

Appendix S1

Additional information on the Samsara2 simulator and the models integration

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1 Tree light interception and light on the forest floor

We used the SamsaraLight ray tracing model (Courbaud et al., 2003) to estimate the light energy intercepted by each tree (DBH greater than 7.5 cm) within each plot over the course of the year. It allowed to derive indicators of light competition to predict the dynamics of trees and saplings. Tree crowns were represented using allometries for tree height, crown base height and crown diameter based on tree diameter and species (adapted from Touzot et al., 2025, see section 2.1). For conifers (spruce and fir) the crown was modelled as a paraboloid, whereas for broadleaves (beech) an ellipsoid was used. In addition, beech was assumed to have a higher leaf area density than spruce and fir (see section 2.2). We projected both diffuse and direct solar radiation onto the stand, taking into account monthly variations in energy and orientation. When a ray was intercepted by the crown of a tree, the absorbed energy was calculated by treating the crown as a turbid medium with the Beer-Lambert law. This approach allowed us to estimate the total intercepted energy for each tree in the stand and the amount of light reaching the forest floor after attenuation by canopy trees.

We used fixed parameters for the SamsaraLight model, corresponding to the default parameters used in the Samsara2 simulator. We calculated light interception only during the growing season, which we set to 1 May to 30 September. For each month of the growing season, the table 1 shows E_{global} - the global energy in a horizontal plane (in $MJ.ha^{-1}$) - and DiffuseRatio - the ratio between diffuse and global energy for a given month of the year (if the energy does not come from diffuse radiation, it comes from direct radiation). To discretise both diffuse and direct rays, the SamsaraLight model needs some parameters: we set the step angle between two direct rays to 5 degrees and between two diffuse rays to 15 degrees (15 degrees corresponds to a step of 1 hour), and the minimum angle between a horizontal plane and the ray is 15 degrees. We

52 use the Standard Overcast Sky (SOC) algorithm to create diffuse rays (rays with an elevation
 53 angle close to the zenith have higher energy). The GMT is set to 0. Rays are not blocked by tree
 54 trunks. More information about the parameters can be found in the SamsaraLight documentation:
 55 https://capsis.cirad.fr/capsis/help_en/samsaralight.

Month	E_{global}	DiffuseRatio
1	0	NA
2	0	NA
3	0	NA
4	0	NA
5	533.5	0.539146523
6	573.9	0.52980456
7	668.9	0.42936429
8	565.8	0.435726902
9	418.2	0.463048184
10	0	NA
11	0	NA
12	0	NA

Table 1: Monthly radiation characteristics

56 2 Tree crown structure

57 2.1 Crown allometries

58 **Methodology and adaptations** We used both the database and methodology of the study
59 by (Touzot et al., 2025) to estimate crown dimensions from tree DBH and species, with some
60 adaptations: (1) *reduce the geographical scale of the study* (remove North American and Spanish
61 data), to adapt to our study context while keeping a large amount of observations; (2) *not consider*
62 *the effect of local competition*, because the implementation of a static calibration in a dynamic
63 simulator led to difficulties and inconsistencies in the simulations (*e.g.* beech crown that infinitely
64 decreases in depth and increases in diameter); (3) *calibrate crown base height directly*, without
65 passing from crown ratio, which facilitates hypotheses on ecological effects. The point (3) could
66 be tricky, as height and crown base height were calibrated independently, and nothing limited the
67 predicted crown base height to be higher than the tree height, hence Touzot et al. calibrated a
68 crown ratio. However, as we only calibrated 3 species (*Picea abies*, *Abies alba* and *Fagus sylvatica*),
69 we were able to manually check a posteriori that this would never happen, facilitated by the
70 asymptotic form of both equations.

71 **Models calibration** We predicted for a tree i of species s , the crown diameter $CDIAM_{i,s}$
72 (equation 1a), the tree height $H_{i,s}$ (equation 1b) and the crown base height $CBH_{i,s}$ (equation 1c)
73 the tree diameter at breast height DBH_i . For each species, we independently calibrated the three
74 allometric models in RStudio (R Core Team, 2022) using the `nls()` function in the base ‘stats’
75 package (for height and crown base height) and using the `gnls()` function in the ‘nlme’ package
76 (Pinheiro et al., 2022). To assess the performance of the models on independent data, we performed
77 a 20-fold cross-validation. For each fold, we calculated the MAE (mean absolute error) and the

RMSE (root mean square error) to assess the prediction quality of each model for each species. Finally, we averaged the estimated parameters and the MAE/RMSE indicators between the 20 folds to obtain a single set of parameters for each species and each allometric variable. The Table 2 shows the number of observations for each species and allometric variable and the Figure 1 shows the geographical range of the data for each variable and each species. The Figure 2 shows the predictions from the fitted models. The parameters of the crown allometries are presented in the Table 3.

$$CDIAM_{i,s} = a1_s \cdot DBH_i^{a2_s} \quad (1a)$$

$$H_{i,s} = 1.3 + b1_s \cdot (1 - e^{-b2_s \cdot DBH_i})^{b3_s} \quad (1b)$$

$$CBH_{i,s} = 1.3 + c1_s \cdot (1 - e^{-c2_s \cdot DBH_i})^{c3_s} \quad (1c)$$

Variable	Species	Number of observations
Crown diameter CDIAM	<i>Picea abies</i>	10,956
	<i>Abies alba</i>	2,493
	<i>Fagus sylvatica</i>	10,592
Tree height H	<i>Picea abies</i>	95,301
	<i>Abies alba</i>	41,128
	<i>Fagus sylvatica</i>	96,359
Crown base height CBH	<i>Picea abies</i>	24,577
	<i>Abies alba</i>	4,769
	<i>Fagus sylvatica</i>	18,178

Table 2: Number of observations for each allometric variable and each species

Integration in the simulator As the allometries depend only on diameter and species, we could recalculate the crown dimensions at each time step from the statically calibrated allometries. In

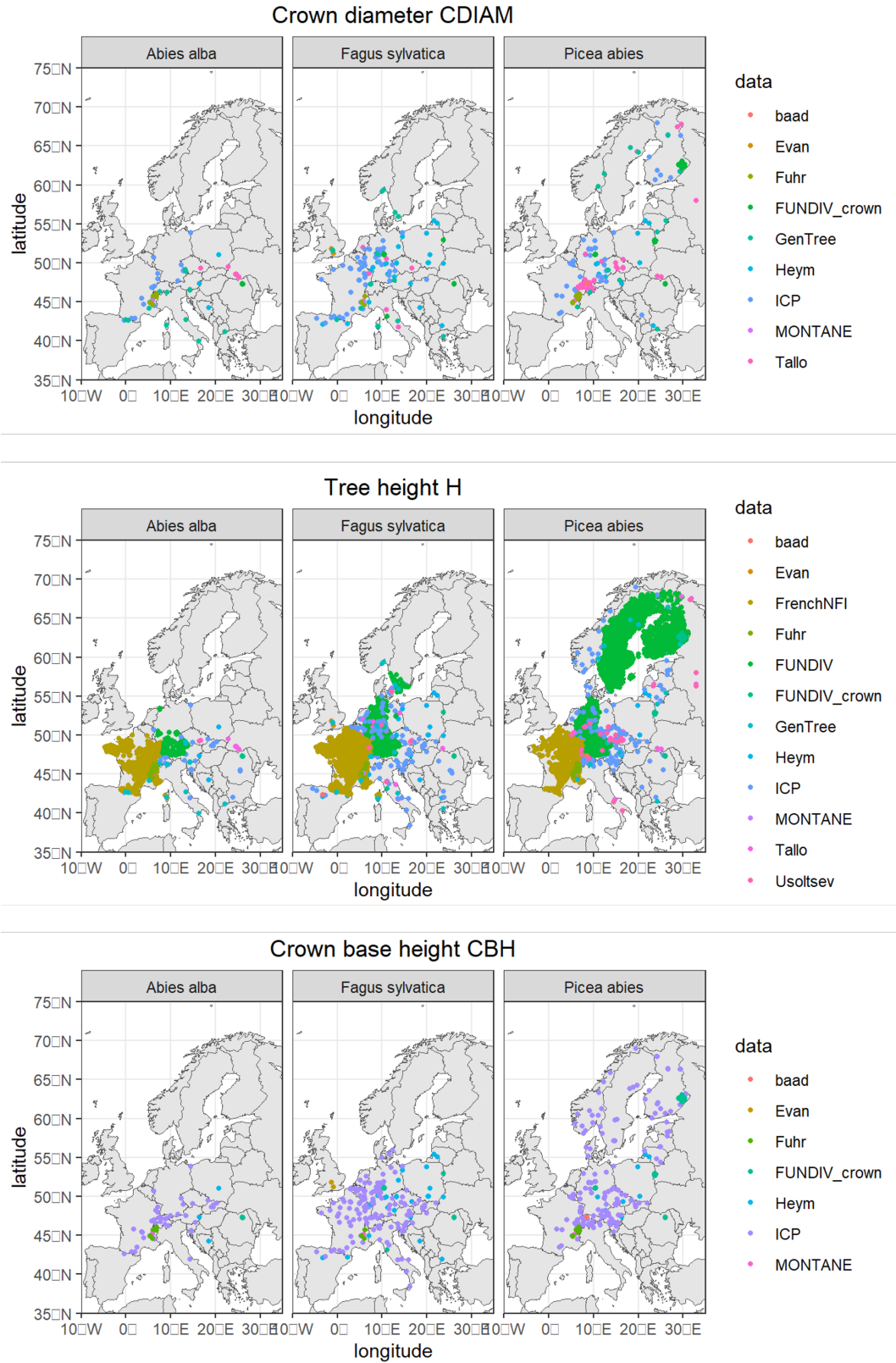


Figure 1: Geographical range of the allometric data for each species. The colours shows the original database of the observations, with the database names correspondence in (Touzot et al., 2025).

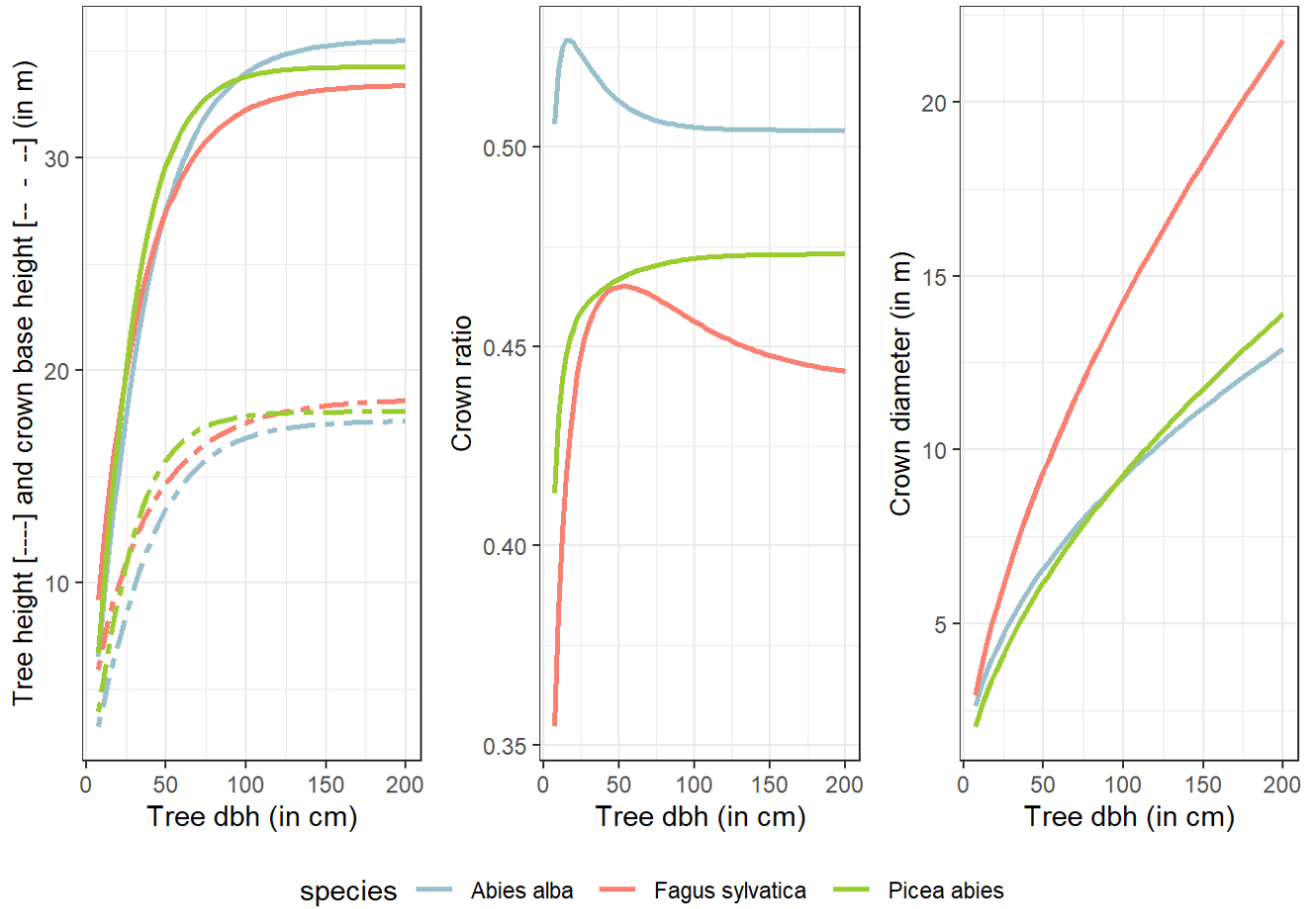


Figure 2: Allometric model predictions for the Silver fir (blue), the European beech (red) and the Norway spruce (green) from the tree diameter at breast height. The first panel shows the prediction of tree height (solid line) and crown base height (irregular lines). We deduced the crown ratio and represented it in the second panel. The third panel shows the predicted crown diameter.

fact, the diameter of the tree could not decrease or change drastically in value. However, the Samsara2 simulator was implemented in such a way that we could easily consider the competition effect in the allometries, which also allowed us to observe the difficulty of currently considering competition in the allometries. Indeed, the competition indicators we tested (based on local basal area) could decrease (*i.e.* less competition, *e.g.* in the case of a tree growing faster than its neighbours) or change drastically (*e.g.* become very low in the case of a thinning cut around a tree). Thus, using static allometry could lead to inconsistent predictions over time, such as a reduction in crown, crown width or height (as competition decreases), or a very large change

in crown size (for example, in the case of thinning). Therefore, we derived the static calibrated allometries with time to implement dynamic equations predicting the increment of a tree i of species s in crown diameter $\Delta CDIAM_{i,s}$ (equation 2a), in tree height $\Delta H_{i,s}$ (equation 2b) and in crown base height $\Delta CBH_{i,s}$ (equation 2c) from the initial dbh DBH_i and the increment in dbh ΔDBH_i . In addition, we constrained increments to be positive, which is mathematically verified when considering only the effect of dbh. After further analysis, this did not significantly change the crown predictions over time, so we have continued to use this dynamic methodology, even though we have not included the competition effect in this study.

$$\Delta CDIAM_{i,s} = a1_s \cdot a2_s \cdot \Delta DBH_i \cdot DBH_i^{a2_s-1} \quad (2a)$$

$$\Delta H_{i,s} = b1_s + b3_s \cdot b2_s \cdot \Delta DBH_i \cdot e^{-b2_s \cdot DBH_i} \cdot (1 - e^{-b2_s \cdot DBH_i})^{b3_s-1} \quad (2b)$$

$$\Delta CBH_{i,s} = c1_s + c3_s \cdot c2_s \cdot \Delta DBH_i \cdot e^{-c2_s \cdot DBH_i} \cdot (1 - e^{-c2_s \cdot DBH_i})^{c3_s-1} \quad (2c)$$

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2.2 Leaf area density

We used the leaf area density values provided in Beauchamp et al., 2025, estimated for 4 groups according to species shade tolerance (shade intolerant, medium tolerant, shade tolerant angiosperms and shade tolerant gymnosperms). For *Picea abies* and *Abies alba* we used the value of "shade tolerant gymnosperms" (*i.e.* $lad = 0.767$) and for *Fagus sylvatica* we used the value of "shade tolerant angiosperms" (*i.e.* $lad = 0.960$).

2.3 Parameters of crown sub-models

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species	Crown diameter		Height			Crown base height			Leaves
	a1	a2	b1	b2	b3	b1	b2	b3	lad
<i>Picea abies</i>	0.62979511	0.58416725	32.9926524	0.04637216	1.47336814	16.7659528	0.04812812	1.54681389	0.767
<i>Abies alba</i>	0.99288228	0.48390246	34.2817776	0.03272306	1.23158461	16.3377291	0.03340427	1.41614586	0.767
<i>Fagus sylvatica</i>	0.86717174	0.60821411	32.1519746	0.03193898	0.91012981	17.3770133	0.02430447	0.73951081	0.960

Table 3: Samsara2 species parameters for the crown sub-models.

3 Tree dynamics

3.1 Global design

We predicted the annual diameter increment and survival probability of individual trees of a given species using the methodology outlined in Beauchamp et al., 2025, with some adaptations to account for the local context that are described below in the section 3.2.

The model accounts for climatic effects on tree growth and mortality, using two climatic variables known to be key factors in forest productivity (Boisvenue et al., 2006): the sum of growing degree days (*sgdd*) and the ratio of actual to potential evapotranspiration (*aet2pet*). *sgdd* is related to annual temperatures and the length of the growing season, and is calculated as the sum of daily mean temperatures above 5.5°C during the year (Zimmermann et al., 1999). *aet2pet* is a proxy for the aridity of the plot and is calculated from an annual water balance by estimating the soil water holding capacity using soil variables and the monthly flux of soil water content from precipitation, snowmelt and potential evapotranspiration using climatic variables.

The models also account for the effect of light competition using a tree-based light competition index *LCI* computed using the SamsaraLight model. *LCI* is calculated from the ratio of the light it intercepts after attenuation by previous crowns to the light it could potentially intercept if it had no neighbours.

The main originality of the tree growth and mortality models is that we considered the interactive effect between light competition and climate. Ecological theory suggests that light competition

intensifies in more productive environments, a pattern confirmed by our model calibration (see ecological interpretation of the calibration in Beauchamp et al., 2025). Specifically, the effect of light competition was found to be more pronounced in warmer and wetter climates, while it was weaker in more stressful, drier, or colder environments, for both growth and survival.

3.2 Adaptation of the models

Methodology and adaptations We used both the database and the methodology of the Beauchamp et al., 2025 study on individual tree growth and mortality, with some adaptations: (1) keep only stands with at least 95% basal area of either fir, beech or spruce, to adapt to the study context (see Figure 3 for differences in climatic range and the tables 4 and 5 for the number of observations for the growth and mortality calibration respectively); (2) consider the effect of total basal area BATOT, to better account for density dependence in the simulator, especially for fir. Indeed, after going back and forth between calibration and simulation tests, our light competition indicator alone was not sufficient to limit forest growth and density.

Species	CZ	DE	ES	FI	FR	PL	SI	SK	SW	Total
<i>Picea abies</i>	2,714	29,956	0	1,678	5,747	2,274	2,664	2,250	9,018	56,301
<i>Abies alba</i>	0	3,075	1,091	0	6,544	2,498	852	240	0	14,300
<i>Fagus sylvatica</i>	441	11,347	11,793	0	7,281	4,206	2,791	1,556	139	39,554

Table 4: Number of observations by species and country in the growth dataset

Species	Status	CZ	DE	ES	FR	PL	SI	SK	SW	Total
<i>Picea abies</i>	alive	2,714	29,956	0	5,747	2,274	2,664	2,250	9,018	54,623
	dead	53	551	0	181	162	163	404	151	1,665
<i>Abies alba</i>	alive	0	3,075	1,091	6,544	2,498	852	0	0	14,060
	dead	0	38	115	133	45	40	0	0	371
<i>Fagus sylvatica</i>	alive	0	11,347	11,793	7,281	4,206	2,791	1,556	0	38,974
	dead	0	97	319	106	103	89	122	0	836

Table 5: Number of observations by species, country and living status in the mortality dataset

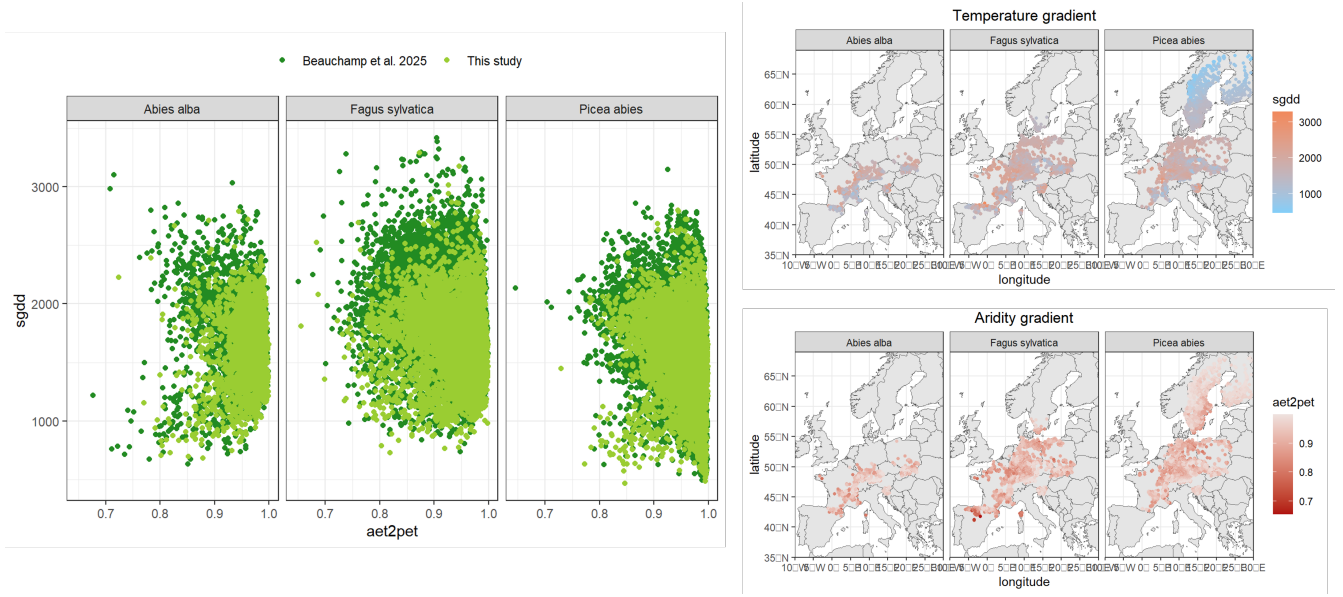


Figure 3: The left figure compares the climatic space (sgdd and aet2pet) of the growth dataset between the study in Beauchamp et al., 2025 (dark green) and the recalibration in this study (light green). The right figures present the climatic distribution across Europe of the temperature index sgdd (above) and the one of the aridity index aet2pet (below) of this current study.

Models calibration For each species, we fitted a linear mixed model (LMM) to predict the logarithm of the annual increment in dbh (equation 3) and we fitted a a generalised linear model (GLM) to predict the annual probability of mortality of an individual (equation 4). See Beauchamp et al., 2025 for more details on the calibration. As we had observations in at least 6 countries for our 3 species, we considered the country effect as a random effect in the growth models. For each species we chose the form of sgdd with the lower AIC; for the growth model: inverse transformation for *Picea abies* and *Abies alba* and quadratic transformation for *Fagus sylvatica*; for the mortality model: inverse transformation for *Abies alba* and *Fagus sylvatica* and quadratic transformation for *Picea abies*. The Figure 4 and the Figure 5 show the predictions for the growth and mortality models respectively. The parameters of the tree growth and mortality models are presented in the Table 6 and the Table 7 respectively.

$$\begin{aligned}
\log(G_{i,p}) = & a_{0,c} + a_{0,p} \\
& + a_1.dbh_i + a_2.\log(dbh_i) \\
& + a_3.BATOT_p + a_4.LCI_i + \\
& + a_5.\frac{1}{aet2pet_p} + a_6.\frac{1}{sgdd_p} + a_7.sgdd_p + a_8.sgdd_p^2 \\
& + a_9.LCI_i.\frac{1}{aet2pet_p} + a_{10}.LCI_i.\frac{1}{sgdd_p} + a_{11}.LCI_i.sgdd_p \\
& + \epsilon_i
\end{aligned} \tag{3}$$

155 where $G_{i,p}$ is the annual increment in diameter at breast height of tree i in plot p ; dbh_i is the
 156 diameter at breast height of tree i at first survey; LCI_i is the light competition index of tree i ;
 157 $sgdd_p$ is the sum of growing degree days for plot p ; and $aet2pet_p$ is the aridity index for plot p .
 158 Parameters a_1 to a_{11} are the estimated regression coefficients. $a_{0,p}$ is a normal random plot effect
 159 to account for the non-independence of the trees in the same plot. $a_{0,p}$ is a normal random country
 160 effect to account for country-specific protocols. ϵ_i is the normal error term.

$$\begin{aligned}
\text{cloglog}(\text{dead}_{i,p}) = & a_{0,c} \\
& + a_1.dbh_i + a_2.\log(dbh_i) \\
& + a_3.BATOT_p + a_4.LCI_i \\
& + a_5.\frac{1}{aet2pet_p} + a_6.\frac{1}{sgdd_p} + a_7.sgdd_p + a_8.sgdd_p^2 \\
& + a_9.LCI_i.\frac{1}{aet2pet_p} + a_{10}.LCI_i.\frac{1}{sgdd_p} + a_{11}.LCI_i.sgdd_p
\end{aligned} \tag{4}$$

161 where $\text{dead}_{i,p}$ is an integer with value 1 if the tree i in plot p died between the two surveys and

0 if it survived, y_p is the number of years between the two surveys added as an offset. dbh_i is the diameter at breast height of tree i at first survey, lci_i is the light competition index of tree i , $sgdd_p$ is the sum of growing degree days of plot p , $aet2pet_p$ is the aridity index of plot p . Parameters a_1 to a_{11} are the estimated regression coefficients $a_{0,c}$ is the country-specific intercept to account for differences between country protocols.

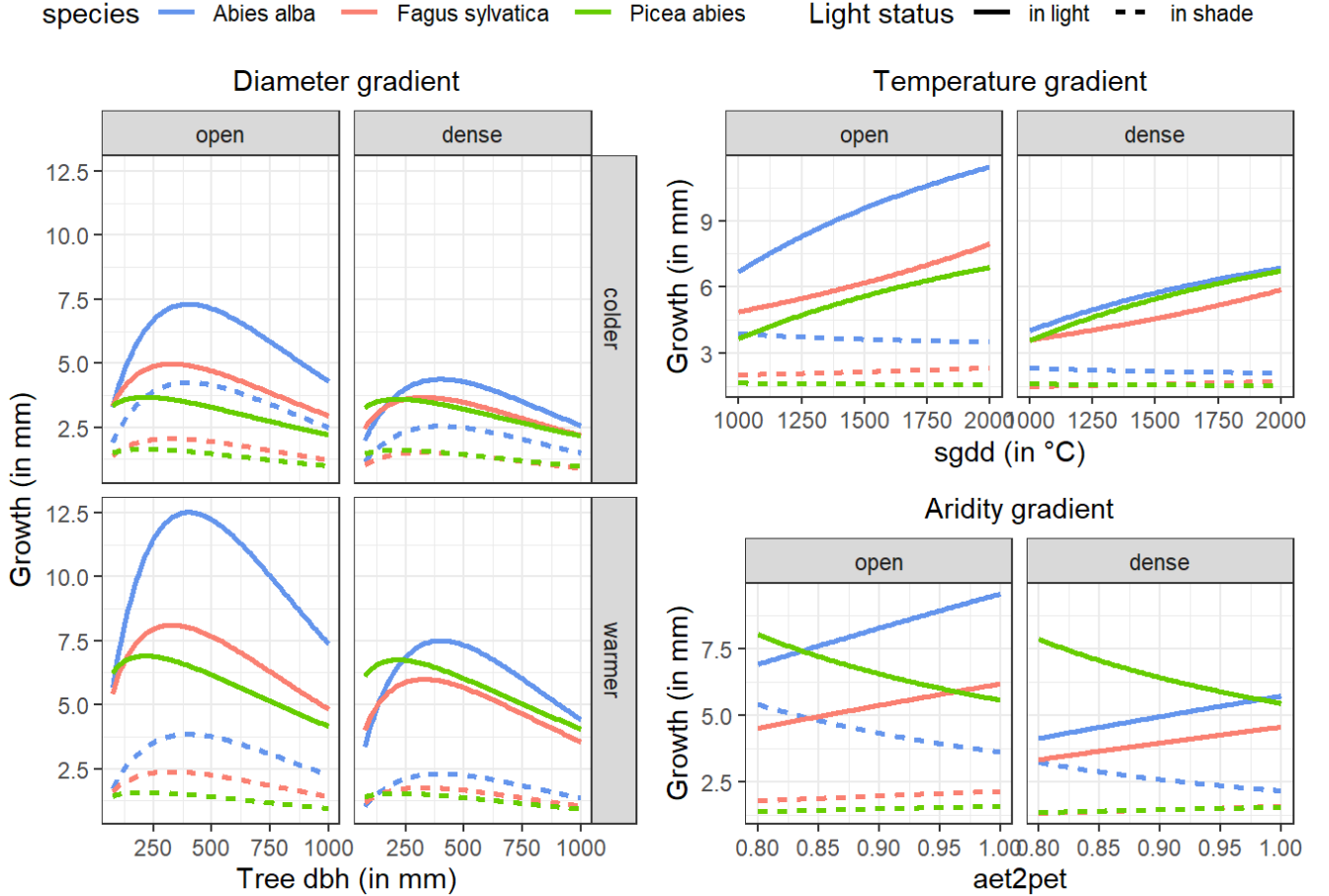


Figure 4: Predictions of annual tree growth (in mm) for each species, and for a tree in light (LCI = 0.1) and in shade (LCI = 0.9). The left panel shows the predicted tree growth across tree dbh (in mm), for two values of total basal area (open = $10m^2.ha^{-1}$ and close = $60m^2.ha^{-1}$) and two values of sgdd (colder = $1000^\circ C$ and warmer = $2000^\circ C$), at a fixed aet2pet of 1. The right panels show the predicted growth across a sgdd gradient (above, at a fixed aet2pet of 1) and across a aet2pet gradient (below, at a fixed sgdd of $1500^\circ C$), both at a fixed dbh of 250mm, also for the same two values of total basal area.

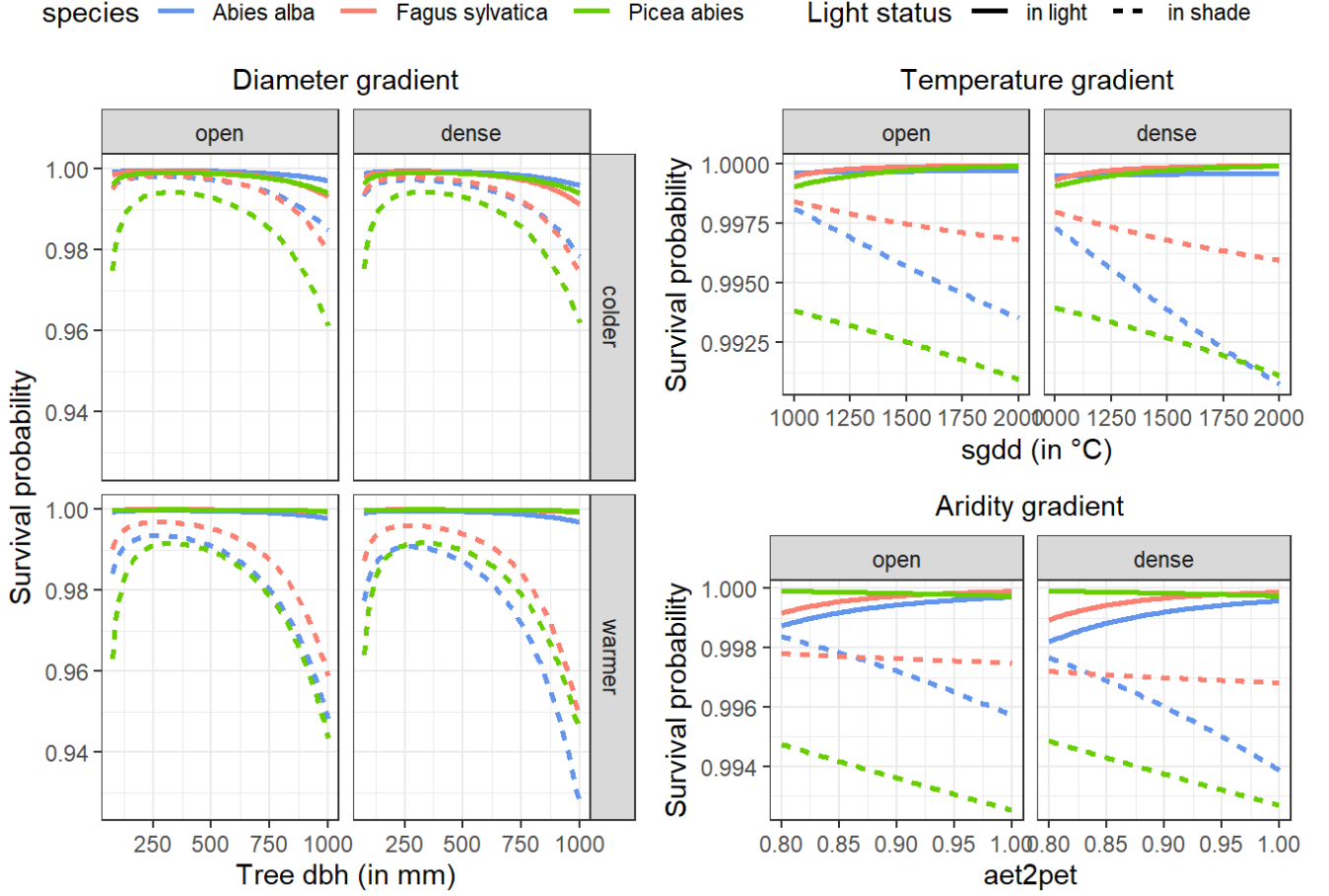


Figure 5: Predictions of annual tree survival probability for each species, and for a tree in light ($LCI = 0.1$) and in shade ($LCI = 0.9$). The left panel shows the predicted survival across tree dbh, for two values of total basal area BATOT (open = $10m^2.ha^{-1}$ and close = $60m^2.ha^{-1}$) and two values of sgdd (colder = $1000^\circ C$ and warmer = $2000^\circ C$), at a fixed aet2pet of 1. The right panels show the predicted survival across a sgdd gradient (above, at a fixed aet2pet of 1) and across a aet2pet gradient (below, at a fixed sgdd of $1500^\circ C$), both at a fixed dbh of 250mm, also for the same two values of total basal area.

3.3 Integration in the simulator

In the Samsara2 simulator, we first compute the variables required for the growth and mortality models: sgdd, aet2pet, LCI, and BATOT. The calculation of the climatic variables sgdd and aet2pet, as well as the light competition index LCI, is described in Beauchamp et al., 2025. The total basal area of a tree BATOT is computed as the sum of basal areas of all trees located within a radius of 17 m around the focal tree (default value in Samsara2; Courbaud et al., 2015).

For each tree, we then compute the annual probability of mortality using the calibrated mortality model. The linear predictor is first transformed through the complementary log-log (cloglog) link, and the corresponding probability is obtained as $\hat{p}_{\text{morta},i} = 1 - \exp(-\exp(\eta_i))$, where η_i is the linear predictor of the mortality model (i.e. $\text{cloglog}(\text{dead}_{i,p})$ in the Eq. 4). A Bernoulli draw is then used to determine whether each tree dies.

For surviving trees, the annual increment in dbh is predicted from the calibrated growth model and added to the current diameter. When estimating growth for tree i , country and plot random effects are set to zero (i.e. predictions are made at the fixed-effect level). Since the growth model is fitted on log-transformed growth ($\log G_i$), predictions are back-transformed to the original scale using a log-normal bias correction $\hat{G}_i = \exp\left(\log(G_i) + \frac{\sigma^2}{2}\right)$.

3.4 Parameters of tree dynamics models

Species	σ	a_0	Diameter		Basal area	Light	Climate				Interactions Light and Climate		
			a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9	a_{10}	a_{11}
<i>Picea abies</i>	0.5484	-0.1138	-1.130×10^{-3}	0.2472	-4.409×10^{-4}	-0.1758	1.713	-1426.6	0	0	-2.510	1685	0
<i>Abies alba</i>	0.6036	0.2669	-2.290×10^{-3}	0.9212	-0.01023	-5.891	-1.658	-1235	0	0	3.618	1598	0
<i>Fagus sylvatica</i>	0.6607	-0.3260	-1.711×10^{-3}	0.5655	-0.006052	-1.305	-1.311	0	4.534×10^{-4}	2.600×10^{-8}	0.6337	0	-4.288×10^{-4}

Table 6: Growth model parameters corresponding to Eq. 3.

Species	a_0	Diameter		Basal area	Light	Climate				Interactions Light and Climate		
		a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9	a_{10}	a_{11}
<i>Picea abies</i>	10.38	6.363×10^{-3}	-2.104	-4.274×10^{-4}	-4.887	-4.567	0	-3.005×10^{-3}	8.870×10^{-9}	3.510	0	3.738×10^{-3}
<i>Abies alba</i>	-8.962	5.724×10^{-3}	-1.580	7.181×10^{-3}	18.08	7.115	879.1	0	0	-12.22	-3743	0
<i>Fagus sylvatica</i>	-13.93	7.116×10^{-3}	-1.987	4.783×10^{-3}	20.62	9.628	5744	0	0	-11.28	-7954	0

Table 7: Mortality model parameters corresponding to Eq. 4.

184 4 Regeneration processes

185 The stand is divided into squared cells (dimensions of the SamsaraLight cells) for which we compute
186 each year (1) the tree fecundity (number of produced seeds), (2) the sapling dynamics (individual
187 height growth and survival probability) and the saplings browsing (individual probability of a
188 sapling to be browsed by an ungulate), and (3) the recruitment (the saplings that are recruited
189 into adult trees). The calibration of tree fecundity, sapling dynamics and sapling browsing is based
190 on the work of Unkule, 2022 (chapter 4), using the data presented in Unkule et al., 2022. The
191 parameters of the regeneration sub-models are presented in the Table 8.

192 4.1 Tree fecundity

193 Each year, we predicted the number of seeds produced $Nseeds_{c,s}$ in a cell c by a species s from
194 a Poisson distribution of parameter $\lambda_{c,s}.area_c$ (Equation 5) (*i.e.* the mean number of seeds per
195 hectare $\lambda_{c,s}$ produced in the cell c by the species s , scaled by the area of the cell $area_c$). The
196 number of seed produced per hectare is computed as a combination of the seeds from the trees
197 composing the stand $\lambda_{stand_{c,s}}$ and a species-specific constant pool of seeds that come from the
198 outside of the stand λ_{immig_s} . $\lambda_{stand_{c,s}}$ depends on the total basal area of conspecific mature
199 trees $BA_{c,s}$ (defined as trees with a $DBH \geq 17.5cm$) within a 25m radius around the cell center
200 (default value in Samsara2, Courbaud et al., 2015). When seeds are produced, they are directly
201 modelled as saplings with an initial height of 10cm, but are not spatialized within the cell. In this
202 study, we assumed no seed input from outside the stand, thus setting $\lambda_{immig_s} = 0$ for all species.

$$Nseeds_{c,s} = Pois(\lambda_{c,s}.area_c)$$

$$with \quad \left\{ \begin{array}{l} \lambda_{c,s} = \lambda_{stand_{c,s}} + \lambda_{immig_s} \\ \lambda_{stand_{c,s}} = a1_s.BA_{c,s} \end{array} \right. \quad (5)$$

203 4.2 Sapling dynamics and browsing

204 Each year, we predicted both the survival probability $\mathbb{P}survival_{i,c,s}$ (Equation 6) and the height
 205 growth $\Delta H_{i,c,s}$ (Equation 7) of a sapling i of species s located in the cell c , considering its height
 206 H_i and the relative light available over the cell $PACL_c$. $PACL$ is a proxy for the light intercepted
 207 by the sapling and is calculated from the ratio between the light arriving from above the canopy
 208 and the light after attenuation by the adult trees composing the stand.

209 Additionally, we predicted the browsing probability by ungulates $\mathbb{P}browsing_{i,s}$ (Equation 8) of
 210 a sapling i of species s considering its height H_i . If a sapling is browsed during the year, its height
 211 increment $\Delta H_{i,c,s}$ is set to zero for this year.

$$\mathbb{P}survival_{i,c,s} = \frac{e^{Z_{i,c,s}}}{1 + e^{Z_{i,c,s}}} \quad (6)$$

$$with \quad Z_{i,c,s} = b1_s + b2_s.H_i + b3_s.PACL_c$$

$$\Delta H_{i,c,s} = c1_s.H_i^{c2_s}.PACL_c^{c3_s} \quad (7)$$

$$\mathbb{P}browsing_{i,s} = \frac{d1_s}{1 + e^{-Z_{i,s}}} \quad (8)$$

$$with \quad Z_{i,s} = d2_s + d3_s.H_i$$

4.3 Tree recruitment

When a sapling of species s reaches the species-specific recruitment height $H_{recruit_s}$, it is recruited as a tree and is randomly placed within the cell. The recruitment height which is computed as the height corresponding to a DBH of 7.5cm based on tree height allometry in Equation 1b. The initial DBH of the tree is computed from the saplings' height and by reverting the tree height allometry in Equation 1b.

4.4 Parameters of the regeneration sub-models

Species	Fecundity $a1$	Survival $b1 \quad b2 \quad b3$			Growth $c1 \quad c2 \quad c3$			Browsing $d1 \quad d2 \quad d3$			Recruitment $H_{recruit}$
<i>Picea abies</i>	6.711	0.87	0.015	0.044	0.237	0.477	0.317	0.039	5.827	-0.029	6.727
<i>Abies alba</i>	13.955	1.737	0.017	0.01	0.156	0.638	0.204	0.28	3.271	-0.018	6.541
<i>Fagus sylvatica</i>	21.351	2.318	0.009	0.011	0.227	0.6	0.264	0.226	5.261	-0.034	9.170

Table 8: Samsara2 species parameters for the regeneration sub-models.

219 5 Silvicultural interventions

220 5.1 The multicriteria thinning algorithm

221 The multi-criteria cutting algorithm (Courbaud et al., in prep) classifies trees into five categories,
222 which are successively evaluated:

- 223 1. *Biological trees*, to be preserved for their ecological value;
- 224 2. *Mature trees*, intended for harvesting;
- 225 3. *Crop trees*, to be promoted by specific thinning;
- 226 4. *Thinning trees*, to be cut for improvement;
- 227 5. Other trees left in place.

228 For each of the first four categories of trees, the user sets quantitative objectives: number of
229 biological trees and crop trees, minimum basal area after cutting, and percentage of basal area to
230 be cut for harvesting (mature trees) and improvement (thinning trees).

231 The trees are then selected based on a score per category, calculated using criteria weighted
232 by the user (diameter, ecological value, economic value, rarity of the species, etc.). This score
233 corresponds to the weighted sum of the values for each criterion per tree. Thus, for each successive
234 category, the score of a tree i for this category is computed as $S_i = \sum_{j=1}^k w_j \cdot V_{ij}$, with V_{ij} as the
235 value of the criterion j of the tree i , and w_j the weight of the criterion j (chosen by the user).

236 The available trees with the highest scores are selected until the target quantity for the category
237 is reached. The selected trees then become unavailable for inclusion in other categories. A graphical
238 representation of how the algorithm works is shown in Figure 6.

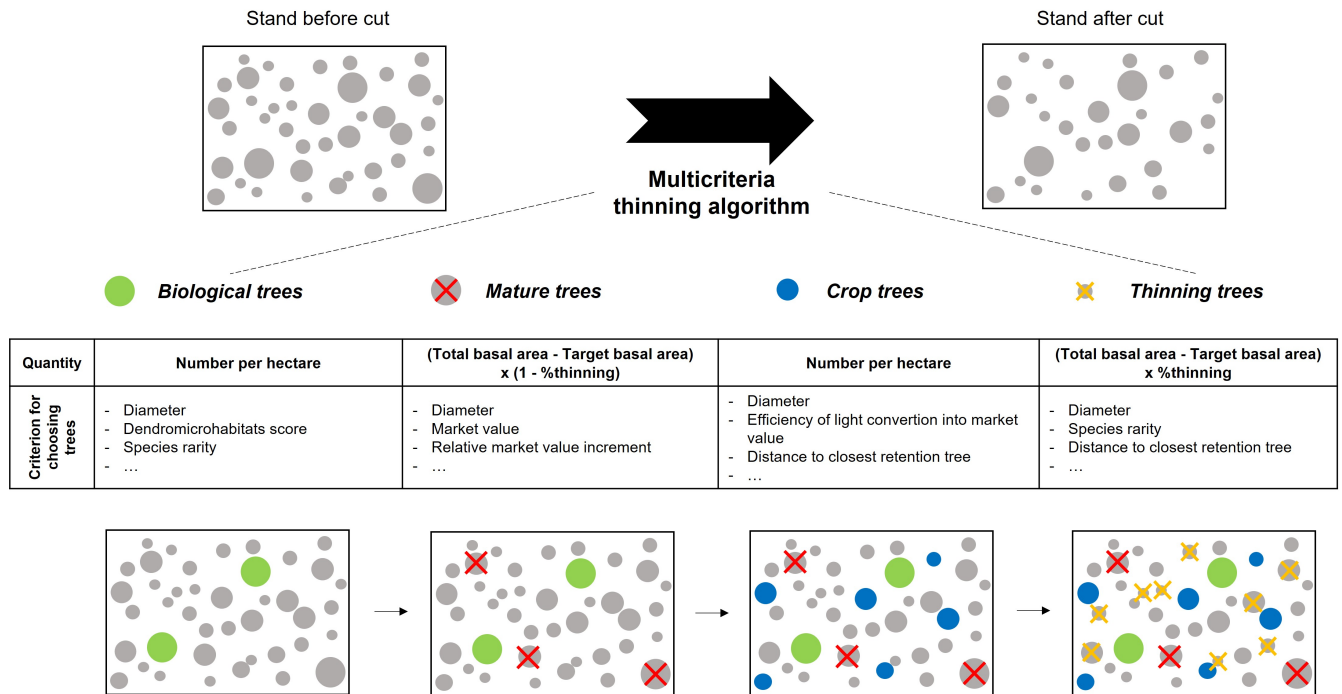


Figure 6: Graphical representation of the consecutive chosen trees by the multicriteria thinning algorithm during a cutting event. Trees selected in a category cannot be selected for the next categories. Source: Louise Rovel

The use of criteria based on distances between trees involves a more elaborate optimisation process. First, the algorithm constructs a matrix listing the distances between each pair of trees in the stand. A set of N candidate trees is then randomly selected. For each of these trees, the distance between it and the nearest candidate tree is determined, and then all of these distances are added together to obtain an overall score for the selected group. The algorithm then performs a random exchange, replacing one of the candidate trees with a tree that has not yet been selected, and calculates the new score for the group thus formed. If this score is higher than that of the previous group, the new configuration is retained. If the score is lower, it is rejected with a probability of (1 - p), or accepted with a probability p in order to explore the space around the local optima. This probability p gradually decreases over the course of the iterations to steer the process towards stable convergence.

250 5.2 Volume and price estimation of marketable wood

251 The volume of marketable wood is estimated from the Equation 9. The species-specific coefficients
 252 of the equation $coef_s$ is set to 0.7 for spruce and fir and 0.9 for beech.

$$V_{i,s} = \frac{PI}{4} * H_i * (coef_s * \frac{DBH}{100})^2 \quad (9)$$

253 The Samsara2 simulator includes a default price table per cubic unit of marketable wood, that
 254 depends on the tree species and the tree quality, presented in the table 9. We assumed that spruce
 255 and fir are always of the highest quality for timber, while all beech trees are always of the lowest
 256 quality for fuel (representative of our uneven-aged study context in mountainous areas).

DBH class (in cm)	[7.5, 25[	[25, 35[	[35, 45[	[45, 55[	[55, 65[	[65, 80[	≥ 80cm
Timber conifers	35	50	70	80	80	90	90
Fuel production Beech	0	10	30	40	40	50	50

Table 9: Prices (in euros) of a unit volume of trees harvested, for each size class and species

6 Environmental indicators

6.1 Tree microhabitats score

We used models that estimate, for each species, tree microhabitat (TreM) formation rates from observations of TreM presence/absence, calibrated in Courbaud et al. (2022) and based on the methodology of Courbaud et al. (2017). 11 TreM groups were defined based on their morphology and role in biodiversity: woodpecker breeding hole, roth hole, dendrotelm, root concavity, bark loss, exposed heartwood, crack, crown deadwood, burr or canker, polypore, sap run. The models were integrated into the Samsara2 simulator by deriving the TreMs models to estimate the probability of formation of a given TreM on a tree growing between a 1-year simulation time step (Courbaud et al. 2017).

We then computed the tree microhabitat score $TremScore$, a stand-scale indicator that account for the amount, diversity and rarity of tree microhabitats (TreMs) on the trees composing the plot p. The methodology and the output parameters are based on non published works of Laurent Larrieu and Céline Emberger. $TremScore_p$ is computed by summing the score of each of the N trees $TremScore_{p,i}$ (i in $[1, N]$) (equation 10a), computed with a scoring system $TreMsubscore_{p,d}$ based on the TreMs hosted by the tree i, $TreMs_i$ (equation 10b). For each TreM d hosted in a tree i in plot p, $TreMsubscore_{p,d}$ (equation 10c, with parameters for each TreM in Table ??) sums points associated to a given TreM d: $repTime_d$ (related to the appearance time of the TreM) and $rarManaged_d$ (related to the rarity of the TreM in managed forests), and points associated to the abundance of the TreM d in the plot p: $abundBonus_{p,d}$ (equation 10d) and $rarRel2Subnat_{p,d}$ (equation 10e, rarity relative to subnatural forests, based on the ratio between $percentTrees_{p,d}$ - the percentage of trees hosting the TreM d in the plot p - with $percentTreesSubnat_d$ - the average percentage of trees hosting the TreM d in subnatural forests).

$$TremScore_p = \sum_{i=1}^N TremScore_i \quad (10a)$$

$$TremScore_{p,i} = \sum_{d \text{ in } TreMs_i} TreMsubscore_{p,d} \quad (10b)$$

$$TreMsubscore_{p,d} = repTime_d + rarManaged_d + abundBonus_{p,d} + rarRel2Subnat_{p,d} \quad (10c)$$

$$abundBonus_{s,d} = \begin{cases} 0 & \text{if } 0 \leq N(TreMs)_{p,d} < 3 \\ 2 & \text{if } N(TreMs)_{p,d} \geq 3 \end{cases} \quad (10d)$$

$$rarRel2Subnat_{s,d} = \begin{cases} +1 & \text{if } \frac{percentTrees_{p,d}}{percentTreesSubnat_d} < 0.7 \\ -1 & \text{if } \frac{percentTrees_{p,d}}{percentTreesSubnat_d} > 1.3 \end{cases} \quad (10e)$$

280

Tree microhabitat	TreM	replacementTime	rarityManaged	percentTreesSubnat
Woodpecker breeding hole		2	6	0.23
Rot Hole		4	5	1.8
Dendrotelm		3	3	1.8
Root Concavity		3	4	9.0
Bark Loss		1	2	5.66
Exposed Heartwood		3	5	1.56
Crack		4	3	8.47
Crown Deadwood		3	3	3.66
Burr or canker		3	4	2.34
Polypore		4	5	2.67
Sap Run		3	6	0.82

Table 10: Parameters to compute the tree ecological score

281 6.2 Deadwood

282 The Samsara2 simulator simulates the process of transition between dead wood decomposition
283 stages and the reduction in volume (and mass) associated with decomposition. To do this, we used

the work of Lafond, 2014 (in chapter 3.4), which details the integration of the deadwood models into the Samsara2 simulator. Globally, the simulator considers two sub-compartments depending on the size of the deadwood: one for Coarse Woody Debris (CWD) and one for Fine Woody Debris (FWD). The CWD compartment includes (1) trees that have died naturally and are considered to be standing ('snags') and then have an annual probability of falling, and (2) trees that have been felled but not harvested and are lying down ('logs'). The other smaller parts of the trees (branches and non-marketable part of the trunk) are stored in the FWD compartment as a volume (and mass) pool. It is possible to harvest some of the fresh dead trees in the CWD compartment to simulate the annual harvesting of dead or dying trees as practised in the field. A different decomposition model is then integrated for each of the FWD and CWD sub-compartments. The CWD decay model is adapted from Holeksa et al., 2008 and simulates the transition of individual pieces of dead wood between decay classes and the reduction in their volume (and mass) as a function of their decay state and diameter. The FWD decay model is based on a simpler methodology by considering an annual decay rate of the volume (and mass) of the FWD pool.

6.3 Carbon storage

The Samsara2 simulator includes the CAT carbon accounting tool (Pichancourt et al., 2018) to estimate the total carbon stored in the stand as the sum of the carbon stored in the living biomass (above and below ground) and the carbon stored in dead organic matter (DOM). The carbon stored in the living biomass at time t (in Mg C) is estimated using the Tier 1 methodology (Eggleston et al., 2006), which converts the commercial volume of a tree from the species-specific basic density, carbon fraction and above ground/below ground expansion factors. The carbon stored in the DOM is calculated independently of the deadwood models presented above. In the CAT tool, the DOM is filled with windfall, dead trees and residues from harvested trees and is divided into three

307 categories for which the carbon content is calculated differently: fine woody debris (difference
308 between aboveground carbon content and carbon content in the commercial part of the tree),
309 commercial woody debris (carbon content of the commercial biomass of dead or windfall trees)
310 and coarse woody debris (carbon in stumps and roots). Finally, they simulated a decomposition
311 model of the DOM based on a first-order decay rate.

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