547; 15824; 15959; 16533. A given year was defined as having an exceptional windstorm when one of the 20 points had a maximum daily wind gust over

40 m s^{-1}, which corresponds to the characteristics of severe windstorms such as Lothar in 1999 (Bonnesoeur *et al.*, 2013).

B. MATHILDE and CAT[3]

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 B.1.

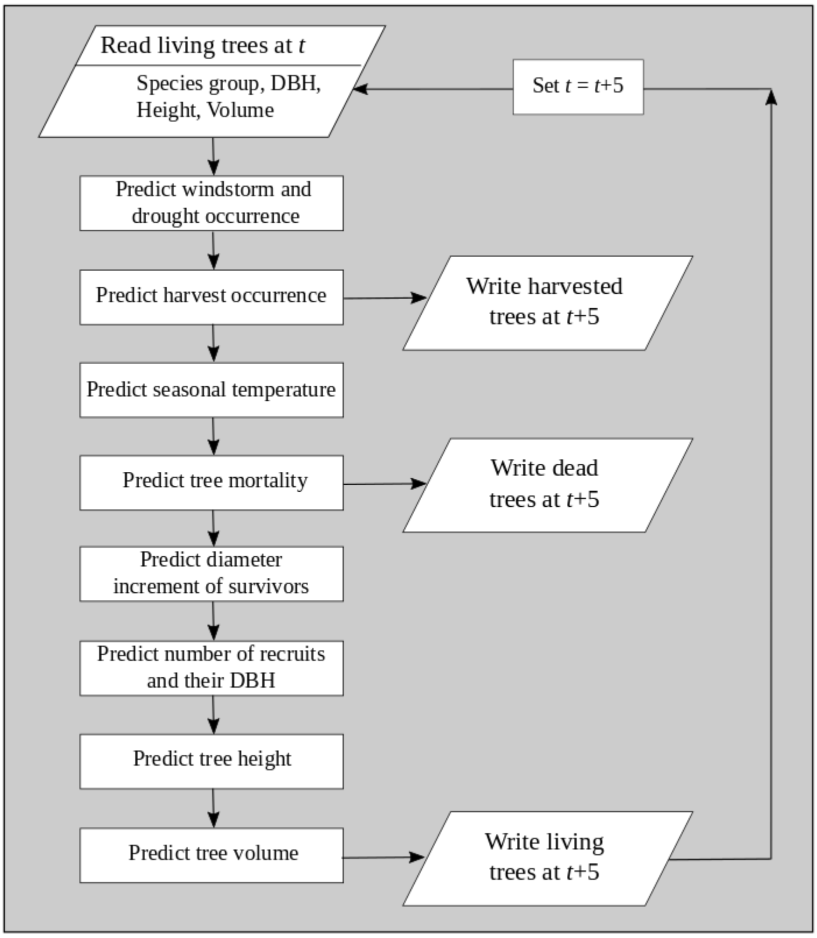

Figure B.1: Flowchart of the sub-models composing MATHILDE.

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 or a windstorm occurs during the period.

[3] Text similar to Brèteau-Amores *et al*. (2020).

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). The management scenarios is implement using MATHILDE's built-in harvest algorithm based on bounds of basal area. Whenever the upper bound is crossed, the harvesting is triggered and the trees are harvesting until the lower bound is reached. The bounds were assumed to reproduce the management of even-aged and uneven-aged stands and are shown in Table B.2.

Management scenario	Stand age (years)	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 B.2: Basal area bounds (m^2ha^{-1}*) that were used in the different management scenarios (source: CRPF). The bounds are age dependent for even-aged management scenarios. n/a: not applicable.*

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 (CH_4) 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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C. Sensitivity analysis of the discount rate on LEV

Carbon price			0				28				54				110			
Discount rate			0.01	0.02	0.03	0.04	0.01	0.02	0.03	0.04	0.01	0.02	0.03	0.04	0.01	0.02	0.03	0.04
PAST		Baseline_B	7042	1670	509	176	7309	1729	525	185	7557	1784	542	194	8092	1902	600	223
		Baseline_O	23515	6289	2283	900	23515	6405	2329	917	24022	6522	2371	934	24578	6774	2462	969
RCP 4.5	Drought (D)	B_EA	5491	1259	404	143	5586	1316	420	159	5674	1369	435	178	5948	1484	528	218
		Mix50_EA	1129	1762	1931	1980	1322	1832	1952	1987	1569	1898	1971	1993	2152	2039	2013	2006
		B_UA	2502	1664	1025	642	2534	1668	1025	642	4664	1945	1072	660	11647	4837	2657	1629
		Mix50_UA	6611	3904	2355	1459	6643	3907	2355	1459	6673	3910	2356	1459	6815	3916	2357	1459
	Storm (S)	B_EA	4934	1170	374	132	5022	1221	388	147	5103	1268	401	163	5531	1371	484	198
		Mix50_EA	1188	1799	1964	2013	1358	1862	1984	2020	1580	1925	2003	2026	2130	2059	2043	2038
		B_UA	2424	1633	1009	634	2457	1636	1010	634	4666	1946	1073	660	11658	4842	2660	1631
		Mix50_UA	6476	3856	2333	1449	6507	3859	2334	1449	6536	3862	2334	1449	6665	3868	2335	1449
	D+S	B_EA	5092	1182	381	134	5200	1240	397	148	5301	1295	413	165	5619	1412	490	203
		Mix50_EA	1046	1723	1892	1941	1247	1789	1911	1947	1494	1850	1930	1953	2034	1981	1969	1965
		B_UA	2297	1585	987	622	2328	1588	987	622	4763	1986	1095	674	11843	4919	2702	1656
		Mix50_UA	6208	3758	2286	1424	6238	3761	2286	1424	6267	3764	2286	1424	6328	3770	2287	1424
RCP 8.5	Drought (D)	B_EA	2607	789	304	127	3011	907	348	145	3385	1017	389	161	4192	1253	477	205
		Mix50_EA	2784	831	313	129	3030	902	340	141	3300	976	374	160	3967	1221	479	204
		B_UA	2027	1531	978	623	2037	1532	978	623	4700	1960	1081	665	11720	4868	2674	1639
		Mix50_UA	5482	3630	2267	1430	5492	3631	2268	1430	5502	3632	2268	1430	5888	3634	2268	1430
	Storm (S)	B_EA	2398	711	269	111	2667	791	300	124	2934	872	330	135	3543	1046	400	190
		Mix50_EA	1753	2184	2256	2270	1772	2187	2256	2270	1789	2190	2257	2270	1825	2197	2258	2270
		B_UA	1865	1462	942	604	1875	1463	943	604	4755	1983	1093	673	11831	4914	2699	1655
		Mix50_UA	6657	3935	2377	1474	6689	3938	2377	1474	6717	3941	2377	1474	6949	3947	2378	1474
	D+S	B_EA	2384	717	274	116	2726	817	312	131	3045	910	346	145	3730	1111	421	182
		Mix50_EA	1699	2125	2224	2248	1719	2132	2226	2248	1737	2138	2228	2249	1777	2152	2231	2249
		B_UA	1717	1398	910	586	1726	1399	910	586	4845	2020	1113	685	12028	4995	2743	1682
		Mix50_UA	5135	3495	2198	1391	5146	3496	2198	1391	5156	3497	2198	1391	5285	3499	2199	1391

Table C.1: Land expectation value in EUR/tC of each scenario for four carbon prices (0, 28, 54 and 110 EUR/tC*) and four discount rates (1, 2, 3 and 4%).*

D. Synergy analysis of adaptation strategies[4]

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.

[4] Text similar to Brèteau-Amores *et al*. (2020).

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 harvested timber volume and the land expectation value. The results are presented in Tables D.1 and D.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.

		Carbon price	0				28				54				110			
		Discount rate	0.01	0.02	0.03	0.04	0.01	0.02	0.03	0.04	0.01	0.02	0.03	0.04	0.01	0.02	0.03	0.04
RCP 4.5	Drought (D)	Mix50	0	0	0	1	0	0	0	1+	0	0	0	1+	0	0	1+	1+
		B_FI	1+	1+	1+	1+	1+	1+	1+	1+	0	0	0	0	0	0	0	0
		Mix50_FI	1	1	1	1	1	1	1	1	1+	1+	1+	1+	1+	1+	1+	1+
	Storm (S)	Mix50	0	0	1	1	0	0	1	1+	0	0	1	1+	0	0	1+	1+
		B_FI	1+	1+	1+	1+	1+	1+	1+	1+	0	0	0	0	0	0	0	0
		Mix50_FI	1	1	1	1	1	1	1	1	1+	1+	1+	1+	1+	1+	1+	1+
	D+S	Mix50	1	0	0	1	0	0	1	1+	0	0	1	1+	0	0	1+	1+
		B_FI	1+	1+	1+	1+	1+	1+	1+	1+	0	0	0	0	0	0	0	0
		Mix50_FI	1	1	1	1+	1	1	1	1+	1+	1+	1+	1+	1+	1+	1+	1+
RCP 8.5	Drought (D)	Mix50	1+	1+	1+	1+	1+	1+	1+	0	1+	1+	0	0	0	0	0	1
		B_FI	1+	1+	1+	1+	1+	1+	1+	1+	0	0	0	0	0	0	0	1
		Mix50_FI	1	1	1	1	1	1	1	1	1+	1	1	1	1+	1	1	1
	Storm (S)	Mix50	1+	1+	1+	1+	1+	1+	1+	1+	1+	1+	1+	1+	1+	1+	1+	1+
		B_FI	1+	1+	1+	1+	1+	1+	1+	1+	1	1	1	1	0	0	1	1+
		Mix50_FI	1+	1+	1+	1+	1+	1+	1+	1+	1+	1+	1+	1+	1+	1+	1+	1+
	D+S	Mix50	1+	1+	1+	1+	1+	1+	1+	1+	1+	1+	1+	1+	1+	1+	1+	1+
		B_FI	1+	1+	1+	1+	1+	1+	1+	1+	1+	1+	1+	1+	1+	1+	1+	1+
		Mix50_FI	1	1	1	1+	1	1	1	1+	1+	1+	1+	1+	1+	1+	1+	1+

Table D.1: Results of the tested synergy of mixed stands in total harvested timber volume 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%).

		Carbon price	0.01				0.02				0.03				0.04			
		Discount rate	0	28	54	110	0	28	54	110	0	28	54	110	0	28	54	110
RCP 4.5	Drought (D)	Mix50	0	0	0	0	0	0	0	0	1	1	1	1	1+	1+	1+	1+
		B_FI	0	0	0	0	0	0	0	1	1	1	1	1+	1	1	1	1+
		Mix50_FI	0	0	0	0	1	1	0	0	1	1	1	1	1	1	1	1
	Storm (S)	Mix50	0	0	0	0	0	0	0	0	1	1	1	1	1+	1+	1+	1+
		B_FI	0	0	0	1	0	0	0	1	1	1	1	1+	1	1	1	1+
		Mix50_FI	0	0	0	0	1	1	1	0	1	1	1	1	1	1	1	1
	D+S	Mix50	0	0	0	0	0	0	0	0	1	1	1	1	1+	1+	1+	1+
		B_FI	0	0	0	1	0	0	0	1	1	1	1	1+	1	1	1	1+
		Mix50_FI	0	0	0	0	0	0	0	0	1	1	1	1	1	1+	1+	1+
RCP 8.5	Drought (D)	Mix50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		B_FI	0	0	0	1	0	0	0	1	1	1	1	1+	1	1	1	1+
		Mix50_FI	0	0	0	0	1	1	1	0	1	1	1	1	1	1	1	1
	Storm (S)	Mix50	0	0	0	0	0	0	0	0	1+	1+	1+	1+	1+	1+	1+	1+
		B_FI	0	0	0	1	1	0	1	1+	1	1	1	1+	1+	1+	1+	1+
		Mix50_FI	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
	D+S	Mix50	0	0	0	0	0	0	0	0	1+	1+	1+	1+	1+	1+	1+	1+
		B_FI	0	0	0	1	0	0	1	1	1	1	1	1+	1	1	1	1+
		Mix50_FI	0	0	0	0	1	1	1	0	1	1	1	1	1+	1+	1+	1+

Table D.2: Results of the tested synergy of mixed stand on land expectation value with a carbon price of 0, 28, 54, 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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