

Appendix S2

Additional information on the simulation study

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1 Initial stands used in the study

FNFI database We selected the initial plot structures from the French National Forest Inventory (FNFI) database (IGN, 2023). FNFI plots are sampled throughout the country using a systematic 1 km² grid. Within each inventory, trees are sampled within three concentric plots according to their circumference at 1.3 metres. Specifically, trees with a girth greater than 23.5 cm are measured within a 6 m radius plot, those greater than 70.5cm within a 9m radius plot, those greater than 117.5cm within a 15m radius plot and those with a girth of less than 23.5 cm ($dbh < 7.5cm$) are excluded from measurement. Only the diameter at breast height (DBH) of the trees and the species were retained from these inventories.

Filtering We applied filters to the FNFI plots to retain only mixed, uneven-aged, mature stands of spruce, fir and beech (dominated by conifers) from mountainous areas. After filtering, only 10 plot structures were retained from the first visit surveys of all FNFI plots between 2005 and 2022. Firstly, we kept closed forests that are not used for agriculture, landscape or fruit growing. Second, we kept plots in the French mountainous regions of the Alps, Vosges and Jura. Third, we filtered plots to keep only fir-spruce-beech stands by keeping plots with at least 95% of the total basal area composed of the three species, with each species represented by at least 10%. We removed stands with more than 40% beech in order to maintain only stands dominated and managed in favour of conifers. Finally, we selected plots defined by the FNFI as having an "irregular vertical structure" and kept mature stands with a total basal area between 30m².ha⁻¹ and 40m².ha⁻¹. The Figure 1 shows the structural and climatic characteristics of the 10 initial stands selected from the FNFI database.

Virtual 1ha-plot In order to use the FNFI plots in the Samsara2 model, we needed to create a spatialised and individualised representation of the plots. However, trees in the FNFI are statistically sampled within circular plots of varying radius and do not provide a complete representation of the stand. Sampled trees are therefore given a statistical weight equal to the number of equivalent trees (trees of the same species and size) in a one-hectare stand. Thus, for each plot we generated a representative virtual one-hectare stand (100x100m) consisting of the sampled trees replicated as many times as their associated weight per hectare and randomly positioned in the stand. To account for stochasticity in tree location, we created 3 replicates of the same FNFI plots (also allowing for stochasticity in tree and sapling dynamics), leading to a total of 30 initial virtual stands. As the selected stands were not composed entirely of spruce, fir and beech (at least 95% of the total basal area), we considered other broadleaves as beech and other conifers as either fir or spruce (with a probability calculated from the proportion of spruce and fir in the stand).

Saplings distribution The FNFI database does not provide information on saplings within the plot, which is required for the Samsara2 simulator inputs. To simulate initial sapling distribution, we run a burning-period on the initial stand with no adult tree growth and mortality for 100 years. Saplings that reach the recruitment height during this burning-period were removed from the saplings pool. In this way, we simulated only the regeneration process (tree fecundity and sapling dynamics) to approximate the sapling distribution in equilibrium with the tree distribution.

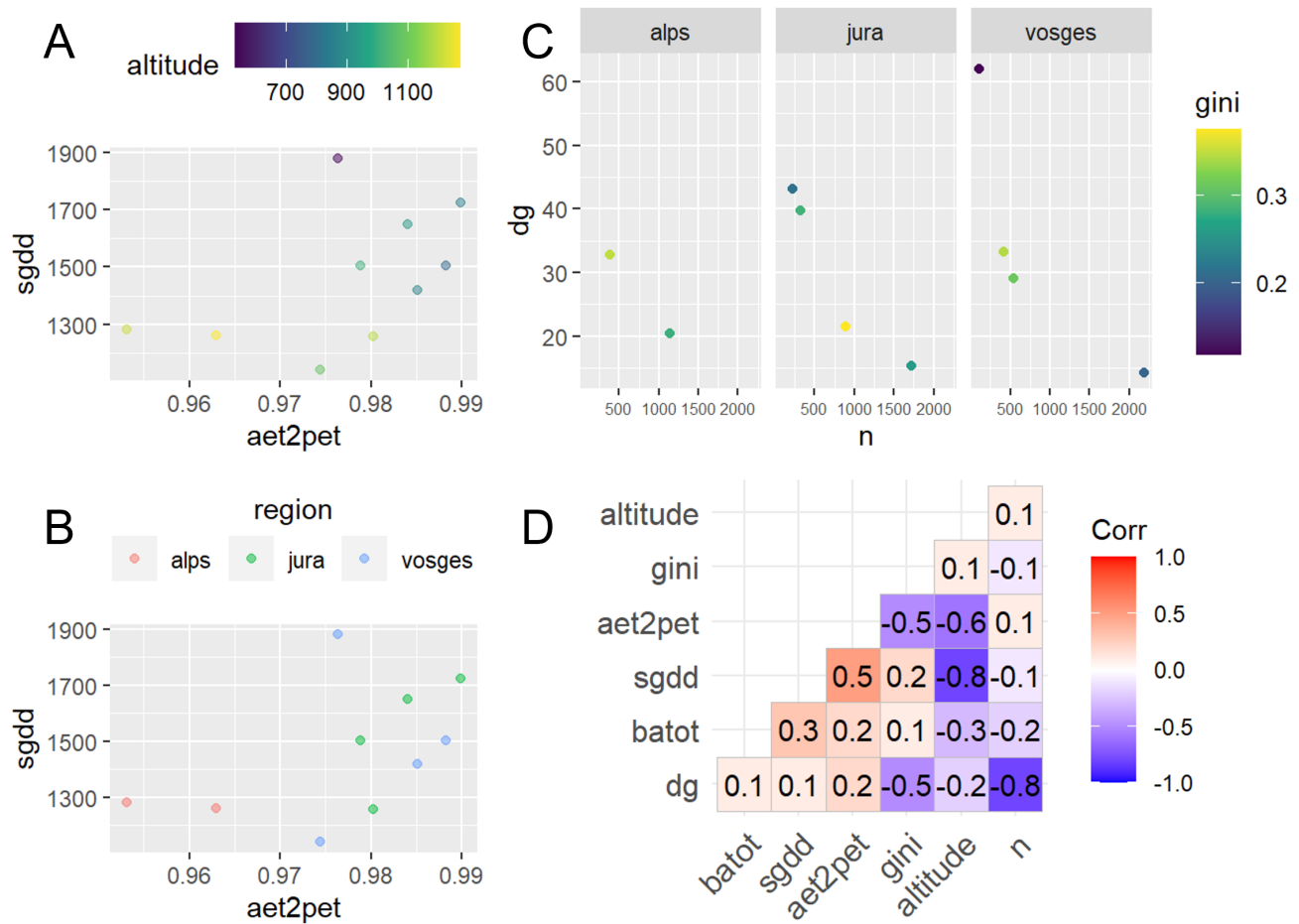


Figure 1: Panels A and B show the climatic distribution of the 10 selected initial stands, with colours varying with altitude (panel A) or with regions (panel B). Panel C shows the correlation between stand density n and stand mean quadratic diameter dg , with colours varying with stand heterogeneity $gini$. Panel D shows the correlation between stand characteristics.

2 Parametrization of the silvicultural algorithm used in this study

Table 1 shows the criteria and associated weights used in the silvicultural algorithm for each tree-selection strategy. Appendix S1-5 presents the silvicultural algorithm.

Strategy	Category	Target	Criterion 1	Criterion 2	Criterion 3	Criterion 4
Random selection <i>Random</i>	Retain	0 trees/ha				
	Release	0 trees/ha				
	Cut for harvest	100%				
	Cut for improvement	0%				
Aggregated selection <i>Aggreg</i>	Retain	0 trees/ha				
	Release	0 trees/ha				
	Cut for harvest	20%	Relative Value Inc. (-50)	DBH (25)	Market value (25)	
	Cut for improvement	80%	Beech species (25)	Dist. closest harvest (-75)	Species rarity (-25)	
Crop-tree selection <i>Crop</i>	Retain	0 trees/ha				
	Release	100 trees/ha	Beech species (-100)	DBH (25)	Light-to-value C.E. (50)	Dist. closest release (25)
	Cut for harvest	50% BA cut	Relative Value Inc. (-75)	Market value (25)		
	Cut for improvement	50% BA cut	Beech species (25)	DBH (25)	Dist. closest release (-50)	Species rarity (-25)

Table 1: Criteria with associated weights (in parentheses) of the silviultural algorithm for each tree-selection strategy.

3 Indicators analysed

Stand structure We analysed the number of trees per hectare ("Density", in $trees.ha^{-1}$), the stand mean quadratic diameter ("Mean diameter", in cm , giving more weight to larger trees than the mean diameter) and the proportion of beech in basal area ("Beech proportion"). In addition, we analysed the tree size distribution as basal area of trees within four size classes: small trees ($17.5cm < DBH < 27.5cm$), medium trees ($27.5cm < DBH < 47.5cm$), large trees ($47.5cm < DBH < 67.5cm$) and very large trees ($DBH > 67.5cm$).

Demographic processes We analysed the annual mean tree DBH increment ("Growth", in $cm.ha^{-1}.year^{-1}$), the annual tree mortality rate ("Mortality", in $trees.ha^{-1}.year^{-1}$, computed as the proportion of deaths compared to all trees in the given year), the annual recruitment rate ("Recruitment", in $trees.ha^{-1}.year^{-1}$, computed as the proportion of recruits compared to living trees in the given year) and the total annual volume increment of living trees ("Production", in $m^3.ha^{-1}.year^{-1}$).

Functions and services We analysed the tree microhabitats score ("Tree biodiversity"), the volume of coarse woody debris on the ground ("Deadwood", in $V.m^3.ha^{-1}$), the carbon stored in the living biomass ("Carbon storage", in $MgC.ha^{-1}$, that comprises above and below-ground biomass), the market value of living trees ("Timber capital", in $euros.ha^{-1}$), the volume of harvested wood per intervention ("Harvested timber", in $m^3.ha^{-1}.intervention^{-1}$) and the incomes from the previous harvested wood ("Timber income", in $euros.ha^{-1}.intervention^{-1}$).

4 Effect of silviculture and climate on PACL distribution within the stand

The SamsaraLight ray tracing model estimates a value of PACL for each cell making up the stand (here 10mx10m cells making up the 100mx100m 1ha stand). We calculated the mean PACL between the 100 cells (PACL indicator, which we used in this study as a stand-scale proxy for intercepted light and light available on the ground for regeneration). We also calculated the minimum and maximum values of PACL between the 100 cells of a stand. The figure 2 shows the relationships between silviculture and the minimum, mean and maximum values of PACL.

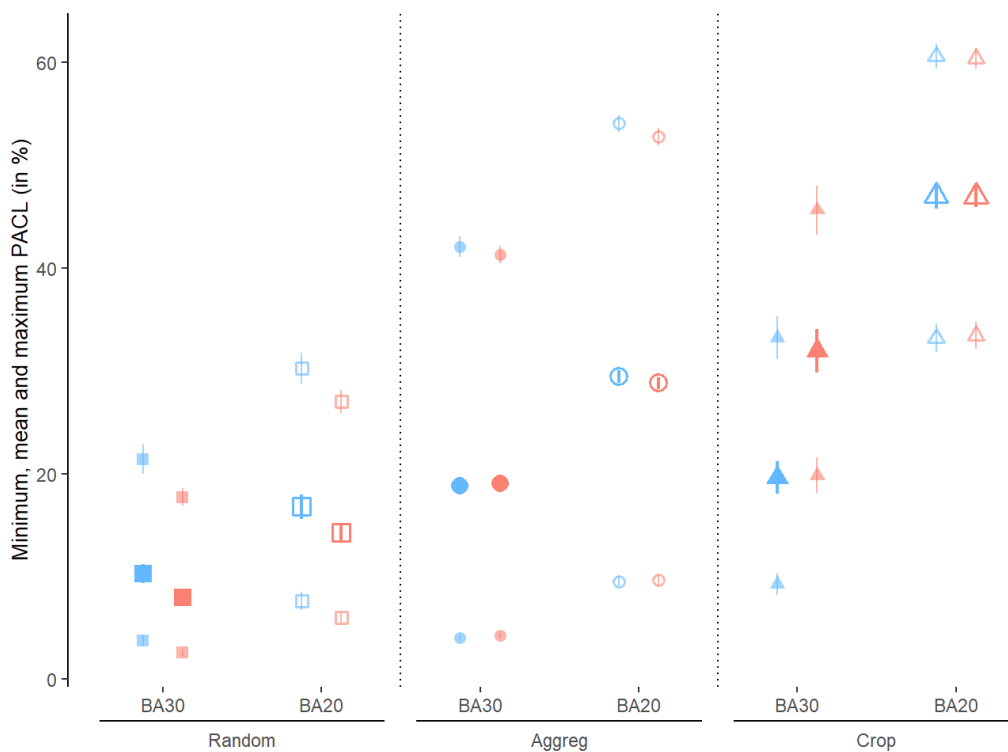


Figure 2: PACL summary statistics for each silviculture in each climate (cold-limited in blue and warmer in red). The larger symbols is the mean PACL and the smaller, brighter symbols are the minimum PACL value within the stand (for the bellow symbol) and the maximum PACL value within the stand (for the above symbol).

5 Relationships between light on the ground and stand structure

We selected the best predictive model based on model performance and parsimony criteria. The retained model highlights the relationships between mean PACL (in %) and key stand structure variables, including mean quadratic diameter (Dg), beech proportion, and total basal area (G).

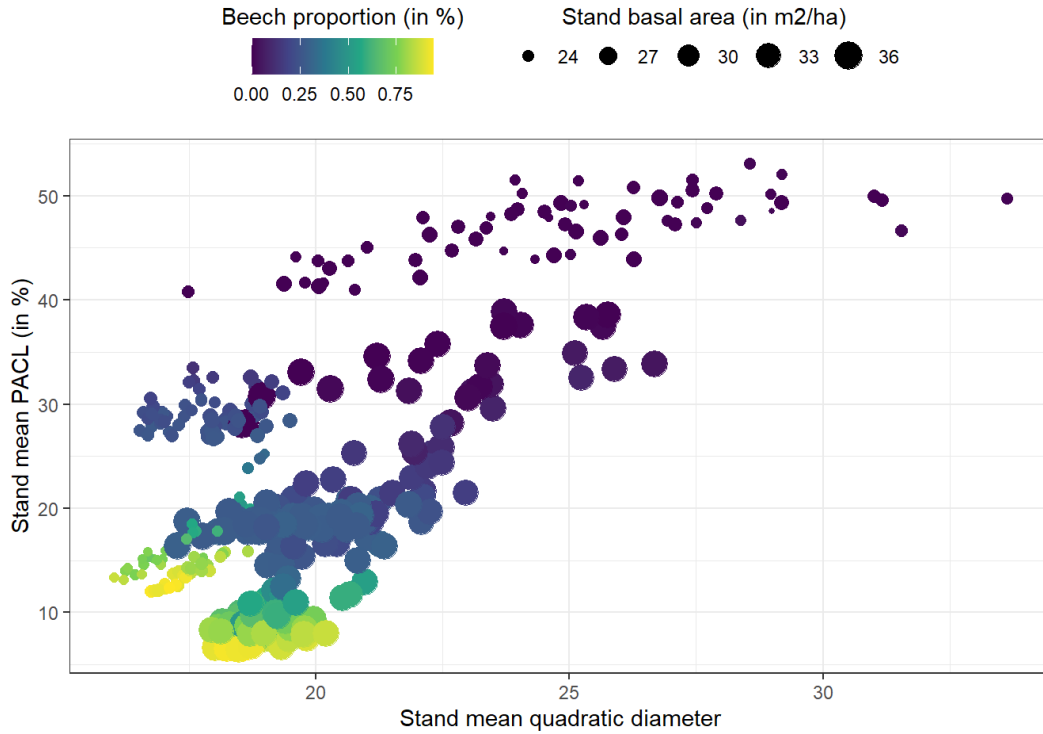


Figure 3: Relationships between mean PACL (in %) and stand structure variables (mean quadratic diameter Dg, beech proportion, and total basal area G).

$R^2 = 0.95$	Estimate	Std. Error	P-value
(Intercept)	40.10257	1.53574	***
G (m ² /ha)	-1.14238	0.02865	***
Dg (cm)	1.33557	0.05865	***
Beech proportion	-25.86675	0.60017	***

Table 2: Linear regression coefficients between mean PACL (in %) and stand structure variables (mean quadratic diameter Dg, beech proportion, and total basal area G).

6 Effect of silviculture and climate on tree size proportions

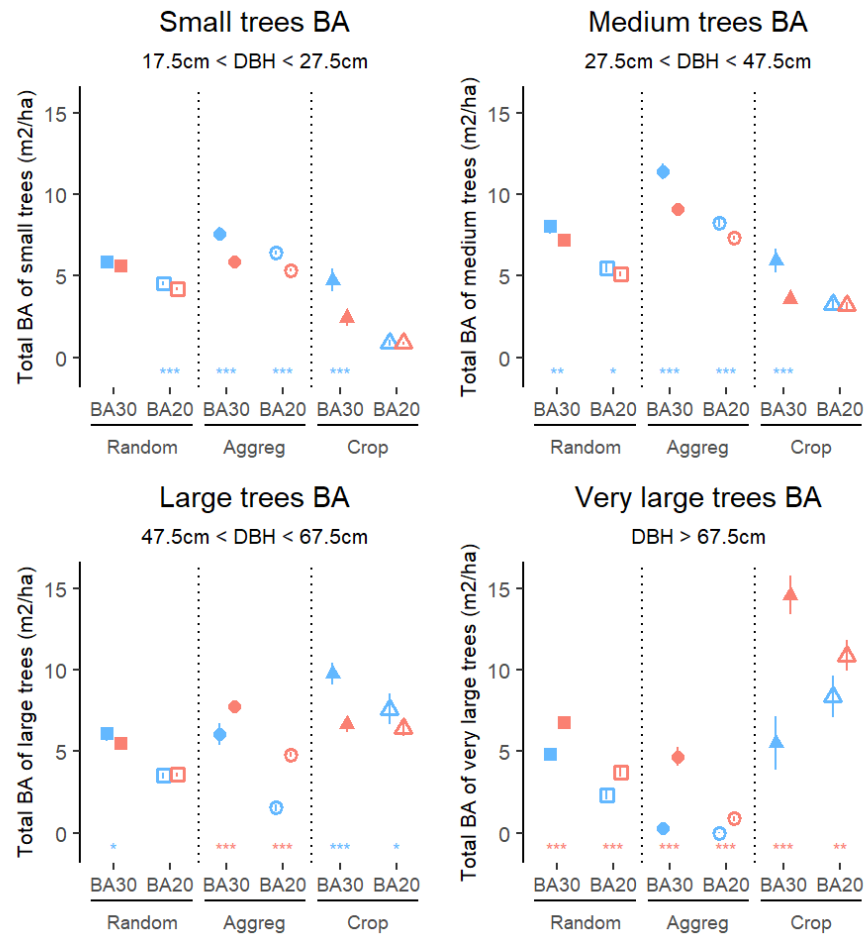


Figure 4: Total basal area per tree size classes for each climate (cold-limited in blue and warmer in red) and for each silviculture.

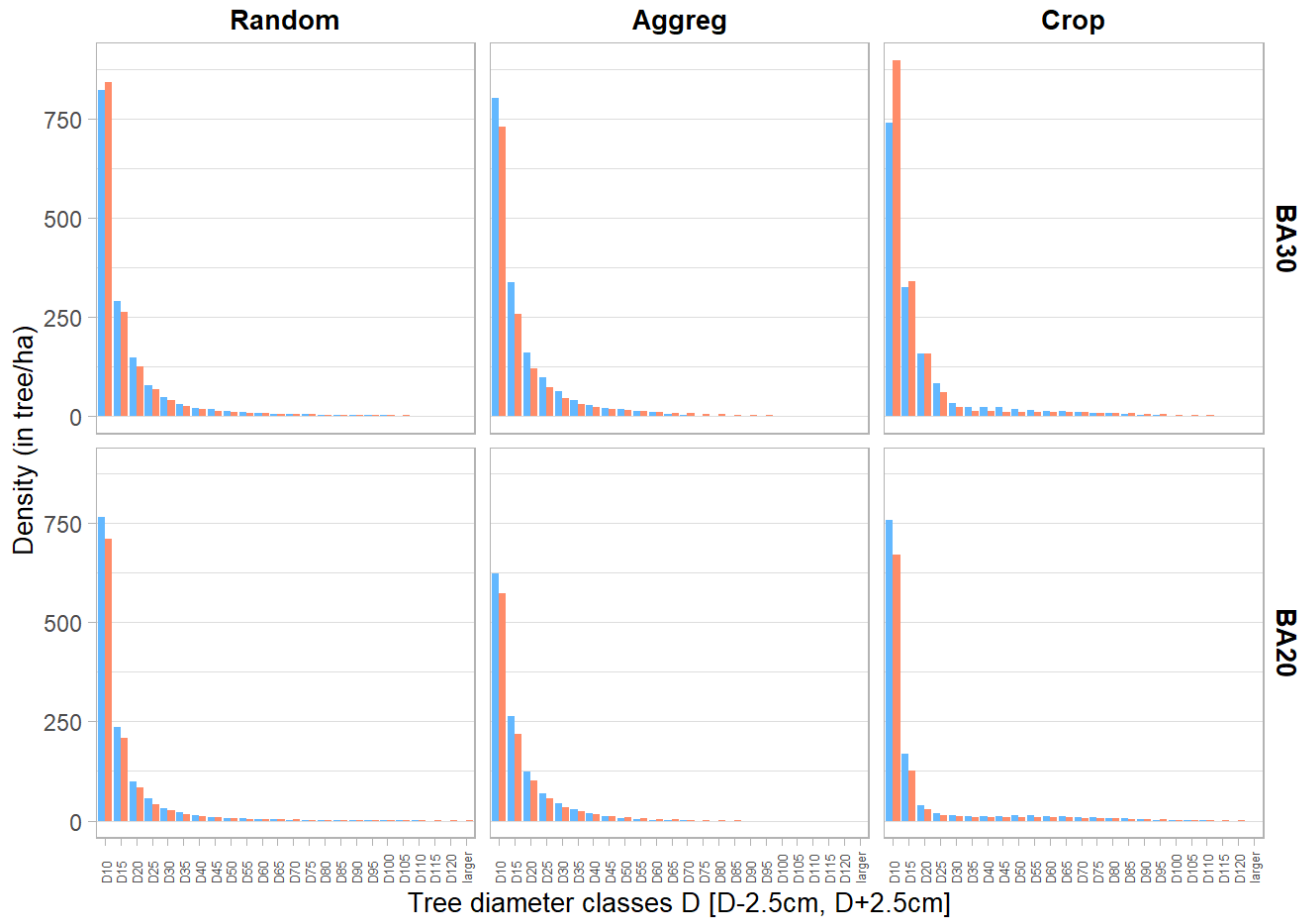


Figure 5: Mean tree density per tree size classes for each climate (cold-limited in blue and warmer in red) and for each silviculture.

97 **8 Effect of light on the ground and climate on demographic**
98 **processes**

GROWTH			
$R^2 = 0.91$	Estimate	Std. Error	P-value
(Intercept)	1.708e-01	2.150e-03	***
PACL	1.841e-03	8.076e-05	***
Climate (warmer)	9.268e-03	3.012e-03	**
Interaction effect	1.445e-03	1.102e-04	***

Table 3: Linear regression coefficients between mean PACL (in %) and climate (base modality: cold-limited) on annual mean tree DBH increment (in cm/year).

MORTALITY			
$R^2 = 0.74$	Estimate	Std. Error	P-value
(Intercept)	3.272e-03	1.338e-04	***
PACL	2.587e-05	5.024e-06	***
Climate (warmer)	4.658e-03	1.874e-04	***
Interaction effect	-9.056e-05	6.858e-06	***

Table 4: Linear regression coefficients between mean PACL (in %) and climate (base modality: cold-limited) on annual stand mortality rate (no unit).

PRODUCTION			
$R^2 = 0.97$	Estimate	Std. Error	P-value
(Intercept)	9.390	0.042	***
PACL (PACL value)	-0.098	0.001	***
Climate (warmer)	2.670	0.036	***

Table 5: Linear regression coefficients between mean PACL (in %) and climate (base modality: cold-limited) on annual stand volume increment (in m³/ha/year).

RECRUITMENT						
$R^2 = 0.93$	Cold-limited			Warmer		
	Estimate	Std. Error	P-value	Estimate	Std. Error	P-value
(Intercept)	-3.763	0.040	***	-3.501	0.030	***
PACL	0.008	0.002	***	0.005	0.002	**
Ψ_1	33.034	1.282	NA	29.306	0.562	NA
PACL after Ψ_1	0.082	0.007	NA	0.066	0.003	NA

Table 6: Segmented linear regression coefficients between mean PACL (in %) and climate (base modality: cold-limited) on annual recruitment rate (no unit, with neperian logarithm transformation). Ψ_1 represents the PACL limit between the two linear regressions.

9 Effect of light on the ground, silviculture and climate on production and recruitment

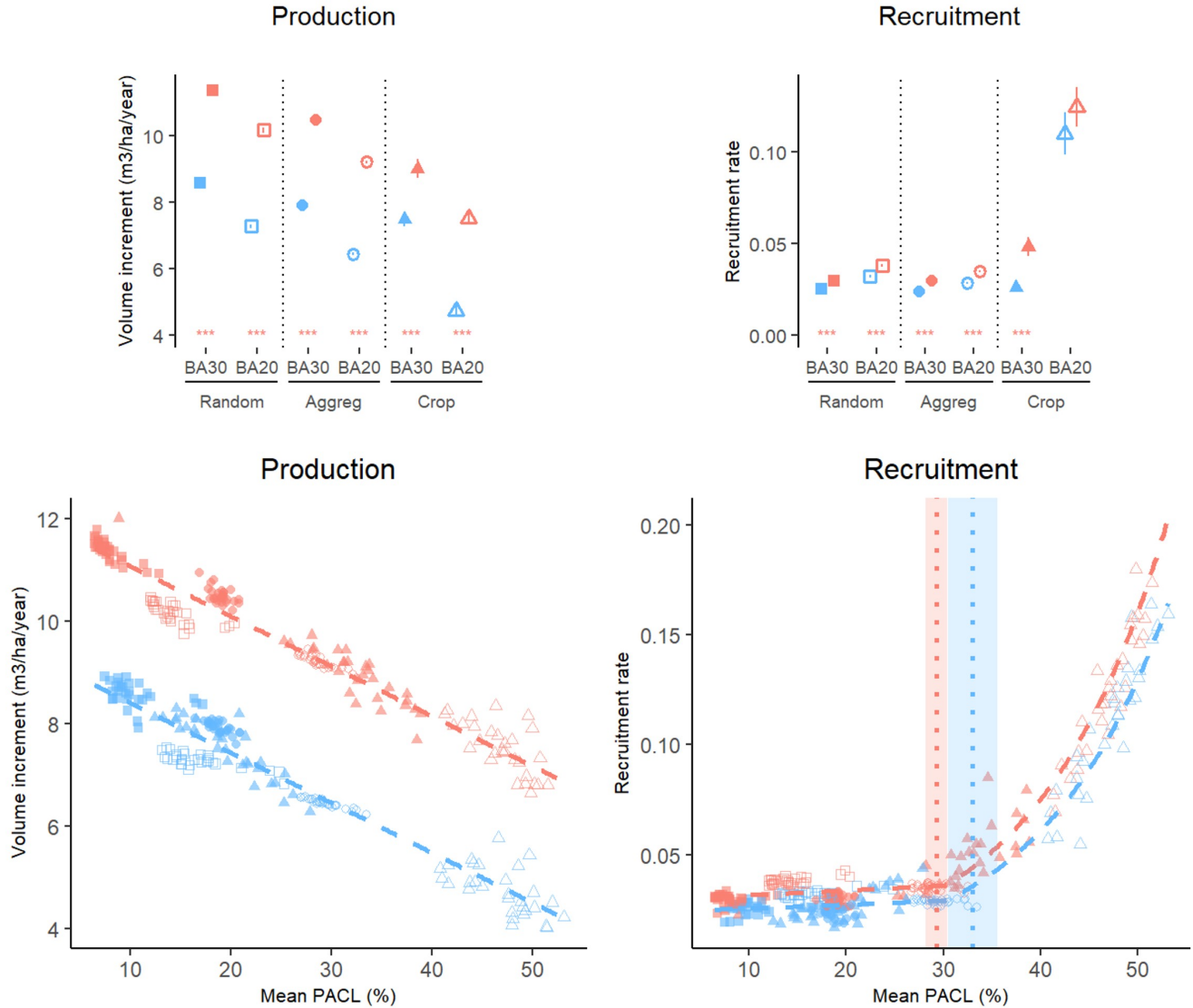


Figure 6: Top panel shows the mean stand volume increment (in m³/ha/year) and annual recruitment rate for each climate (cold-limited in blue and warmer in red), and for each silviculture. Bottom panel shows the relationships between mean PACL (in %) and both production and recruitment demographic process in each climate. For recruitment, the vertical-coloured dotted line represents the estimated breakpoint for each climate, with the associated uncertainties around the mean.

102 **10 Effect of silviculture and climate on harvested timber**
103 **volume**

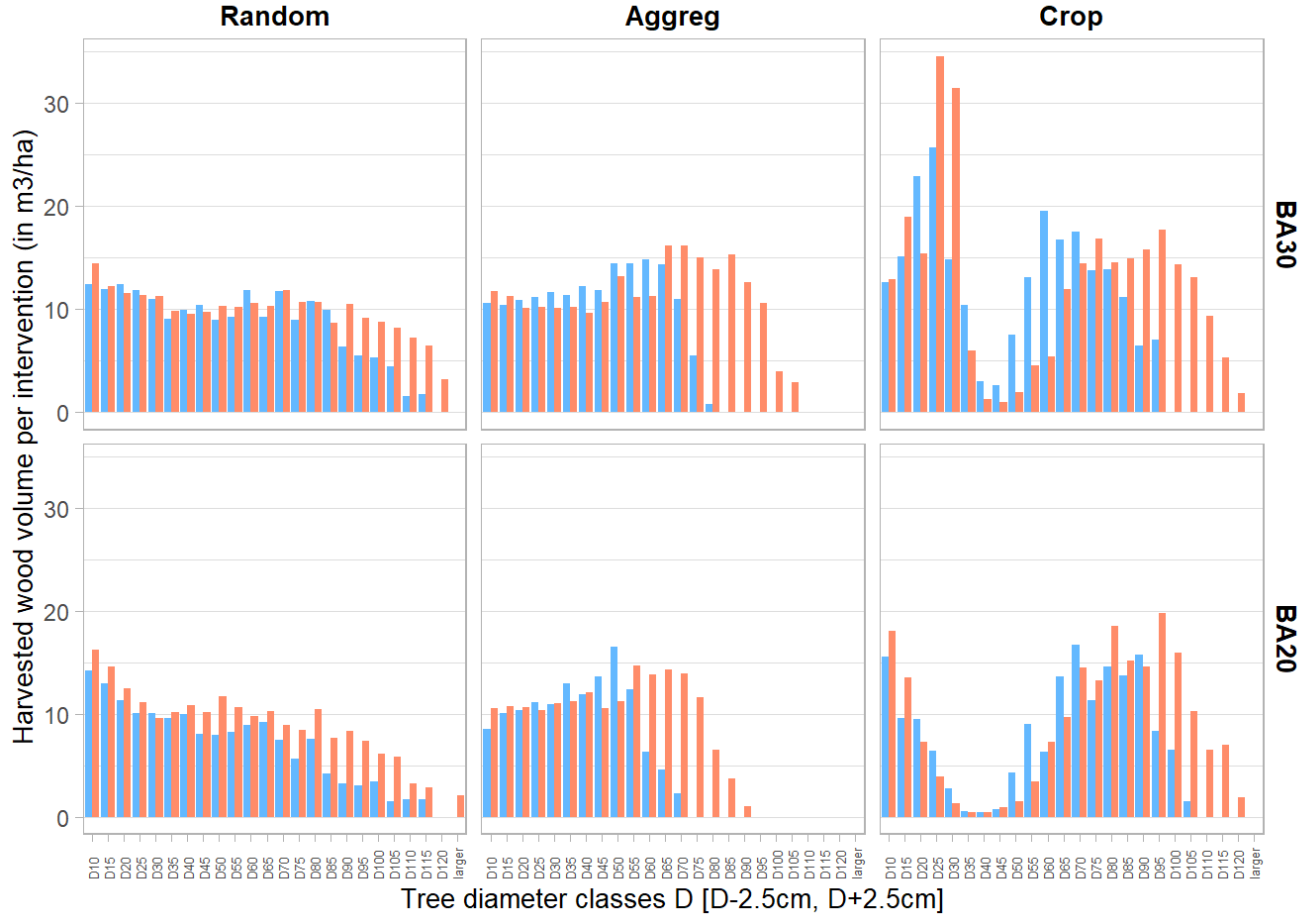


Figure 7: Mean harvested timber volume per intervention in different tree diameter classes, per climate and per silviculture.

104 **11 Effect of silviculture and climate on forest functions**
 105 **and services**

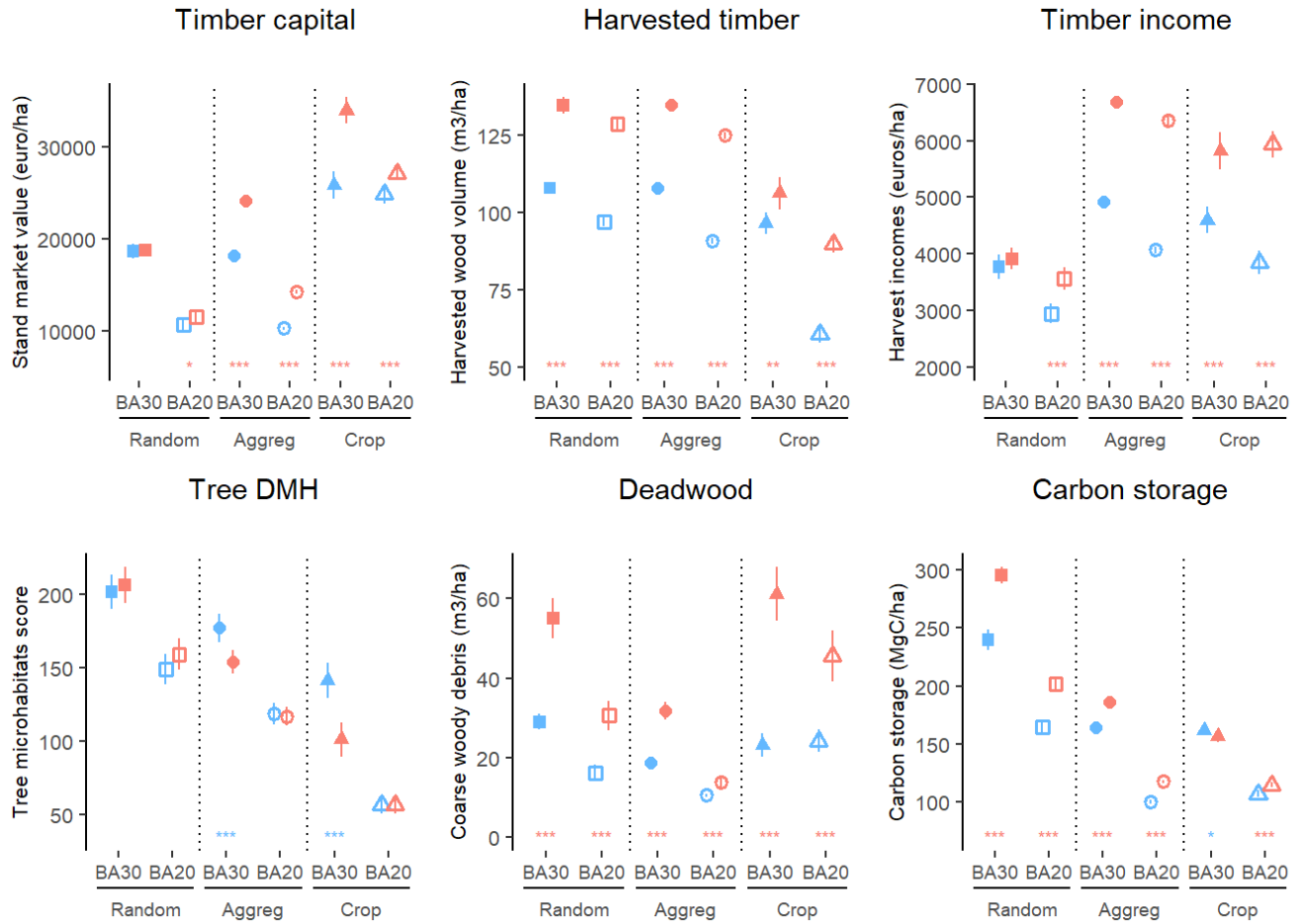


Figure 8: Forest function and services values for each silviculture and each climate (cold-limited in blue and warmer in red).

12 Comparison of economic and environmental score change with climate between silviculture

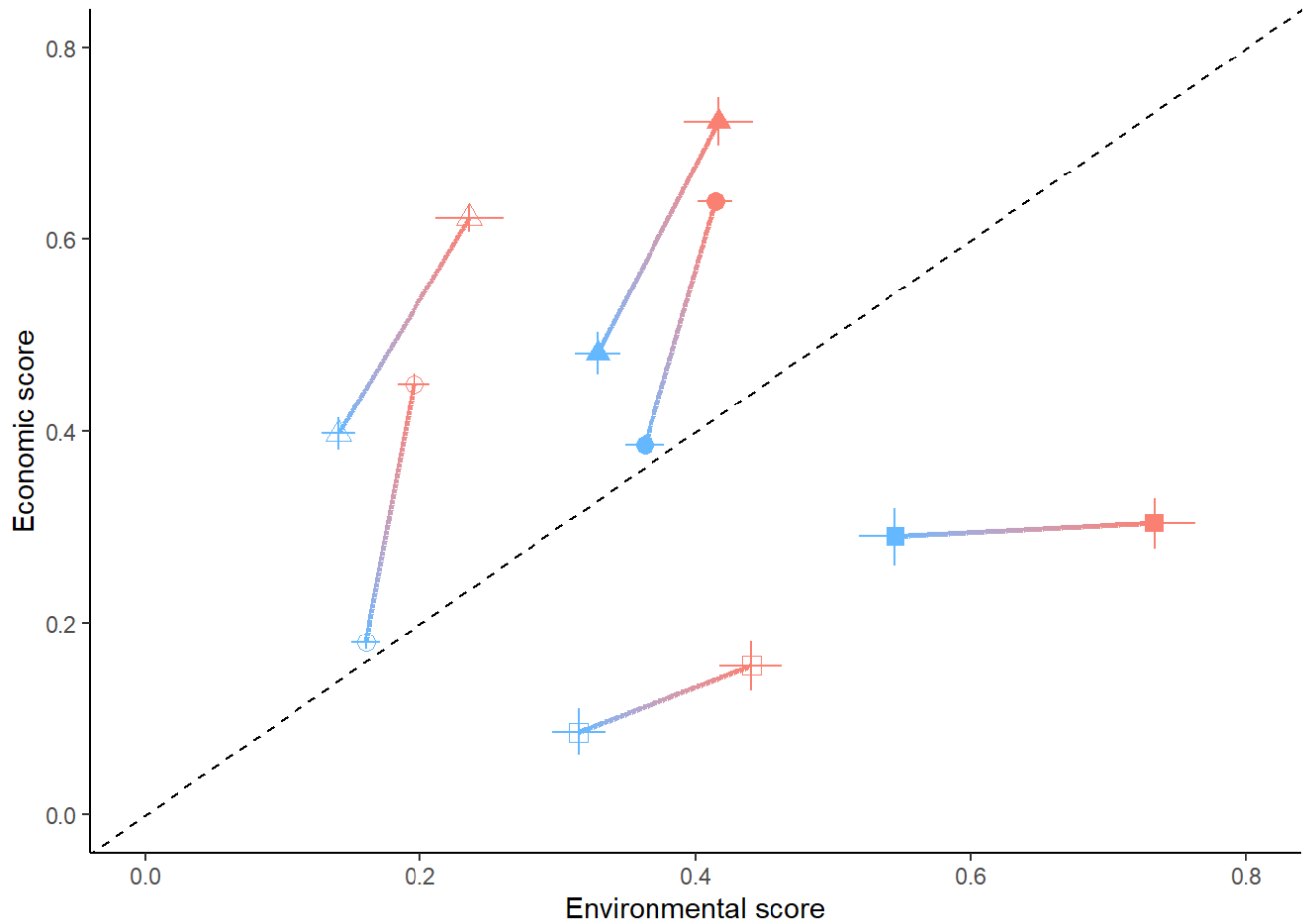


Figure 9: Mean economic and environmental score of each silviculture and climate with the 95% confidence interval. The arrow represents the change of the score of a given silvicultural modality from a cold-limited climate to a warmer climate.