Is Diversification a Suitable Option to Reduce Drought-Induced Risk of Forest Dieback? An Economic Approach Focused on Carbon Accounting

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Electronic Supplementary Material

1 Definition of drought occurrences

Drought occurrence events were defined on the basis of daily soil water content as computed by the daily forest water balance model, BILJOU©.

Water balance computations were performed for a representative beech stand of the Grand-Est region with an average site fertility (i.e., available soil water content of 100 mm and leaf area index of 5.5) for the reference climate, RCP 4.5 and RCP 8.5 (data from the ARPEGE model). More precisely, we hypothesized that (i) the soil properties, especially soil extractable water and soil retention curves, and (ii) canopy leaf area index (since management scenarios do not change stand density) would be unchanged in the future. Only climatic forcing was changed according to the RCPs scenario.

The BILJOU© model requires daily climatic input data to compute potential evapotranspiration, including both radiative and convective terms (global radiation, air humidity, wind speed, air temperature) as the driver for stand transpiration requirements. The potential increase in vapor pressure deficit due to temperature increment in climate change scenarios is then taken into account. Daily rainfall is used to compute rainfall interception and throughfall that refills soil water content. Depending on the relative soil water content, canopy transpiration is reduced thanks to a decrease in canopy conductance. A complete description of the model is available in Granier et al. [5] and a flow chart in Granier et al. [4].

2 Simulation of forest management

Simulations were performed as follows. First, inventory data were loaded. Each inventory file contained the tree records of ten 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 (i.e., thinning) 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 4). 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. In some cases, natural disturbances cause too much damage for the stand to recover. To consider this, we applied a triggering condition whereby if the number of standing trees at any point in time goes below the threshold of 100 trees per hectare, the stand is not deemed viable and it is automatically harvested.

Table 4 Basal area bounds (m^2/ha) that were used in the different management scenarios (source: CRPF[1]). The bounds are age-dependent for even-aged management scenarios. n/a: not applicable

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

3 Creation of fictitious stands

We created a fictitious stand for each management scenario. More precisely, the mixed stand of beech and oak used has the same density as the monoculture stand: the introduced species replaces part of the current species in the stand (25, 50 or 75%) without any change in the leaf area index.

Concerning diversification by structure, the stand is defined as a homogeneous uneven-aged stand according to the structure triangle used in the French forest management. It corresponds to the share of stand basal area of 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.

4 MATHILDE and CAT

MATHILDE is an individual-based model that simulates forest dynamics [2]. It 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 submodels, which are illustrated in Fig. 2.

[1] Regional Center for Privately-Owned Forests.

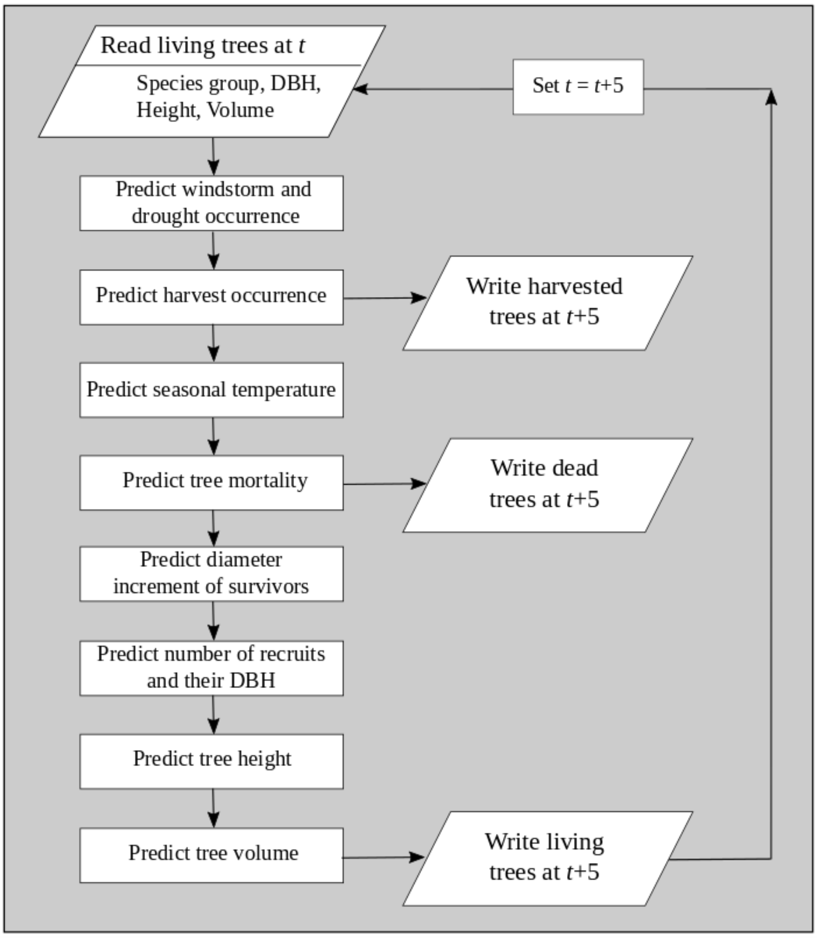

Fig. 2 Flowchart of the submodels composing MATHILDE

The climate submodel is fitted to data from the SAFRAN model over the 1958-2012 period. It predicts the mean seasonal temperature over a period, depending on the initial year of the period and the occurrence of extreme drought events during the period. The growing season temperature is controlled by a parameter that drives its increase. This parameter depends on the given climate scenario and changes when an extreme drought event occurs during the period.

The mortality submodel 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 extreme drought events, windstorm and harvesting [8].

The diameter-increment submodel predicts the increment of a given tree over a period [7]. 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 submodel of tree recruitment predicts the number of trees that cross the threshold of 7.5 cm for each species. This submodel is enabled only in the case of uneven-aged management. The explanatory variables are the all-species basal area as well as the basal area of the species. In addition to the aforementioned submodels, MATHILDE also includes a model of height-diameter relationships [3].

MATHILDE is implemented on the CAPSIS platform [1], which contains a carbon accounting tool (CAT, [9]). CAT allows for the representation of complex emission life cycles inherent to managed forests. It takes the main issues related to carbon accounting tools into account, 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. Simulations are run by default under global warming potential factors of the fifth assessment report on climate change [6]. Results are exported in carbon units with the probability level of the confidence intervals equal to 0.95 by default.

5 Approximation of the LEV by the doubly-weighted LEV

5.1 Derivation of the estimators of LEV

The estimator of the $\hat{E}[NPV(T)]$ is denoted as follows:

$$\hat{E}[NPV(T)] = \frac{1}{Z}\sum_{z=1}^{Z} NPV\ (min(H_z, T))\,. \tag{1}$$

$\hat{E}[NPV(T)]$	Expectation of the net present value in EUR/ha for the target rotation length T
H_z	Age at which the exogenous harvesting condition was reached for realization z
$NPV(T)$	Net present value in EUR/ha for the target rotation length T
T	Target rotation length (i.e., the harvest age) in years
z	Index to denote any given realization
Z	Total number of realizations

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

$$LEV(T) = \sum_{j=0}^{+\infty} \frac{NPV(T)}{(1+r)^{j.T}}\,. \tag{2}$$

j	Rotation number
$LEV(T)$	Land expectation value in EUR/ha for the target rotation length T
$NPV(T)$	Net present value in EUR/ha for the target rotation length T
r	Discount rate
T	Target rotation length (i.e., the harvest age) in years

We only have Z Monte Carlo simulations, but we need an infinite number of revolutions to be able to calculate a LEV. In order to calculate an estimator of the LEV, we will therefore assume that we choose an infinite number of times among the Z Monte Carlo simulations. Finally, we can write exactly:

$$\hat{E}[LEV(T)] = \frac{1}{Z}\sum_{z=1}^{Z}\left[NPV\ (min(H_z,T)) + \frac{1}{Z}\cdot\sum_{z'=1}^{Z}\left[\frac{NPV\ (min(H_{z'},T))}{(1+r)^{H_z}} + \frac{1}{Z}\cdot\sum_{z''=1}^{Z}\left[\frac{NPV\ (min(H_{z''},T))}{(1+r)^{H_z+H_{z'}}} + \cdots\right]\right]\right]. \quad (3)$$

$\hat{E}[LEV(T)]$	Expectation of the land expectation value in EUR/ha for the target rotation length T
H_z	Age at which the exogenous harvesting condition was reached for realization z
$NPV(T)$	Net present value in EUR/ha for the target rotation length T
T	Target rotation length (i.e., the harvest age) in years
z	Index to denote any given realization (with z realizations from the first rotation, z' from the second one, z'' from the third one…)
Z	Total number of realizations

At first sight, it seems that it is possible to aggregate (using the properties of geometric series) to find a compact expression for the expected LEV. However, a simulation has to be performed for each rotation length. In other words, the data from the first NPV sum is not the same as the data from the second sum. Therefore, this type of aggregation is not possible.

If we study each of the terms of this sum, we see that the first term is equal to Eq. 1:

$$\frac{1}{Z}\sum_{z=1}^{Z} NPV\ (min(H_z,T)) = \hat{E}[NPV(T)]. \quad (4)$$

$\hat{E}[NPV(T)]$	Expectation of the net present value in EUR/ha for the target rotation length T
H_z	Age at which the exogenous harvesting condition was reached for realization z
$NPV(T)$	Net present value in EUR/ha for the target rotation length T
T	Target rotation length (i.e., the harvest age) in years
z	Index to denote any given realization
Z	Total number of realizations

For the second term, after separating the two sums, we obtain:

$$\frac{1}{Z^2}\sum_{z=1}^{Z}\sum_{z'=1}^{Z}\frac{NPV\ (min(H_{z'},T))}{(1+r)^{H_z}} = \left[\frac{1}{Z}\sum_{z=1}^{Z}\frac{1}{(1+r)^{H_z}}\right]\cdot\left[\frac{1}{Z}\sum_{z'=1}^{Z} NPV\ (min(H_{z'},T))\right]$$

$$= \left[\frac{1}{(1+r)^{H}}\right].\hat{E}[NPV(T)], \quad (5)$$

$$with\ H\ so\ that \left[\frac{1}{(1+r)^{H}}\right] = \left[\frac{1}{Z}\sum_{z=1}^{Z}\frac{1}{(1+r)^{H_z}}\right].$$

$\hat{E}[NPV(T)]$	Expectation of the net present value in EUR/ha for the target rotation length T
H_z	Age at which the exogenous harvesting condition was reached for realization z
$NPV(T)$	Net present value in EUR/ha for the target rotation length T
r	Discount rate

T	Target rotation length (i.e., the harvest age) in years
z	Index to denote any given realization (with z realizations from the first rotation, z' from the second one, z'' from the third one…)
Z	Total number of realizations

We therefore obtain the average of the NPV, discounted by the estimator of the average of the discountings.

For the third term, we obtain:

$$\frac{1}{Z^3}\sum_{z=1}^{Z}\sum_{z'=1}^{Z}\sum_{z''=1}^{Z}\frac{NPV\ (min(H_{z''}\ ,T))}{(1+r)^{H_z}} = \left[\frac{1}{Z}\sum_{z=1}^{Z}\frac{1}{(1+r)^{H_z}}\right]\cdot\left[\frac{1}{Z}\sum_{z'=1}^{Z}\frac{1}{(1+r)^{H_{z'}}}\right]\cdot\left[\frac{1}{Z}\sum_{z''=1}^{Z}NPV\ (min(H_{z''},T))\right]$$

$$= \left[\frac{1}{(1+r)^{H}}\right]^2 \hat{E}[NPV(T)]\ . \tag{6}$$

$\hat{E}[NPV(T)]$	Expectation of the net present value in EUR/ha for the target rotation length T
H_z	Age at which the exogenous harvesting condition was reached for realization z
$NPV(T)$	Net present value in EUR/ha for the target rotation length T
r	Discount rate
T	Target rotation length (i.e., the harvest age) in years
z	Index to denote any given realization (with z realizations from the first rotation, z' from the second one, z'' from the third one…)
Z	Total number of realizations

Iterating this process *ad infinitum*, we obtain:

$$\hat{E}[LEV(T)] = \sum_{i=1}^{+\infty}\hat{E}[NPV(T)]\,.\left[\frac{1}{(1+r)^{H}}\right]^{j-1}$$

$$= \hat{E}[NPV(T)].\sum_{i=0}^{+\infty}\left[\frac{1}{(1+r)^{H}}\right]^{j}$$

$$= \hat{E}[NPV(T)].\frac{(1+r)^{H}}{(1+r)^{H}-1}\ . \tag{7}$$

$\hat{E}[NPV(T)]$	Expectation of the net present value in EUR/ha for the target rotation length T
$\hat{E}[LEV(T)]$	Expectation of the land expectation value in EUR/ha for the target rotation length T
j	Rotation number
r	Discount rate
T	Target rotation length (i.e., the harvest age) in years

5.2 Numerical intuition and approximation of LEV

In our context of Monte Carlo-based stochastic simulations, there are Z^j possible LEVs for a given scenario (where Z is the total number of realizations and j the rotation number). Indeed, after the first rotation is terminated (at either age H_z or age T), a second rotation begins, etc. (Eq. 3).

Let's look at an example to better understand the complexity with only two realizations (z_1, z_2) and three rotation periods.

In this example, there are eight possible LEVs for a given scenario according to the position of each realization in the time line (first rotation - second rotation – third rotation), as follows:

$z_1 - z_1 - z_1$	$z_2 - z_1 - z_1$
$z_1 - z_2 - z_1$	$z_2 - z_2 - z_1$
$z_1 - z_1 - z_2$	$z_2 - z_1 - z_2$
$z_1 - z_2 - z_2$	$z_2 - z_2 - z_2$

For example, the LEV's calculation for the combination "$z_1 - z_2 - z_1$" will be as follows:

$$LEV(T) = NPV\ (min(H_1, T)) + \frac{NPV(min(H_2, T))}{(1+r)^{min(H_1,T)}} + \frac{NPV\ (min(H_1, T))}{(1+r)^{min(H_1,T)+min(H_2,T)}}\ . \tag{8}$$

H_1	Age at which the exogenous harvesting condition was reached for realization of the first rotation z_1
H_2	Age at which the exogenous harvesting condition was reached for realization of the second rotation z_2
$LEV(T)$	Land expectation value in EUR/ha for the target rotation length T
$NPV(T)$	Net present value in EUR/ha for the target rotation length T
r	Discount rate
T	Target rotation length (i.e., the harvest age) in years

This example shows the impossibility of calculating the infinite possibilities of LEV for each scenario (i.e., with 1000 realizations and, above all, with an infinite number of rotations). For this reason, we have approximated LEV by integrating an average rotation length $\overline{H}(T)$ from the second rotation, defined as:

$$\hat{E}[LEV(T)] = \frac{1}{Z}\sum_{z=1}^{Z}\left[NPV\ (min(H_z, T)) + \frac{\hat{E}[NPV(T)]}{(1+r)^{min(H_z,T)}}\frac{(1+r)^{\overline{H}(T)}}{(1+r)^{\overline{H}(T)}-1}\right], \tag{9}$$

$$where\ \overline{H}(T) = \sum_{z=1}^{Z}\frac{\min(H_z, T)}{Z}. \tag{10}$$

$\hat{E}[LEV(T)]$	Expectation of the land expectation value in EUR/ha for the target rotation length T
$\hat{E}[NPV(T)]$	Expectation of the net present value in EUR/ha for the target rotation length T
H_z	Age at which the exogenous harvesting condition was reached for realization z
$\bar{H}(T)$	Mean of the final harvest age in years for the target rotation length T
$NPV(T)$	Net present value in EUR/ha for the target rotation length T
r	Discount rate
T	Target rotation length (i.e., the harvest age) in years
z	Index to denote any given realization
Z	Total number of realizations

In other words, we are doing the calculation for the combination "$z_1 - z_{mean} - z_{mean}$ …".

If the number of realizations is large enough, then the mean harvest age $\bar{H}(T)$ is representative of the theoretical mean, which allows us to compute the mean economic payoff-to-go after the first rotation as $\widehat{\mathrm{E}}[\mathrm{NPV(T)}].(1+\mathrm{r})^{\bar{\mathrm{H}}(\mathrm{T})}/((1+\mathrm{r})^{\bar{\mathrm{H}}(\mathrm{T})}-1)$. Indeed, if we computed:

$$\hat{E}[LEV(T)] = \frac{1}{Z}\sum_{z=1}^{Z}\left[NPV\ (min(H_z, T)) + \frac{\hat{E}[NPV(T)]}{(1+r)^{\bar{H}(T)}-1}\right], \tag{11}$$

$\hat{E}[LEV(T)]$	Expectation of the land expectation value in EUR/ha for the target rotation length T
$\hat{E}[NPV(T)]$	Expectation of the net present value in EUR/ha for the target rotation length T
H_z	Age at which the exogenous harvesting condition was reached for realization z
$\bar{H}(T)$	Mean of the final harvest age in years for the target rotation length T
z	Index to denote any given realization
Z	Total number of realizations
$NPV(T)$	Net present value in EUR/ha for the target rotation length T
r	Discount rate
T	Target rotation length (i.e., the harvest age) in years

the approximation error between Eq. 9 and Eq. 11 is under 1% and thus negligible.

6 Land expectation value and sensitivity analysis of discount rate

We performed a sensitivity analysis of the discount rate. The results are presented in Table 5 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 6.

Table 5 Scenario codes ranked from the highest economic return to the lowest one for each climate scenario (reference, 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 (W) (top left) or with carbon storage (W+C) for a carbon value of 28 EUR/tC (top right), 54 EUR/tC (bottom left) and 110 EUR/tC (bottom right). Each management scenario corresponds to a color

W	0.01	0.02	0.03	0.04
REF.	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

W+C_28	0.01	0.02	0.03	0.04
REF.	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

W+C_54	0.01	0.02	0.03	0.04
REF.	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

W+C_110	0.01	0.02	0.03	0.04
REF.	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 6 Variation of LEV (in terms of percentage) 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 (W) (top left) or with carbon storage (W+C) for a carbon value of 28 EUR/tC (top right), 54 EUR/tC (bottom left) and 110 EUR/tC (bottom right)

W	**Scenarios**	**0.01**	**0.02**	**0.03**	**0.04**
REF.	Baseline_B	-	-	-	-
	Baseline_O	211±919	251±234	317±74	376±26
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±78	32±30	154±14	349±8
	Mix25_UA	73±466	290±134	622±64	1157±35
	Mix50_UA	20±341	210±102	483±49	920±27
	Mix75_UA	-40±234	92±74	271±37	552±20
RCP 8.5	B_EA	-	-	-	-
	Mix25_EA	-33	177	643	1691
	Mix50_EA	7±366	5±96	3±32	2±12
	Mix75_EA	12±329	-5±88	-17±30	-24±11
	B_UA	-22±77	94±31	222±15	391±8
	Mix25_UA	230±427	480±124	823±59	1283±32
	Mix50_UA	110±341	360±100	646±49	1026±26
	Mix75_UA	-7±220	179±69	369±35	612±19

$W+C_{28}$	**Scenarios**	**0.01**	**0.02**	**0.03**	**0.04**
REF.	Baseline_B	-	-	-	-
	Baseline_O	205±944	244±243	313±76	362±26
RCP 4.5	B_EA	-	-	-	-
	Mix25_EA	-78±20	31±4	337±1	1075
	Mix50_EA	-76±21	39±4	365±1	1150
	Mix75_EA	-76±18	38±3	359±1	1133
	B_UA	-54±78	27±30	144±14	304±8
	Mix25_UA	77±472	274±135	595±64	1030±35
	Mix50_UA	21±346	197±103	461±49	818±27
	Mix75_UA	-40±239	84±75	257±37	486±20
RCP 8.5	B_EA	-	-	-	-
	Mix25_EA	-41±14	141±2	549	1468
	Mix50_EA	1±368	-1±96	-2±32	-3±12
	Mix75_EA	-2±331	-17±88	-27±30	-33±11
	B_UA	-32±77	69±31	181±15	330±8
	Mix25_UA	195±433	405±124	706±59	1111±32
	Mix50_UA	82±346	300±101	552±49	886±26
	Mix75_UA	-19±225	143±69	309±35	523±19

$W+C_{54}$	**Scenarios**	**0.01**	**0.02**	**0.03**	**0.04**
REF.	Baseline_B	-	-	-	-
	Baseline_O	199±957	241±246	308±77	350±26
RCP 4.5	B_EA	-	-	-	-
	Mix25_EA	-74±44	30±9	326±2	953
	Mix50_EA	-72±43	39±9	353±2	1020
	Mix75_EA	-72±37	37±7	347±2	1004
	B_UA	-16±65	42±26	146±13	271±7
	Mix25_UA	79±478	259±137	571±64	910±35
	Mix50_UA	20±351	186±103	442±49	720±27
	Mix75_UA	-40±244	77±75	245±37	424±20
RCP 8.5	B_EA	-	-	-	-
	Mix25_EA	-48±29	115±5	481±1	1312
	Mix50_EA	-3±369	-4±96	-4±32	-1±12
	Mix75_EA	-13±333	-26±89	-35±30	-40±11
	B_UA	39±66	93±27	178±14	313±7
	Mix25_UA	170±439	351±125	622±59	991±32
	Mix50_UA	63±351	257±102	483±49	788±26
	Mix75_UA	-28±229	117±70	266±35	461±19

$W+C_{110}$	**Scenarios**	**0.01**	**0.02**	**0.03**	**0.04**
REF.	Baseline_B	-	-	-	-
	Baseline_O	186±987	234±251	284±78	322±27
RCP 4.5	B_EA	-	-	-	-
	Mix25_EA	-65±95	30±21	259±5	767±1
	Mix50_EA	-64±90	37±20	281±5	820±1
	Mix75_EA	-64±78	36±16	276±3	808±1
	B_UA	96±45	226±15	403±8	647±5
	Mix25_UA	79±490	232±140	453±64	725±35
	Mix50_UA	15±361	164±105	346±50	569±27
	Mix75_UA	-43±256	64±77	184±37	328±20
RCP 8.5	B_EA	-	-	-	-
	Mix25_EA	-57±62	75±11	374±2	1009
	Mix50_EA	-5±373	-3±97	0±32	0±12
	Mix75_EA	-29±336	-39±89	-38±30	-39±11
	B_UA	180±45	289±16	461±8	700±5
	Mix25_UA	138±452	266±128	488±59	757±32
	Mix50_UA	40±362	190±104	375±49	598±26
	Mix75_UA	-41±242	76±72	199±35	341±19

7 Synergy analysis of adaptation strategies

From an economic perspective, the combination of different strategies (or species) can be more beneficial for the forest owner than each strategy (species) separately, i.e., synergies between adaptation strategies (or species) can appear. According to Pretzsch and Schütze [10], two levels of synergies exist.

First, overyielding is defined as a higher observed parameter P_{mix} in the mixed stand than the expected parameter $\widehat{P_{mix}}$ [10], 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 a monoculture stand.

Transgressive overyielding of the mixed stand can then be observed, when the observed parameter P_{mix} is higher than the parameter of both species in a monoculture stand (P_1 and P_2) [10], i.e.,

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

The tested parameters were the total volume harvested and the land expectation value. In order to test the presence of synergies, even-aged and uneven-aged oak stands were simulated. The results are presented in Tables 7 and 8. Overyielding is represented by a coefficient of 1 and transgressive overyielding by a coefficient of 1+. An absence of overyielding is represented by a coefficient of 0.

Table 7 Results of the tested synergy of mixed stands in terms of total volume harvested characterized 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%)

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 8 Results of the tested synergy of mixed stands in terms of LEV considering only timber production (W) or with carbon storage for a carbon value of 28 EUR/tC, 54 EUR/tC and 110 EUR/tC, characterized 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	**W**	**28**	**54**	**110**	**W**	**28**	**54**	**110**	**W**	**28**	**54**	**110**	**W**	**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

References

[1] Dufour-Kowalski, S., Courbaud, B., Dreyfus, P., Meredieu, C., and De Coligny, F. (2012). Capsis: an open software framework and community for forest growth modelling. *Annals of Forest Science*, *69*(2), 221-233. https://doi.org/10.1007/s13595-011-0140-9

[2] Fortin, M., and Manso, R. (2016). *Le simulateur MATHILDE dans CAPSIS*. Available at: http://capsis.cirad.fr/capsis/_media/mathildeuserguidefr.pdf

[3] Fortin, M., Van Couwenberghe, R., Perez, V., and Piedallu, C. (2019b). Evidence of climate effects on the height-diameter relationships of tree species. *Annals of Forest Science*, *76*(1), 1. https://doi.org/10.1007/s13595-018-0784-9

[4] Granier, A., Badeau, V., Ehinger, G., Maurice, D., Grosdidier, M., Robert, N., and Bréda, N. (2016). Modelling water balance of forests with BILJOU©. In: Forest and the water cycle: quantity, quality, management. Lachassagne, P., and Laforgue, M. (eds.). Cambridge Scholars Publishing. Chapter 2.4, 136-152. ISBN: 978-1-4438-8825-7

[5] Granier, A., Bréda, N., Biron, P., and Villette, S. (1999). A lumped water balance model to evaluate duration and intensity of drought constraints in forest stands. *Ecological modelling*, *116*(2-3), 269-283. https://doi.org/10.1016/S0304-3800(98)00205-1

[6] IPCC (2013a). *Climate change 2013: The physical science basis. Contribution of working group I to the fifth assessment report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., Qin, D., Plattner, G.K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P.M. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

[7] Manso, R., Morneau, F., Ningre, F., and Fortin, M. (2015a). Effect of climate and intra- and inter-specific competition on diameter increment in beech and oak stands. *Forestry: An International Journal of Forest Research*, *88*, 540-551. https://doi.org/10.1093/forestry/cpv020

[8] Manso, R., Morneau, F., Ningre, F., and Fortin, M. (2015b). Incorporating stochasticity from extreme climatic events and multi-species competition relationships into single-tree mortality models. *Forest Ecology and Management*, *354*, 243-253. https://doi.org/10.1016/j.foreco.2015.06.008

[9] Pichancourt, J.B., Manso, R., Ningre, F., and Fortin, M. (2018). A carbon accounting tool for complex and uncertain greenhouse gas emission life cycles. *Environmental Modelling & Software*, *107*, 158-174. https://doi.org/10.1016/j.envsoft.2018.06.005

[10] Pretzsch, H., and Schütze, G. (2009). Transgressive overyielding in mixed compared with pure stands of Norway spruce and European beech in Central Europe: evidence on stand level and explanation on individual tree level. *European Journal of Forest Research, 128*(2), 183-204. https://doi.org/10.1007/s10342-008-0215-9