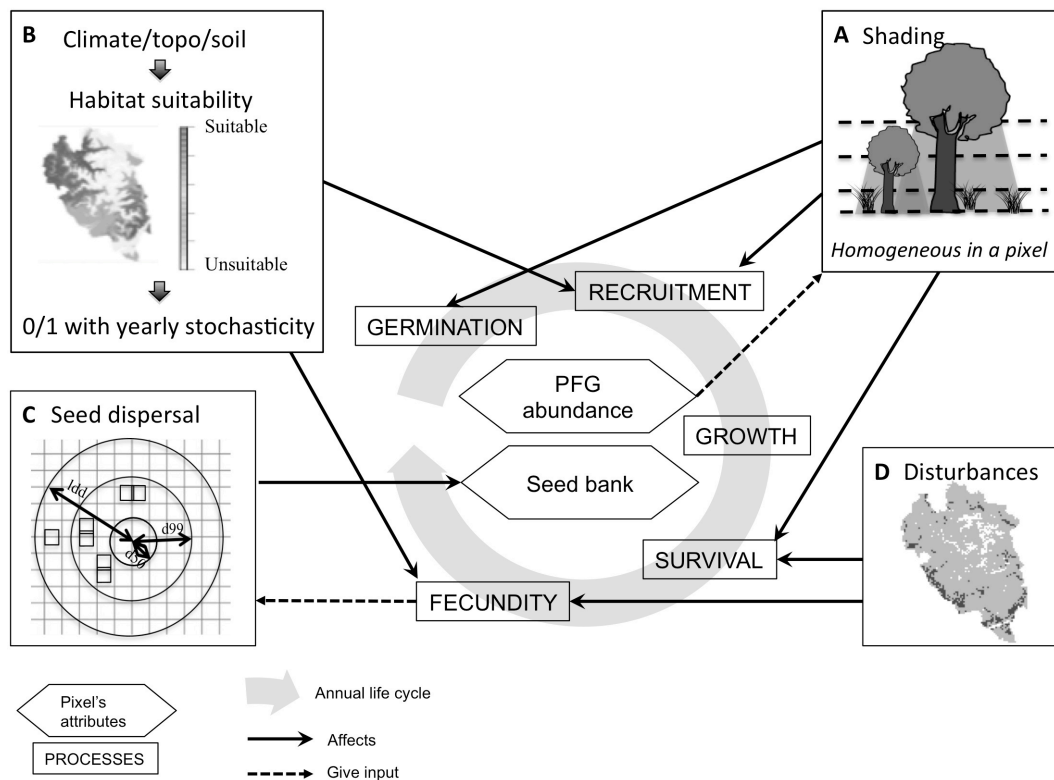


Anticipating the spatio-temporal response of plant diversity and vegetation structure to climate and land use change in a protected area, Boulangeat, I., Georges, D., Dentant, C., Bonet, R., Van Es, J., Abdulhak, S., Zimmermann, N.E., Thuiller, W.

Appendix A1: Model and parameters

The FATE-HD model with the same parameterization is presented and validated in Boulangeat *et al.* (in press).

a - THE MODEL



(A) In each pixel, PFG cohorts are located in height strata. The number of strata and the transition heights are free parameter that can be set according to the vegetation under investigation. The available light in each stratum is calculated 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. Two other PFG specific parameters are used: (1) maximum abundance

weighting the abundance of younger cohort (e.g. for trees) in the calculation of the available light.

- (B) Each year, the habitat suitability maps with values ranging from 0 to 1 are converted to binary filters according to a threshold randomly drawn from a uniform law. The annual variability in environmental conditions thereby affects all PFGs in the same way, representing “good” and “bad” years for the vegetation.
- (C) The seed dispersal model determines seed influx in each pixel, which depends on the distance from the sources. 50% of the seeds fall uniformly in the immediate neighborhood of adjacent cells. 49% of the seeds are distributed further, with the same concentration as in the immediate neighborhood but by pairs of pixels. This dispersal by packages simulates the spatial autocorrelation of dispersed seeds and avoids meaningless dilutions. Finally, 1% of the seeds fall into a random long distance pixel. See Boulangeat *et al.* (in press) for comparison with kernel functions.
- (D) Each disturbance removes a percentage of each cohort abundance, or affect the seed bank, and may impede seed production. The sensitivity of different cohorts are given as parameters for defined age class, vegetation height, and PFG.

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 when the habitat filter is drawn as favorable and the light conditions are suitable to the PFG. The number of seedlings S produced in a favorable environment is determined so that PFG demography is stable (death=recruitment) when the PFG reaches its maximum abundance. It therefore depends on the number of years the PFG will produce seeds and the maximum abundance of the PFG:

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

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: A set of fixed parameters defines the ages at which each PFG reaches each stratum.

Survival: A PFG cohort dies when it reaches its longevity, when it is disturbed, or when light conditions are no longer favorable.

Fecundity: Fecundity is considered as relative to an unknown maximum fecundity reached when mature PFG abundance equals to the maximum abundance parameter of the PFG. It is proportional to the abundance of mature PFG in a pixel. No seeds are produced when the habitat is not favorable.

b – THE PLANT FUNCTIONAL GROUPS

List of the 24 plant functional groups used in the simulations and the species which determined these groups. H1 to H10 represent herbaceous plants (mostly Hemicryptophyts). C1 to C6 represent Chamaephyts. P1 to P8 represent Phanerophyts. The interpretation was made *a posteriori* based on expert knowledge of determinant species and the PFG's average attributes.

PFG	Species list
H1 Alpine species (which do not tolerate shade, and have a short dispersal distance)	<i>Oxyria digyna, Polygonum viviparum, Ranunculus glacialis, Ranunculus kuepferi, Ranunculus montanus, Geum montanum, Geum reptans, Potentilla aurea, Potentilla erecta, Potentilla grandiflora, Saxifraga stellaris robusta, Linaria alpina alpina, Carex capillaris, Carex curvula, Carex foetida, Carex frigida, Carex nigra, Carex panicea, Carex rupestris, Eriophorum latifolium, Eriophorum polystachion, Eriophorum scheuchzeri, Kobresia myosuroides, Trichophorum cespitosum, Juncus alpinoarticulatus alpinoarticulatus, Juncus trifidus, Luzula alpinopilosa, Agrostis alpina, Agrostis rupestris, Alopecurus alpinus, Avenula versicolor versicolor, Festuca halleri halleri, Festuca quadriflora, Phleum alpinum, Poa alpina, Poa cenisia, Poa laxa, Doronicum grandiflorum, Trisetum distichophyllum, Athamanta cretensis, Hieracium glaciale, Leontodon montanus, Leontodon pyrenaicus helveticus, Taraxacum alpinum, Campanula cochleariifolia, Astragalus alpinus, Lotus alpinus, Trifolium alpinum, Trifolium pallescens, Achillea nana, Gentiana punctata, Arnica montana, Epilobium anagallidifolium, Plantago alpina.</i>
H2 Mountainous species which tolerate nitrophilous soils and have a long dispersal distance	<i>Rumex acetosa, Rumex pseudalpinus, Fragaria vesca, Galium aparine, Galium verum, Carex caryophyllea, Carex sempervirens, Agrostis capillaris, Agrostis stolonifera, Festuca nigrescens, Sesleria caerulea, Astrantia major, Leucanthemum vulgare, Carum carvi, Meum athamanticum, Chenopodium bonus-henricus, Lathyrus pratensis, Lotus corniculatus, Onobrychis montana, Trifolium montanum, Trifolium pratense, Geranium sylvaticum, Plantago media.</i>
H3 Mountainous to lowland species found in wet niches and which have a long dispersal distance	<i>Ranunculus acris, Trollius europaeus, Urtica dioica, Aegopodium podagraria, Anthoxanthum odoratum, Arrhenatherum elatius elatius, Dactylis glomerata, Deschampsia cespitosa, Festuca rubra, Crepis pyrenaica, Poa pratensis, Taraxacum officinale, Heracleum sphondylium, Pimpinella major, Trifolium repens, Vicia cracca, Plantago lanceolata.</i>
H4 Undergrowth and shadow species which do not tolerate full light	<i>Aconitum lycoctonum vulparia, Aruncus dioicus, Dryopteris dilatata, Dryopteris filix-mas, Athyrium filix-femina, Prenanthes purpurea.</i>

<p>H5 Mountainous to subalpine species which have a short dispersal distance and tolerate dry soils</p>	<p><i>Pulsatilla alpina, Ranunculus bulbosus, Anthericum liliago, Luzula sieberi, Achnatherum calamagrostis, Agrostis agrostiflora, Briza media, Bromus erectus, Deschampsia flexuosa, Festuca acuminata, Festuca flavescens, Festuca laevigata, Festuca marginata gallica, Koeleria vallesiana, Phleum alpinum rhaeticum, Stipa eriocalis eriocalis, Trisetum flavescens, Leontodon autumnalis, Leontodon hispidus, Tolpis staticifolia, Festuca melanopsis, Hugueninia tanacetifolia, Laserpitium halleri, Laserpitium siler, Silene flos-jovis, Hypericum maculatum, Salvia pratensis, Epilobium dodonaei fleischeri.</i></p>
<p>H6 Tall plants typical of megaphorbiaies which can form undergrowth</p>	<p><i>Ranunculus aduncus, Cacalia alliariae, Saxifraga rotundifolia, Valeriana officinalis, Carex flacca, Cicerbita alpina, Luzula nivea, Avenula pubescens, Brachypodium rupestre, Calamagrostis varia, Festuca altissima, Melica nutans, Milium effusum, Molinia caerulea arundinacea, Poa nemoralis, Hieracium murorum, Hieracium prenanthoides, Senecio ovatus ovatus, Chaerophyllum aureum, Chaerophyllum villarsii, Cardamine pentaphyllos, Laserpitium latifolium, Knautia dipsacifolia, Mercurialis perennis, Gentiana lutea, Epilobium angustifolium.</i></p>
<p>H7 Plants species found in rocky habitats and undergrowth at all elevations</p>	<p><i>Cacalia alpina, Cryptogramma crispa, Asplenium ramosum, Asplenium septentrionale septentrionale, Asplenium trichomanes quadrivalens, Equisetum arvense, Cystopteris fragilis, Gymnocarpium robertianum, Woodsia alpina, Hieracium pilosella, Homogyne alpina, Petasites albus, Tussilago farfara.</i></p>
<p>H8 Subalpine to alpine species not usually grazed and which have a short dispersal distance</p>	<p><i>Cacalia leucophylla, Cirsium spinosissimum, Omalotheca supina, Murbeckiella pinnatifida pinnatifida, Gentiana alpina.</i></p>
<p>H9 Short subalpine to alpine species which have long dispersal distance</p>	<p><i>Anthoxanthum odoratum nipponicum, Nardus stricta, Poa supina, Silene vulgaris prostrata.</i></p>
<p>H10 Mountainous species which have a long dispersal distance and tolerate shade</p>	<p><i>Heracleum sphondylium elegans.</i></p>
<p>C1 Thermophilous chamaephytes which have a long dispersal distance</p>	<p><i>Rumex acetosella, Cotoneaster integerrimus, Potentilla neumanniana, Rubus idaeus, Rubus saxatilis, Valeriana montana, Lonicera caerulea, Helianthemum grandiflorum, Helianthemum nummularium, Anthyllis montana, Hippocrepis comosa, Achillea millefolium, Stachys recta, Teucrium chamaedrys, Thymus pulegioides.</i></p>
<p>C2 Alpine and subalpine chamaephytes species</p>	<p><i>Rumex scutatus, Salix hastata, Saxifraga aizoides, Saxifraga oppositifolia, Helictotrichon sedenense sedenense, Leucanthemopsis alpina, Cerastium alpinum, Cerastium cerastoides, Cerastium latifolium, Cerastium pedunculatum, Cerastium uniflorum, Sempervivum arachnoideum, Vaccinium uliginosum microphyllum, Antennaria dioica, Thymus polytrichus, Artemisia umbelliformis eriantha, Artemisia umbelliformis umbelliformis.</i></p>

C3 Chamaephytes which have a short dispersal distance	<i>Androsace pubescens, Androsace vitaliana, Primula hirsuta, Primula latifolia, Dryas octopetala, Salix herbacea, Salix reticulata, Salix retusa, Saxifraga bryoides, Saxifraga exarata, Eritrichium nanum nanum, Noccaea rotundifolia, Pritzelago alpina alpina, Gypsophila repens, Sagina glabra, Sagina saginoides, Silene acaulis, Silene acaulis bryoides, Sedum album, Sedum alpestre, Sedum dasyphyllum, Empetrum nigrum hermaphroditum, Rhododendron ferrugineum, Globularia cordifolia.</i>
C4 Tall shrubs	<i>Amelanchier ovalis, Crataegus monogyna, Rosa pendulina, Salix laggeri, Juniperus communis, Alnus alnobetula, Lonicera xylosteum, Cornus sanguinea, Corylus avellana, Ribes petraeum.</i>
C5 Mountainous to subalpine heath found in dry climates	<i>Arctostaphylos uva-ursi crassifolius, Calluna vulgaris, Hippocrepis emerus.</i>
C6 Mountainous to subalpine heath found in wet climates	<i>Vaccinium myrtillus, Vaccinium vitis-idaea vitis-idaea.</i>
P1 Thermophilous pioneer trees (deciduous trees and pines)	<i>Prunus avium, Sorbus aria, Sorbus aucuparia, Sorbus mougeotii, Pinus cembra, Pinus sylvestris.</i>
P2 Small deciduous pioneer trees (e.g. colonising riversides)	<i>Populus tremula, Salix daphnoides.</i>
P3 Tall forest edge trees	<i>Tilia platyphyllos, Acer pseudoplatanus Fraxinus excelsior.</i>
P4 Tall pioneer	<i>Larix decidua.</i>
P5 Late succession trees found in wet climates	<i>Picea abies, Fagus sylvatica.</i>
P6 Intermediate succession trees found in dry climates	<i>Pinus uncinata, Betula pendula.</i>
P7 Small forest edge trees	<i>Acer opalus, Acer campestre campestre.</i>
P8 Small pioneer found in cold climates	<i>Betula alba.</i>

Demographic parameters

Relative germination performance was chosen with the aim of decreasing germination performance in response to increasing shade for herbaceous plants (90%, 80%, 50%), and ensuring the germination performance of woody plants is unaffected by light conditions (90%, 90%, 90%), according to the results obtained by Milberg *et al.* (2000).

Trees and shrubs' ages at which they reach each stratum were determined using a growth rate equation involving maturity age, life span, relative shade of immature, and maximum plant canopy height. H (height) is expressed as a function of A (age) as:

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

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

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

PFG longevities and maturity ages were given by expert knowledge from the Ecrins National park and the literature (ANDROSACE database, Boulangeat *et al.* 2012).

	H1	H10	H2	H3	H4	H5	H6	H7	H8	H9
Maturity age (year)	4	4	3	3	4	4	4	4	4	4
Life span (year)	11	9	10	9	7	7	8	7	8	9

	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

Habitat suitability

The habitat suitability models were calibrated over the whole French Alps in order to increase the robustness of projections into the future climatic conditions (Barbet-Massin *et al.* 2012).

We used species observations from the database of the Conservatoire Botanique National

Alpin (CBNA), which includes all records of the Ecrins National Park and additional records in the entire region of the French Alps (Boulangeat *et al.* 2012). We used the 15,000 community plots of the database for which the exhaustive list of species was recorded to infer true absences. The observation of one representative species of a PFG determined its presence. A PFG true absence was considered where none of its determining species were observed in a community plot. We used seven environmental variables to model the large-scale abiotic constraints for each PFG: (1) the slope angle, taken from the French Digital Elevation Model with 50x50m resolution, made by the IGN-France (<http://professionnels.ign.fr/bdalti>) (2) the percentage of calcareous soil was calculated from the European Soil Database <http://eusoils.jrc.ec.europa.eu/data.html> with a 1km resolution. (see also Dullinger *et al.* 2012). (3) isothermality, (4) temperature seasonality, (5) temperature annual range, (6) mean temperature of coldest quarter, and (7) annual precipitation. These five bioclimatic variables are known to influence the physiology of species in the Alps (Körner 2004) and their pairwise correlations were low. Temperature and precipitation from the 1 km Worldclim climate grids available online were downscaled to a resolution of 100m, using a specific method that was developed for Mountainous areas (Dullinger *et al.* 2012).

Habitat suitability models were built using the *biomod2* package (Thuiller *et al.* 2009) in R (2011) and using five algorithms from different families: (1) Generalized Linear Model, (2) Boosted Regression Trees, (3) Generalized Additive Model, (4) Multivariate Adaptive Regression Splines and (5) Random Forest. We weighted the presence and absence of each PFT to give a prevalence of 0.5 in order to be able to compare the models whatever the PFG distribution (narrow, wide spread, etc.). We used a ten-fold cross validation procedure with 70% of the data for calibration and 30% for evaluation with True Skill Statistics (TSS, Allouche *et al.* 2006). All models from different repetitions and algorithms were combined using an ensemble forecasting strategy: (1) All models gave binary projections using the

threshold maximising the TSS in the evaluation procedures. (2) These projections were averaged, each one having its TSS score as weight. (4) The average projection were rescaled to fall between 0 and 1, which is the percentage of agreement between models.

Seed dispersal

Dispersal classes were given as the median of representative species values. We found most of our species in Vittoz *et al.* (2007). Missing data were given by local experts (J. Van Es, R. Douzet, P. Vittoz) following the same protocol as in Vittoz *et al.* (2007). The two first distance parameters are reported from Vittoz *et al.* (2007). Long distance parameter was set according to the dispersal class following 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

Disturbances

Responses to mowing and grazing were parameterized by the experts of the National Park.

Mowing parameters table. Mowing was assumed to include the removal of all trees in the field. Other PFG were partly killed or had their mature plants not producing seeds.

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	
PFG	Mature plants that did not produced seeds	Mature plants that were killed	PFG	Mature plants that did not produced seeds	Mature plants killed	PFG	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%					

Grazing parameters 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

Grazing parameters 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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