

FATE-HD: A spatially and temporally explicit integrated model for predicting vegetation structure and diversity at regional scale. Boulangeat Isabelle, Georges Damien, Thuiller Wilfried.

Appendix S1 Detailed model description

SHADING

The vegetation in each pixel is stratified and the number of strata is a free parameter that can be set according to the vegetation under investigation. The light condition is calculated for each stratum according to the total abundance of the PFGs across all the upper strata and then converted to three classes (shade, half-shade, and full high) according to the respective abundance thresholds: 3,000; 7,000; 10,000. Shade tolerance is given as binary parameters for these three classes. The light conditions influence the germination, recruitment and survival for each PFG depending on its tolerance (see below).

DEMOGRAPHIC PROCESSES

Germination: For each light class (shade, half-shade, full light), the germination rate of a PFG is given as a proportion of the germination under optimal conditions.

Recruitment: Recruitment occurs at a probability given by the habitat suitability and if the light conditions are suitable to the PFG. To determine the number of seedlings, we assume that age-related mortality is equal to recruitment in the best conditions (i.e. when habitat and light conditions are suitable, and considering a balance between the number of dispersed seeds and the seed input). The number of seedlings S in a favorable environment is thus expressed as:

$$S = G \cdot A_{\max} / (L - M),$$

where G is the number of germinants, A_{\max} is the maximum abundance of mature PFG, L the longevity and M the maturity age.

Growth is taken into account using a set of fixed parameters that define the ages at which each PFG reaches each pre-defined stratum.

Survival: In addition to age-related survival (longevity), a PFG cohort dies when light conditions are no longer favourable.

Fecundity: The maximum number of produced seeds is a constant (=10,000) and fecundity only depends on the proportion of mature PFG among the maximum abundance of mature PFG. Fecundity is equal to zero when the habitat is not favorable.

THE INFLUENCE OF HABITAT SUITABILITY

Each year, the habitat (for each PFG in each pixel) is randomly assigned as suitable or unsuitable according to a Bernoulli distribution where parameter p equals the habitat suitability provided by the habitat suitability model. In practice, at each one-year step, a random number is drawn between 0 and 1, according to a uniform law, which gives the threshold to convert all suitability maps of all PFG into binary outputs. The annual variability in environmental conditions thereby affects all PFG in the same way, representing “good” and “bad” years for the vegetation.

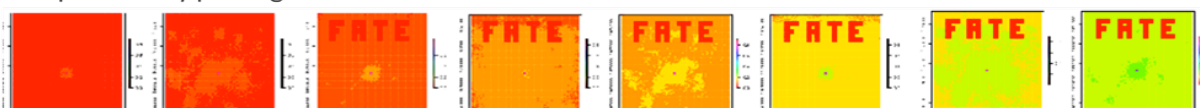
SEED DISPERSAL

The seed dispersal model is very fast to compute and gives very similar results to a probabilistic kernel (Fig. S1a). It is based on three parameters: $d50$ is the maximum distance within which 50% of the seeds are dispersed, $d99$ is the maximum distance within which 99% of the seeds are found in total, and ldd is the maximum long distance dispersal. For instance, for $d50 = 100\text{m}$, $d99 = 500\text{m}$ and $ldd = 1\text{km}$, the seeds available for dispersal will be allocated as follows:

- The central and four nearest neighbor pixels (red pixels, Fig. S1b) each receive 10% of the seeds for a total of 50% of the seeds
- Among the pixels in the first crown (blue pixels, Fig. S1b), six pixels (same number of pixels as in the central disc plus one to give an even number) are randomly chosen by grouping two adjacent pixels and each receives 8.17% of the seeds (see blue pixels marked with a circle, Fig. S1b), which gives a total of 49% of the seeds for the first crown.
- Among the pixels of the second crown (between 500m and 1km), one randomly chosen pixel receives 1% of the seeds

Fig. S1a. Comparison of the proposed seed dispersal algorithm with a probabilistic kernel function. Virtual tree species diffusion was simulated in a landscape of 100x100 cells. The simulation was initialised with four occupied pixels in the landscape. The dispersal parameters correspond to those described above. The habitat is unsuitable in the “FATE” zone only. The density of mature plants is shown every 10 years, from year 30 (left) to 100 (right). The succession parameters correspond to P1 (pioneer trees). In the first line, seed dispersal is modeled using the algorithm presented above. In the second line, seed dispersal is modeled using a negative exponential kernel function parameterised with the corresponding values. The colour scale ranges from red (no abundance) to light green (high abundance).

Dispersal « by packages »



Probabilistic dispersal kernel

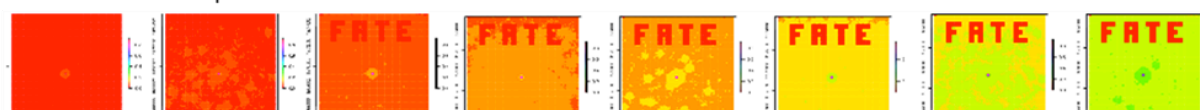
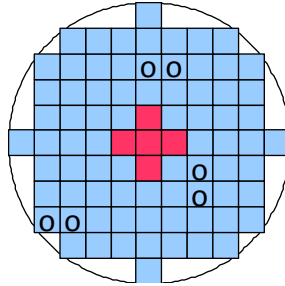


Fig. S1b. Neighbouring pixels considered in a short distance dispersal example. The resolution is 100m. The central pixel is the source. The maximum distance for 50% of the seeds is 100m and determines the position of the circle where 50% of the seeds are uniformly distributed. The maximum distance for 99% of the seeds is 500m, which means that 49% of the seeds end up in the crown between 100 and 500m. The remaining 1% seeds contribute to the long distance dispersal.



DISTURBANCES

The effects of each disturbance on the vegetation can be described by using the following parameters:

Parameters	Unit	Comments
Disturbance frequency	Year	
Response age classes thresholds	Year	For each PFG
Killed plants	Percentage	For each PFG and response age class
Resprouting plants	Percentage	For each PFG and response age class
Resprouting ages	Year	For each PFG and response age class
Activated seeds	Percentage	For each PFG
Killed seeds	Percentage	For each PFG

Fig. S1c. FATE Succession model structure. Within each grid-cell of the study area an independent FATE model object is created. This model object contains the PFGs cohorts from which the available amount of light in each stratum is calculated. In FATE-HD, all FATE model objects are spatially linked to each other through the seed dispersal model.

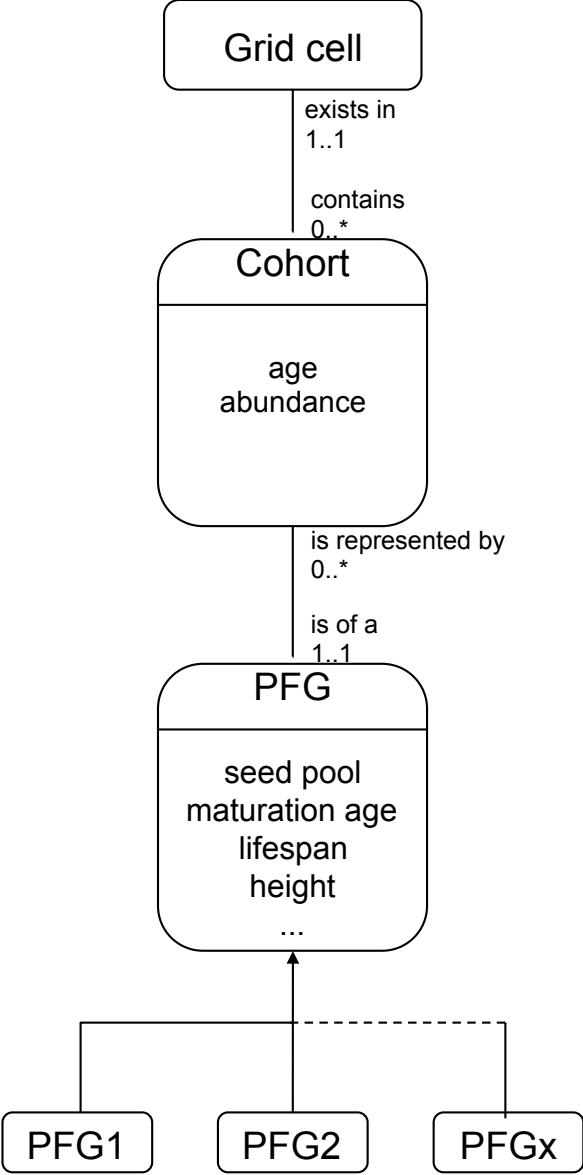


Fig. S1d. Influence of the three sub-models on the life cycle of each PFG in FATE-HD.

Only three age classes are considered: germinant, juvenile and mature. The recruitment is influenced by the habitat suitability and the biotic interactions. Mortality occurs when light conditions are not favorable or when the PFG completes its life span. In addition, the disturbance regime directly affects juvenile or mature PFG and may for instance result in PFG death, impede seed production by reducing mature PFG age to N-1, or revitalize senescent by reducing their age to M-1.

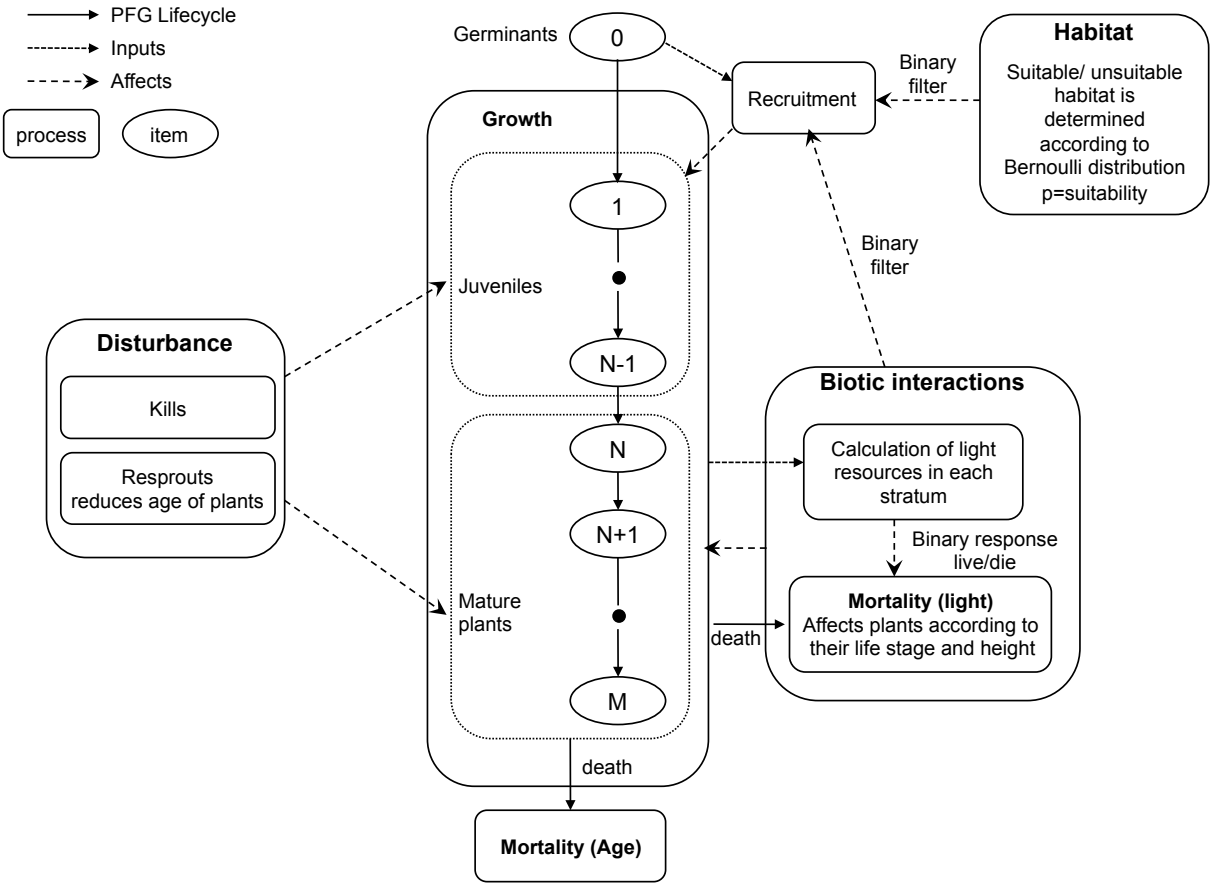


Fig. S1e. Seed cycle in FATE-HD. The seed cycle is central in FATE-HD because it is at the crossroads of all sub-models (habitat, disturbance, dispersal and succession). Mature PFG produce seeds in function of the suitability of the habitat in the grid-cell. Seeds are then dispersed and join the active seed pool of the grid-cell where they fall. Disturbance can affect the seed pool by killing seeds or activating dormant seeds (e.g. in fire-disturbed ecosystems). Seed dormancy can be parameterized, and in this case, seeds are aged. Germination rate may vary in function of light conditions.

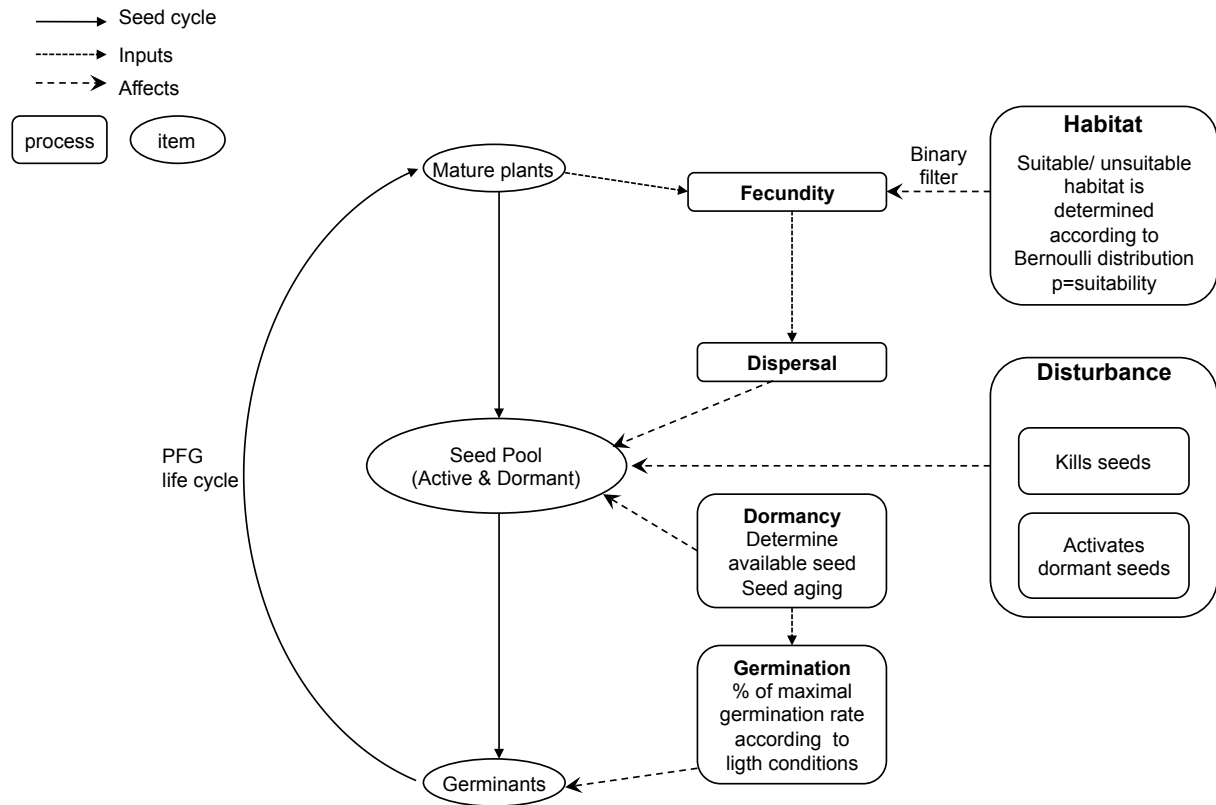
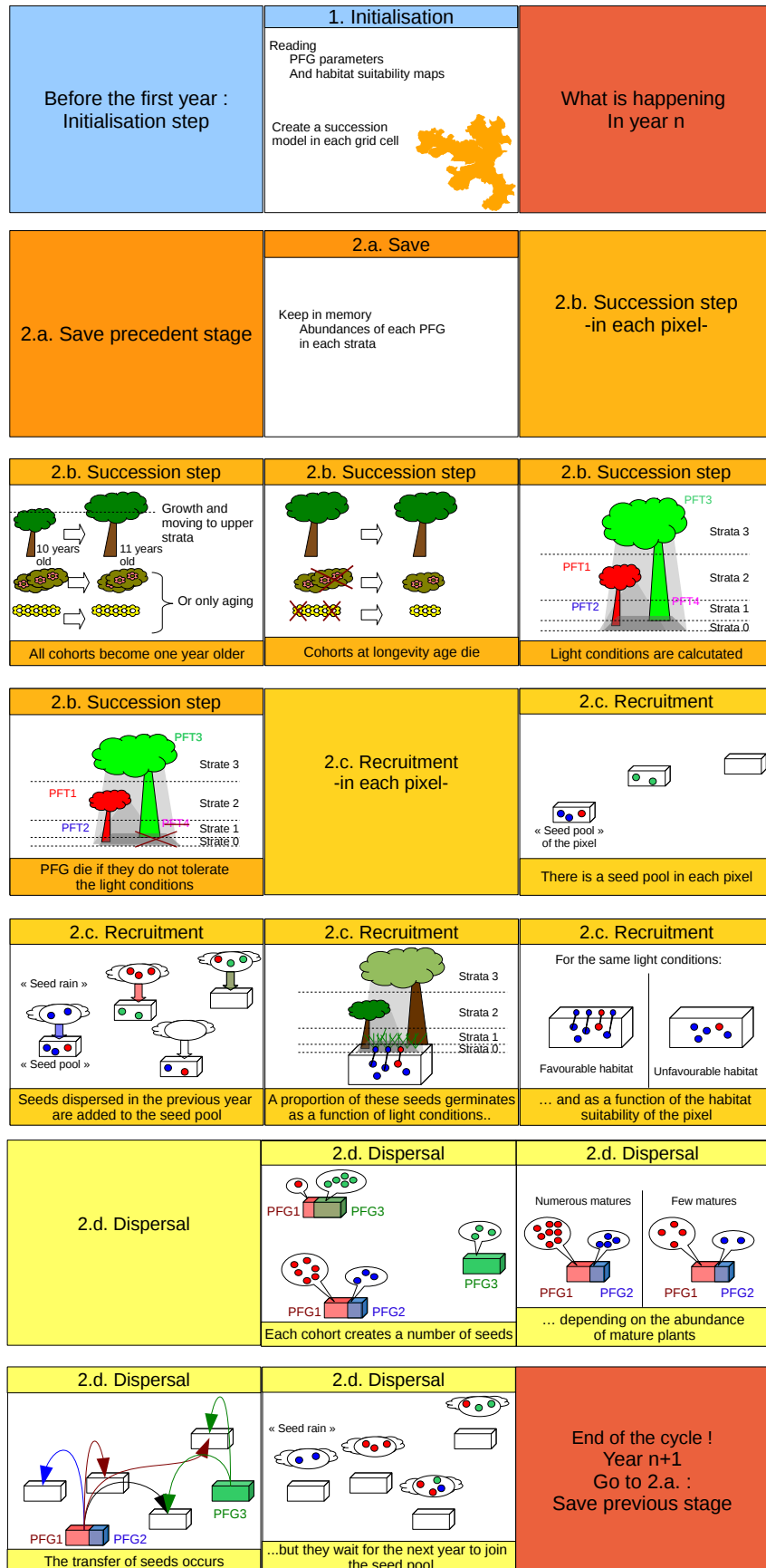


Fig. S1f. A graphic representation of FATE-HD workflow. The model is presented step by step and as a general overview.



	C1	C2	C3	C4	C5	C6	P1	P2	P3	P4	P5	P6	P7	P8
Maturity age (year)	5	4	6	10	8	8	15	15	18	15	25	20	15	15
Life span (year)	27	19	45	158	39	92	193	177	351	600	450	160	310	100
Maximum shade	3000	3000	3000	7000	3000	3000	10000	10000	10000	10000	10000	10000	10000	10000
Relative shade of immature vs mature plants (%)	100	100	100	50	100	100	10	50	10	10	10	10	50	50
Age to reach stratum 2 (1.5m)	10000	10000	10000	10	10000	10000	10	3	9	5	8	10	4	3
Age to reach stratum 3 (4m)	10000	10000	10000	10000	10000	10000	30	9	24	13	21	27	12	8
Age to reach stratum 4 (10m)	10000	10000	10000	10000	10000	10000	136	10000	79	37	61	89	10000	10000
Age to reach stratum 5 (20m)	10000	10000	10000	10000	10000	10000	10000	10000	10000	115	191	10000	10000	10000
Relative germination performance in the shade	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%
Relative germination performance in half-shade	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%
Relative germination performance in full light	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%
Tol. of germinants to shade	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
Tol. of germinants to half-shade	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
Tol. of germinants to full light	yes	yes	yes	yes	yes	yes	yes	yes	no	yes	no	yes	no	yes
Tol. of immature plants to shade	no	no	no	yes	yes	yes	yes	yes	yes	no	yes	no	yes	no
Tol. of immature plants to half-shade	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
Tol. of immature plants to full light	yes	yes	yes	yes	yes	yes	yes	yes	no	yes	yes	yes	yes	yes
Tol. of mature plants to shade	no	no	no	yes	yes	yes	yes	yes	yes	no	yes	no	yes	no
Tol. of mature plants to half-shade	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
Tol. of mature plants to full light	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
% of seeds that died each year	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Seed dormancy	no	no	no	no	no	no	no	no	no	no	no	no	no	no

Eq. S2. Growth. H (height) is expressed as a function of A (age).

$$H = H_{max} \cdot (1 - \exp(-k \cdot A))$$

where H_{max} is the canopy height and $k = -\frac{\log(1 - H_{imm})}{\frac{1}{2} \cdot A_{mat}}$ with H_{imm} as the relative size of immature

versus mature plants and A_{mat} the maturity age.

Tab. S2b Dispersal parameters. A dispersal class was given to each species of the study area according to the methodology proposed by Vittoz *et al.* (2007). This classification is based on the most efficient dispersal mode and takes into account plant dispersal attributes, distinguishing seven ordinal classes. For each PFG, the dispersal distance class was given by the median dispersal distance class of its determinant species. For each dispersal class, the two first distance parameters were estimated in Vittoz *et al.* (2007) and are reported below. They correspond to the upper limits of the distances within which 50% and 99% of the seeds of a PFG cohort within a pixel are dispersed. The long dispersal distance was set to 1km for classes 1 to 3, 5km for the classes 4 and 5 and 10km for classes 6 and 7, as proposed in Engler & Guisan (2009).

PFG	Dispersal class	Maximal distance for 50% of seeds (m)	Maximal distance for 99% of seeds (m)	Long distance dispersal (m)
C1	6	400	1500	10000
C2	4	40	150	5000
C3	1	0.1	1	1000
C4	6	400	1500	10000
C5	6	400	1500	10000
C6	7	500	5000	10000
H1	3	2	15	1000
H10	7	500	5000	10000
H2	6	400	1500	10000
H3	7	500	5000	10000
H4	3	2	15	1000
H5	3	2	15	1000
H6	3	2	15	1000
H7	5	100	500	5000
H8	3	2	15	1000
H9	7	500	5000	10000
P1	6	400	1500	10000
P2	5	100	500	5000
P3	4	2	15	1000
P4	6	400	1500	10000
P5	6	400	1500	10000
P6	4	40	150	5000
P7	4	40	150	5000
P8	4	40	150	5000

Disturbance parameters

Tab.S2c Response to mowing. The parameterisation was carried by the experts of the National Park. Mowing was assumed to include the removal of all trees in the field.

Herbaceous			Chamaephytes			Phanerophytes	
Juveniles were unaffected Senescents (longevity – 2) were all killed			One year old individuals were not affected All other juveniles were killed Senescents (longevity – 2) were all killed			Trees above 1.5m were all killed, assuming that mowing is associated with destruction of trees	
PF _G	Mature plants that did not produced seeds	Mature plants that were killed	PF _G	Mature plants that did not produced seeds	Mature plants killed	PF _G	Juveniles of one year that were killed
H1	50%	40%	C1	50%	50%	P1	80%
H2	90%	0%	C2	50%	50%	P2	80%
H3	90%	0%	C3	-	100%	P3	100%
H4	-	100%	C4	-	100%	P4	100%
H5	90%	0%	C5	-	100%	P5	100%
H6	50%	40%	C6	-	100%	P6	100%
H7	50%	40%				P7	100%
H8	50%	40%				P8	100%
H9	90%	0%					
H10	90%	0%					

Tab.S2d Response to grazing for herbaceous and herbaceous chamaephytes. C3, C5, H4, H7 and H8 were unaffected. 3 different types of grazing were differentiated: G1= light grazing; G2= extensive grazing; G3= intensive grazing. The parameterisation was carried out with PNE experts and according to the palatability of the determinant species of each PFG (Jouglet *et al.*)

	C6		C1, C2, H1, H2, H3, H5, H6, H9, H10	
G1	<i>Juv.</i>	10% killed	<i>Juv.</i>	10% killed
	<i>Mat.</i>	10% no seeds	<i>Mat.</i>	50% no seeds
	<i>Sen.</i>	10% respr.	<i>Sen.</i>	10% respr.
G2	<i>Juv.</i>	10% killed	<i>Juv.</i>	50% killed
	<i>Mat.</i>	90% no seeds	<i>Mat.</i>	100% no seeds
	<i>Sen.</i>	50% respr.; 10% killed	<i>Sen.</i>	50% respr.; 10% killed
G3	<i>Juv.</i>	50% killed	<i>Juv.</i>	90% killed
	<i>Mat.</i>	100% no seeds	<i>Mat.</i>	90% no seeds; 10% killed
	<i>Sen.</i>	50% respr.; 10% killed	<i>Sen.</i>	50% respr.; 50% killed

Tab. S2e Response to grazing for phanerophytes and shrub chamaephytes. 3 different types of grazing were differentiated: G1= light grazing; G2= extensive grazing; G3= intensive grazing. Individuals above 1.5m were unaffected. Percentages represent the proportion of killed plants.

	Age classes	P1	P2	P3	P4	P5	P6	P7	P8	C4
G1	1 year old	100%	100%	80%	100%	0%	-	40%	100%	100%
	<1.5m	-	-	-	-	-	-	-	-	-
G2	1 year old	100%	100%	80%	100%	-	-	40%	100%	100%
	<1.5m	-	-	-	50%	-	-	-	-	-
G3	1 year old	100%	100%	80%	100%	40%	100%	40%	100%	100%
	<1.5m	40%	40%	10%	80%	10%	40%	-	-	40%

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Appendix S3 Habitat suitability models

Calibration area

The habitat suitability models were calibrated over the whole French Alps (see Fig. 1 in the main text). We thus hope to better capture the potential niche of each plant functional group to then be able to project it onto our study area, the Ecrins National Park (Barbet-Massin *et al.* 2012).

From vegetation relevés to PFG presence-absence

We used the vegetation database from the Conservatoire Botanique National Alpin (CBNA), which has records of more than 3 million occurrences of plant species in the French Alps and 15,000 community plots for which the exhaustive list of species was recorded together with cover abundances (Braun-Blanquet, 1946). All records older than 1980 were excluded as well as ones made by unknown botanists and spatially inaccurate plots (uncertainty > 200m). Species nomenclature was standardised according to the *Index synonymique de la flore de France* (Kerguélen, 1993).

We considered a PFG to be present where at least one of its representative species was observed. A community plot (complete survey) where none of its determining species were observed was considered to be a true absence. In this way, we built presence-absence data for each PFG.

Environmental variables

We used seven environmental variables to model the large-scale abiotic constraints for each PFG.

- **The slope angle**, taken from the French Digital Elevation Model with 50x50m resolution, made by the IGN-France (<http://professionnels.ign.fr/bdalti>)
- **The percentage of calcareous soil** was calculated from the European Soil Database <http://eusoils.jrc.ec.europa.eu/data.html> with a 1km resolution. We calculated the percentage of the area of Soil Typological Units (STU) with calcareous dominant parent material for every Soil Mapping Unit (SMU) within the borders of the Alpine range (see also Dullinger *et al.* 2012).
- **Five bioclimatic variables** (isothermality, temperature seasonality, temperature annual range, mean temperature of coldest quarter, and annual precipitation). We selected these five variables because they are known to influence the physiology of species in the Alps (Körner 2004) and their pairwise correlations were low. Temperature and precipitation maps were downscaled to a resolution of 100m, from the 1 km Worldclim climate grids

available online, using a specific method that was developed to represent the topographic variation of climate in Mountainous areas better (Dullinger *et al.* 2012).

Building the habitat suitability models

All models were built using the *biomod2* package (Thuiller *et al.* 2009) in R (2011). Amongst the available algorithms, we selected five different ones using default settings: Generalized Linear Model, Boosted Regression Trees, Generalized Additive Model, Multivariate Adaptive Regression Splines and Random Forest. We selected the algorithms which are known to provide good predictions and which encompass the different families available in the field.

In order to compare the habitat suitability of all PFG, we made sure that equal weightings were given to the presences and absences for each PFG. We thus weighted the presence and absence of each PFT in the modelling procedure to give a prevalence of 0.5. This ensured that the models were comparable, one to another, whatever the PFG distribution (narrow, wide spread, etc.).

The models were calibrated using a random data sample (70%) and evaluated using the remaining 30% with True Skill Statistics (TSS, Allouche *et al.* 2006). The whole cross-validation process was repeated 10 times.

Ensemble Forecasting

We used an ensemble forecasting strategy to derive the probability of occurrence (i.e. habitat suitability value) for each PFG across the national park using the following method: (1) All models were used to project the potential habitat suitability for each PFG; (2) We transformed the probabilities of presence into presences and absences using the threshold which maximised the TSS in the evaluation procedures. (3) We calculated the sum of all binary projections weighted according to their TSS score. (4) We rescaled the projection to fall between 0 and 1. This latter projection gives the habitat suitability map for each PFG (Figure S3). This ensemble forecast gives the percentage of agreement between the different algorithms and the different cross-validation datasets for predicting a presence. The higher the value, the more plausible the presence.

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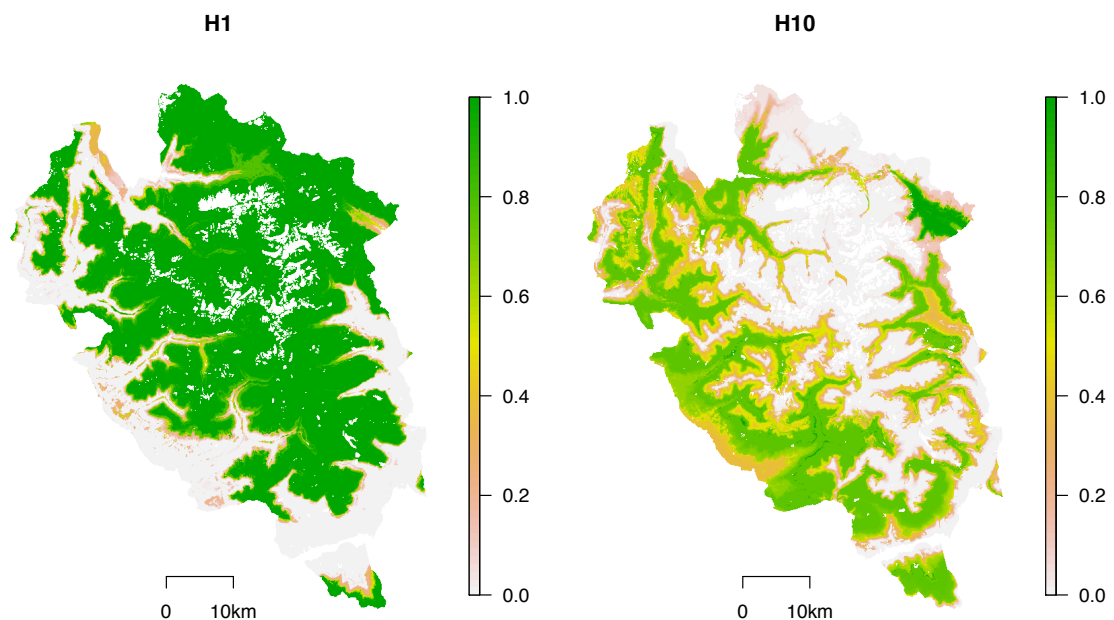
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Figure S3. Habitat suitability map for each PFG. The following set of figures represents the habitat suitability under current conditions for (a) Herbaceous, (b) Phanerophyts and (c) Chamaephyts. The habitat suitability varies from 0 (unsuitable area, light grey) to 1 (high suitability, green). The interpretation of each PFG is given in Tab. 2 (main text).

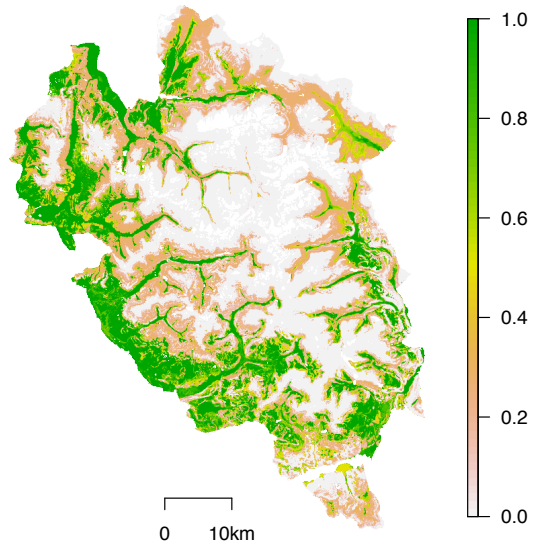
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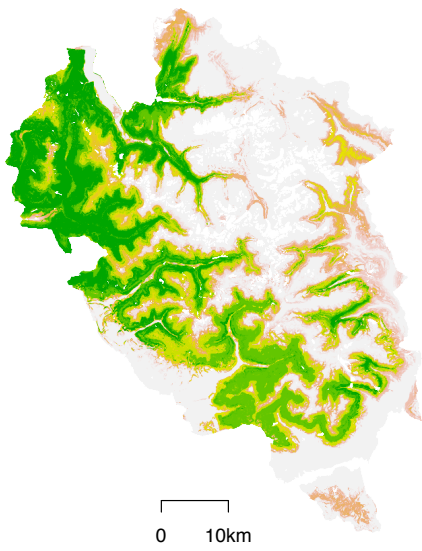
H2



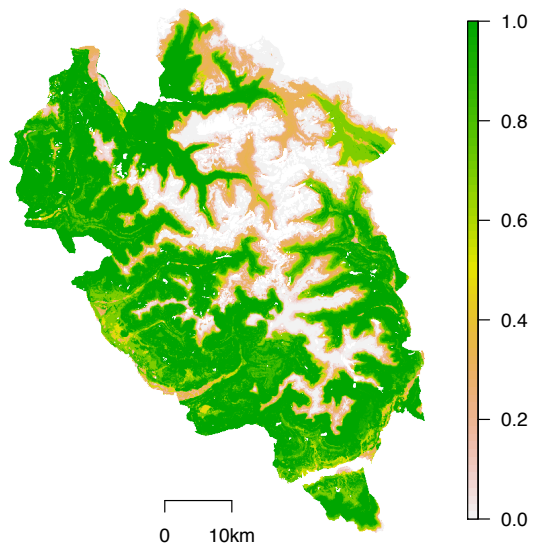
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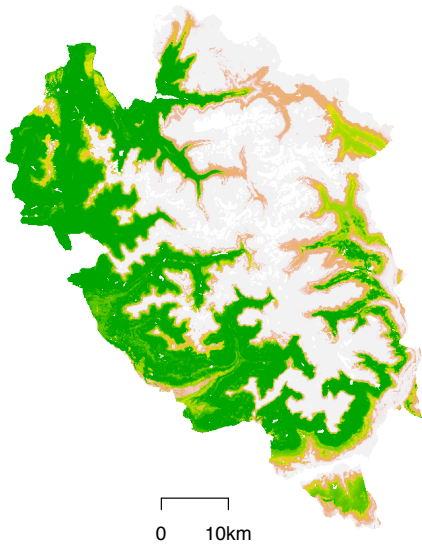
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H5



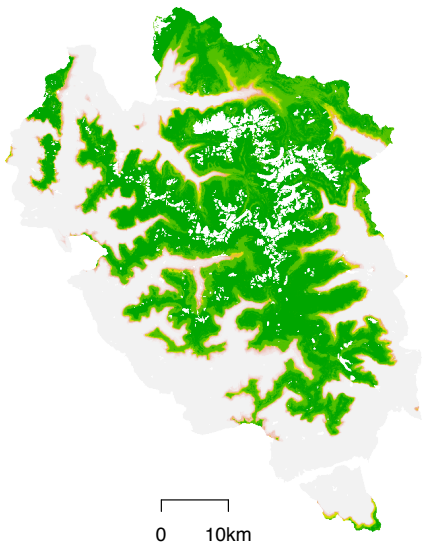
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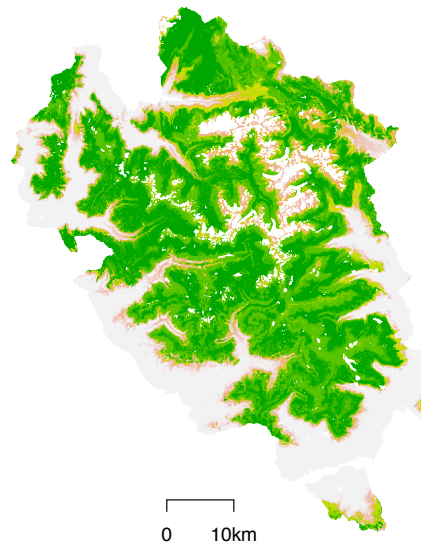
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H8

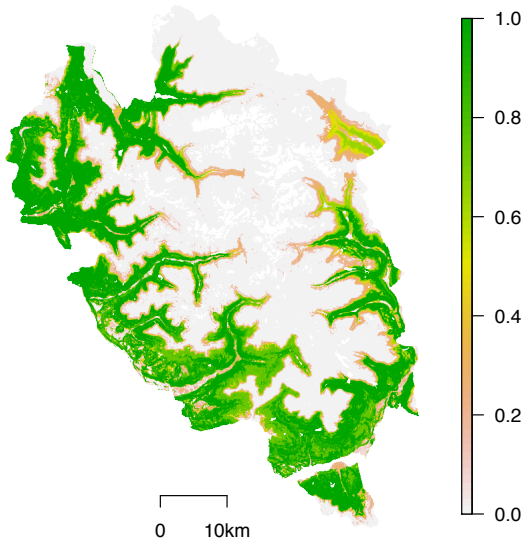


H9

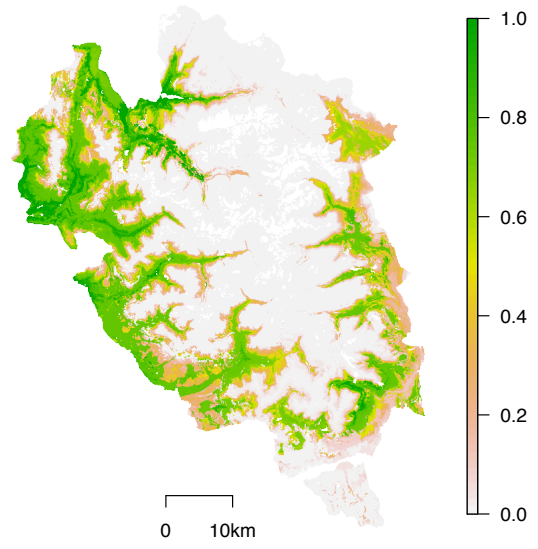


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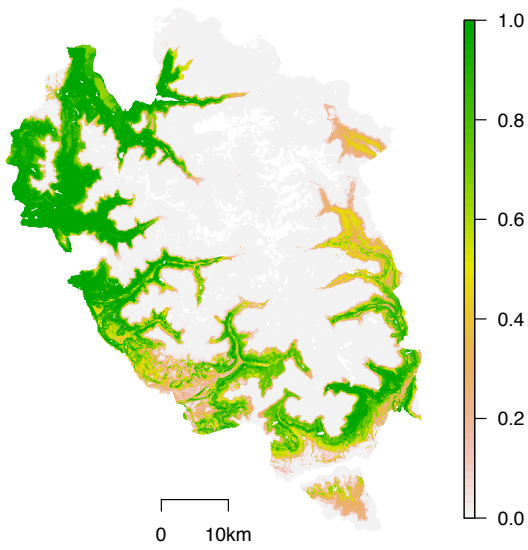
P1



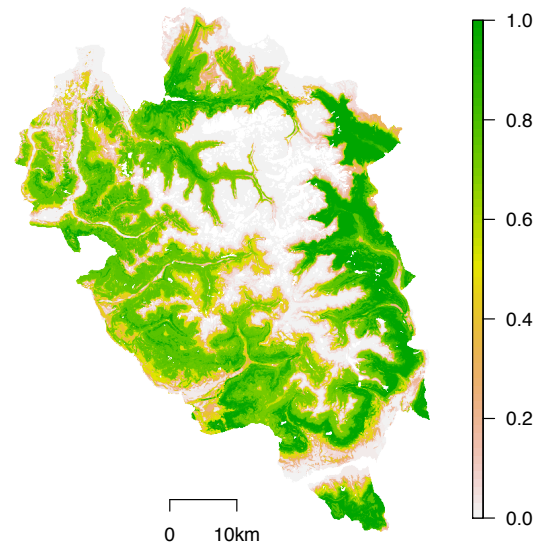
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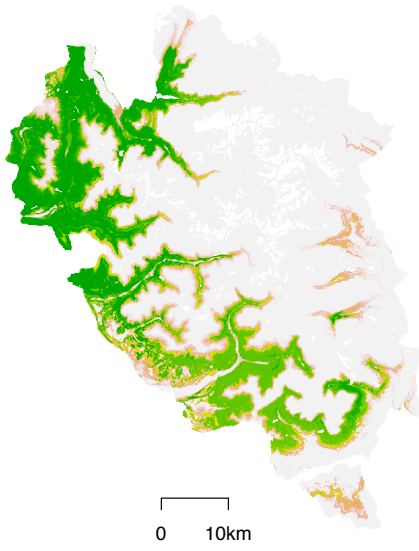
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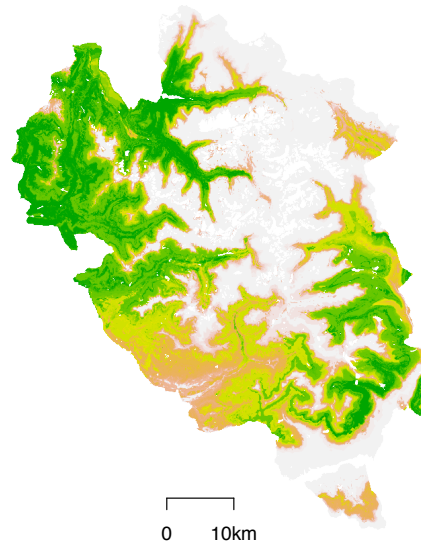
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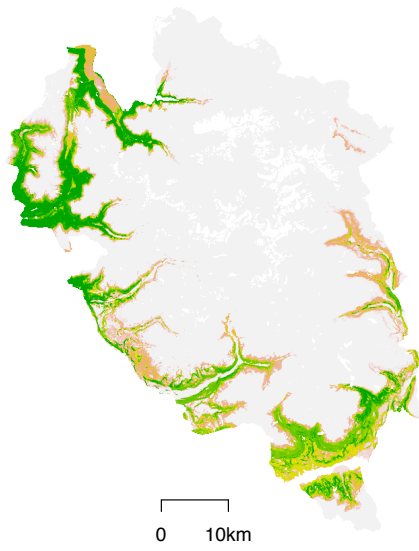
P5



P6



P7

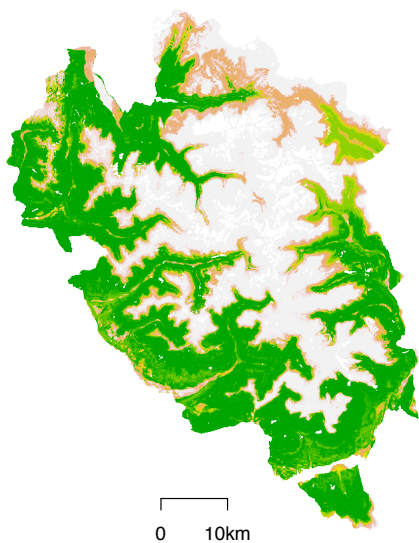


P8

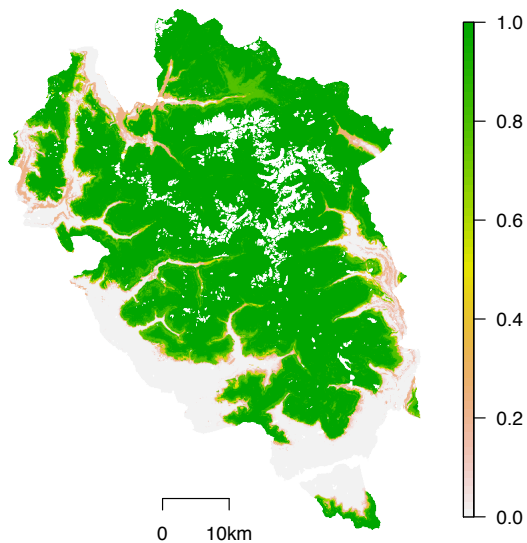


(c)

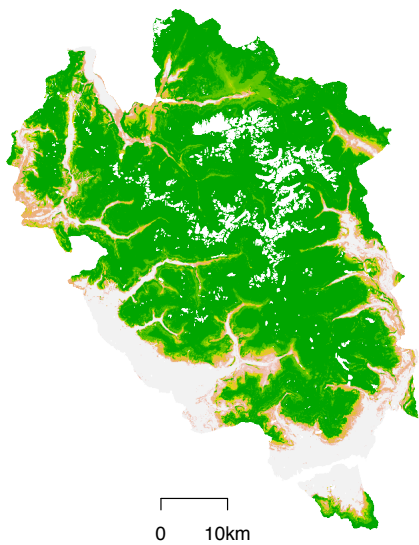
C1



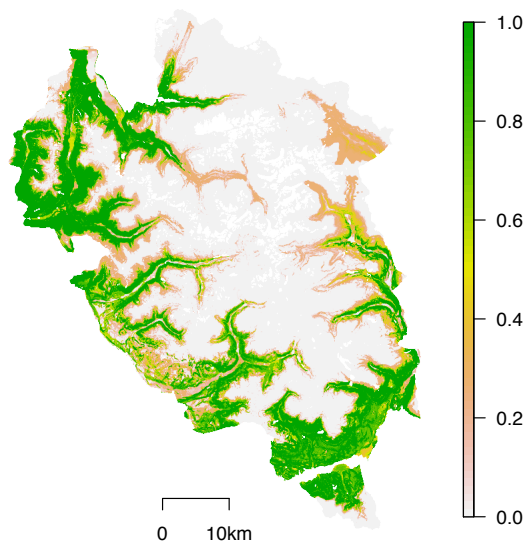
C2



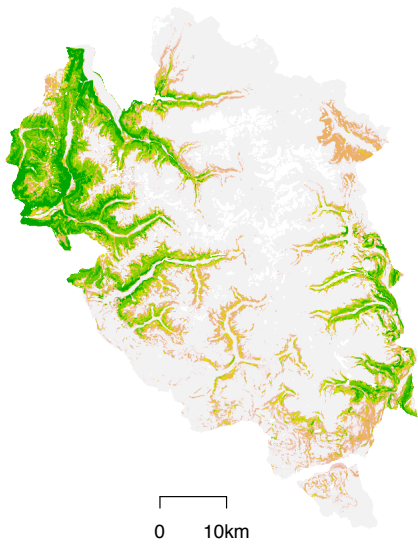
C3



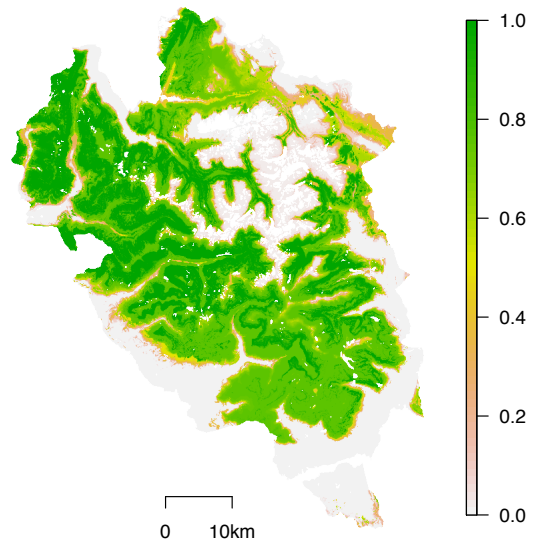
C4



C5



C6



Appendix S4 PFGs to vegetation types correspondence table

Broad category	Habitat type	Name of the vegetation type	H1	H2	H3	H4	H5	H6	H7	H8	H9	H10	C1	C2	C3	C4	C5	C6	P1	P2	P3	P4	P5	P6	P7	P8	
Alpine habitats	Snow packs	Snow pack with mosses	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	
		Snow pack	1	0	0	0	0	0	0	0	1	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0
		Snow-covered grassland	2	0	0	0	0	0	0	0	0	2	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
	Alpine grasslands	Sparse grassland	2	2	0	0	1	0	0	1	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
		Dense alpine grassland	1	2	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Heathland with <i>Vaccinium uliginosum</i>	2	0	0	0	0	0	1	1	1	0	1	1	2	1	1	1	0	0	0	0	0	0	0	0	0
	Alpine calcareous crests	Alpine crests	2	1	0	0	0	0	0	1	1	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0
		Alpine slopes	2	1	0	0	0	0	0	1	1	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0
		Crest's dwarf-shrub heathland	1	0	1	0	0	0	0	0	0	0	0	0	2	2	0	0	0	0	0	0	0	0	0	0	0
	Alpine silicious crests	Siliceous sunny slope	2	1	0	0	0	0	0	1	1	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0
Siliceous north slope		2	1	0	0	0	0	0	1	1	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	
Dwarf-shrub heathland		2	1	0	0	1	0	0	0	1	0	1	2	2	0	1	0	0	0	0	0	0	0	0	0	0	
North slope subalpine habitats	Cold megaphorbia and alder bush	0	2	2	2	1	2	0	0	0	2	1	0	0	2	0	0	0	0	0	1	2	0	0	0	1	
	Ericaceous heathland	0	2	2	2	1	1	1	1	1	1	1	1	0	2	1	2	2	1	0	0	1	0	1	0	0	
	Dwarf-shrub heathland without trees	0	2	2	2	1	1	1	1	1	1	1	1	2	2	1	2	2	1	0	0	1	0	1	0	0	
Sunny slope subalpine habitats	Mesotherm megaphorbia and segde meadow	0	1	1	2	1	2	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
	Open heathland	0	1	1	1	1	1	0	1	0	1	1	1	2	2	1	1	1	1	0	0	0	0	1	0	0	
	Closed heathland	0	1	1	1	1	1	0	1	0	1	1	1	2	2	1	1	1	1	1	1	1	1	1	1	1	
	Wooded heathland	0	1	1	1	1	1	0	1	0	1	1	1	2	2	1	1	2	1	1	2	1	1	1	1	1	
	White birch (<i>Betula alba</i>) forest	0	1	1	2	1	1	1	0	0	1	1	1	1	1	0	1	1	1	0	0	0	0	0	0	2	
	Calcicolous vegetation	1	1	1	0	2	2	0	0	0	0	1	1	0	1	1	1	1	0	0	0	0	0	0	0	0	
	Junipers' heathland	0	0	0	0	1	0	1	1	1	0	1	1	2	2	2	1	1	1	1	0	0	1	0	0	0	
Naturally disturbed subalpine habitats	Wooded heathland with <i>Vaccinium myrtillus</i>	0	0	1	1	1	1	1	0	0	0	1	0	2	1	1	2	1	1	1	1	0	1	0	0	0	
	Wooded heathland without <i>Vaccinium myrtillus</i>	0	0	1	1	1	1	1	0	0	0	2	0	2	1	1	0	1	1	1	1	0	2	0	0	0	
	Heathland under larch forest	0	0	1	1	1	1	1	0	0	0	2	0	2	1	0	1	1	0	0	2	0	0	0	0	0	
	Deciduous forest stand	0	1	1	1	0	1	1	0	0	1	0	0	0	1	1	1	1	2	2	2	0	1	1	2	2	

FATE-HD: A spatially and temporally explicit integrated model for predicting vegetation structure and diversity at regional scale. Boulangeat Isabelle, Georges Damien, Thuiller Wilfried.

Appendix S5 Initialization

Fig. S5a Evolution of PFG distribution areas as a function of time during seeding. Vertical orange dotted line indicates 150, 300 and 600 years after the beginning of the simulation. After 300 years, we can consider a quasi-equilibrium for all PFGs.

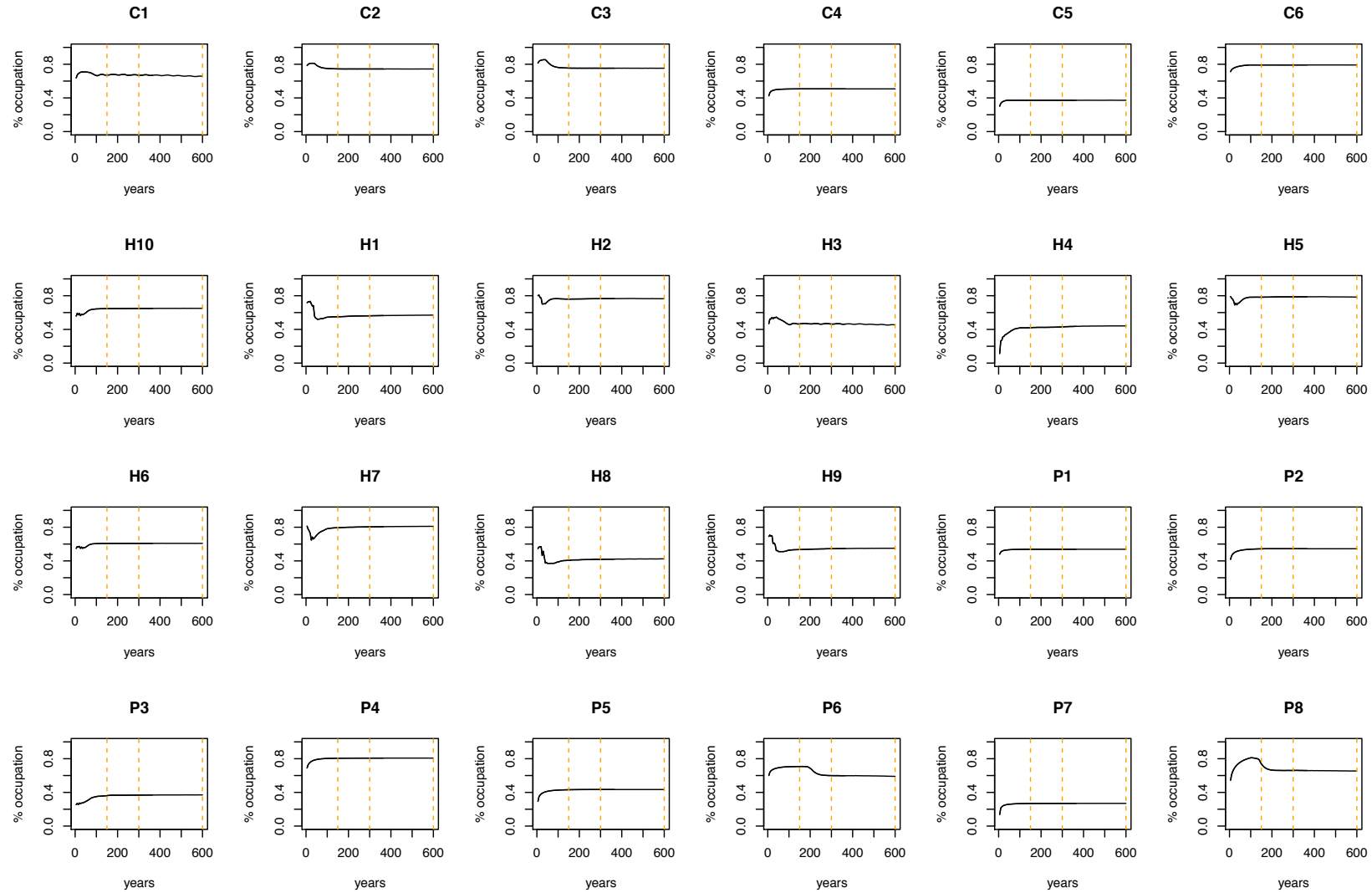


Fig. S5b Evolution of PFG distribution areas as a function of time after seeding stopped. Vertical orange dotted line indicates 150 and 300 years after seeding stop. After 500 years, we can consider a quasi-equilibrium.

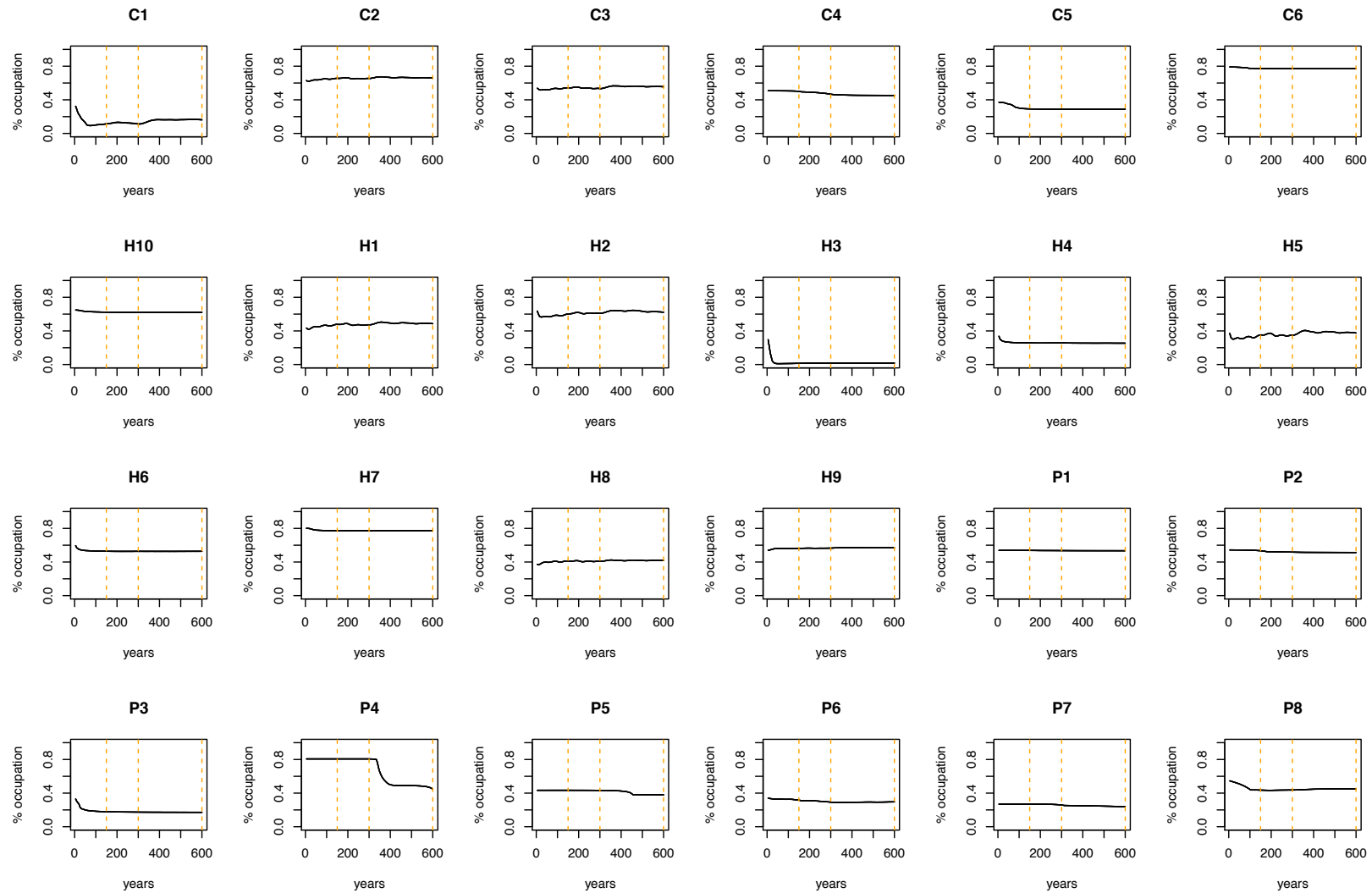


Fig. S5c Evolution of PFG distribution areas as a function of time after seeding stopped. Vertical black lines indicate the cut of all trees. Orange dotted line delineates the window where outputs were recorded.

