Alternative states in the structure of mountain forests across the Alps and the role of disturbance and recovery

Supporting information

1 Potential natural vegetation types in the Alps

Table S1: Description of the main potential natural vegetation types in the Alps adapted from Bohn et al. 2004, with the percentage of forest area in the European Alps covered by each type and the number of available GEDI footprints. The types in bold are most widespread in the Alps, including 88 % of the forest area.

Short name	**Description**	**% of forest area**	**Number of GEDI footprints**
Alpine	Alpine vegetation (Alpine grasslands, low creeping shrub, dwarf shrub and shrub vegetation, rock and scree vegetation)	5.3	93'094
Subalpine	Subalpine vegetation (forests, scrub and dwarf shrub communities in combination with grasslands and tall-forb communities)	12.1	279'575
Mesophytic coniferous	Montane to altimontane, partly submontane fir (*Abies alba*) and spruce forests (*Picea abies*)	19.8	569'474
Mesophytic deciduous	Mesophytic deciduous broad-leaved and mixed coniferous-broad-leaved forests, including: beech and mixed beech forests (*Fagus sylvatica, Abies alba*), oak and mixed oak forests (*Quercus robur, Q. petraea, Pinus sylvestris, Castanea sativa*), mixed oak-hornbeam forests (*Carpinus betulus, Q. robur, Q. petraea, Tilia cordata*)	45.6	1'294'437
Submediterranean	Thermophilous mixed deciduous broad-leaved forests, mainly Sub-Mediterranean and meso-supra-Mediterranean downy oak forests, as well as mixed forests (*Quercus pubescens, Fraxinus ornus, Ostrya carpinifolia, Carpinus orientalis*)	10.7	333'379
Mediterranean	Mediterranean sclerophyllous forests and scrub (*Quercus ilex*)	2.2	77'710
Pine forests	Pine forests and pine woodlands (*Pinus sylvestris, P. nigra* agg.)	2.8	74'880
Floodplain	Vegetation of flood-plains, estuaries and fresh-water polders and other moist or wet sites	1.0	19'766

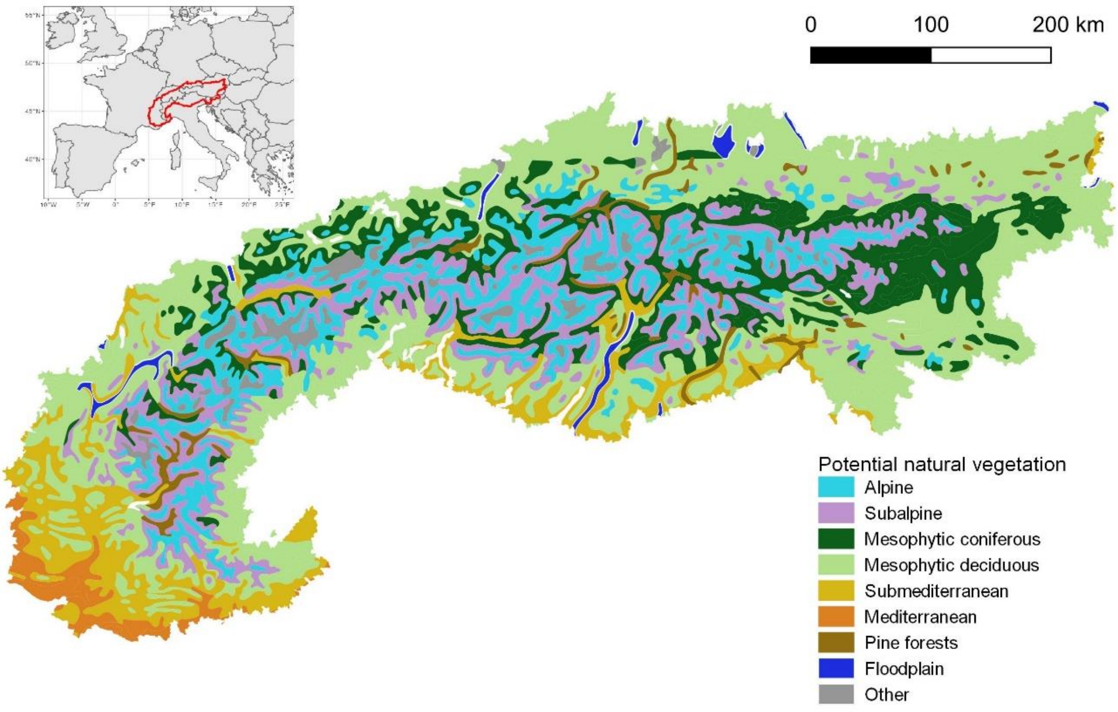

Figure S1: Map of potential natural vegetation types in the Alps according to Bohn et al. (2014).

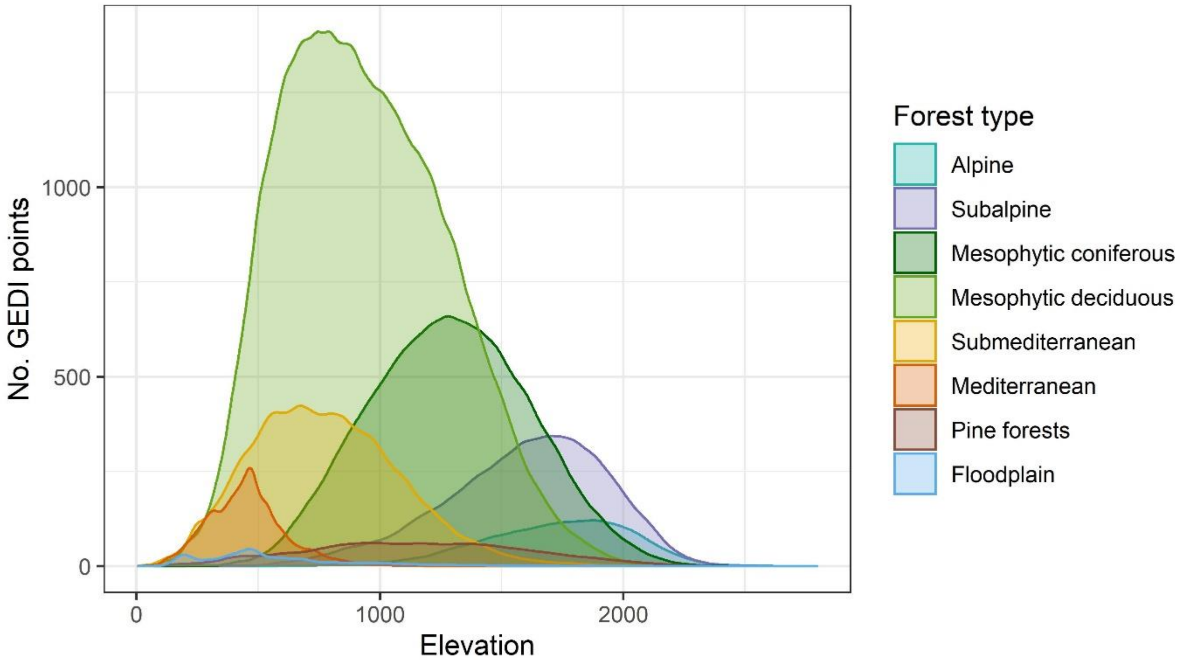

Figure S2: Distribution of available GEDI points by elevation in forests of different potential natural vegetation types.

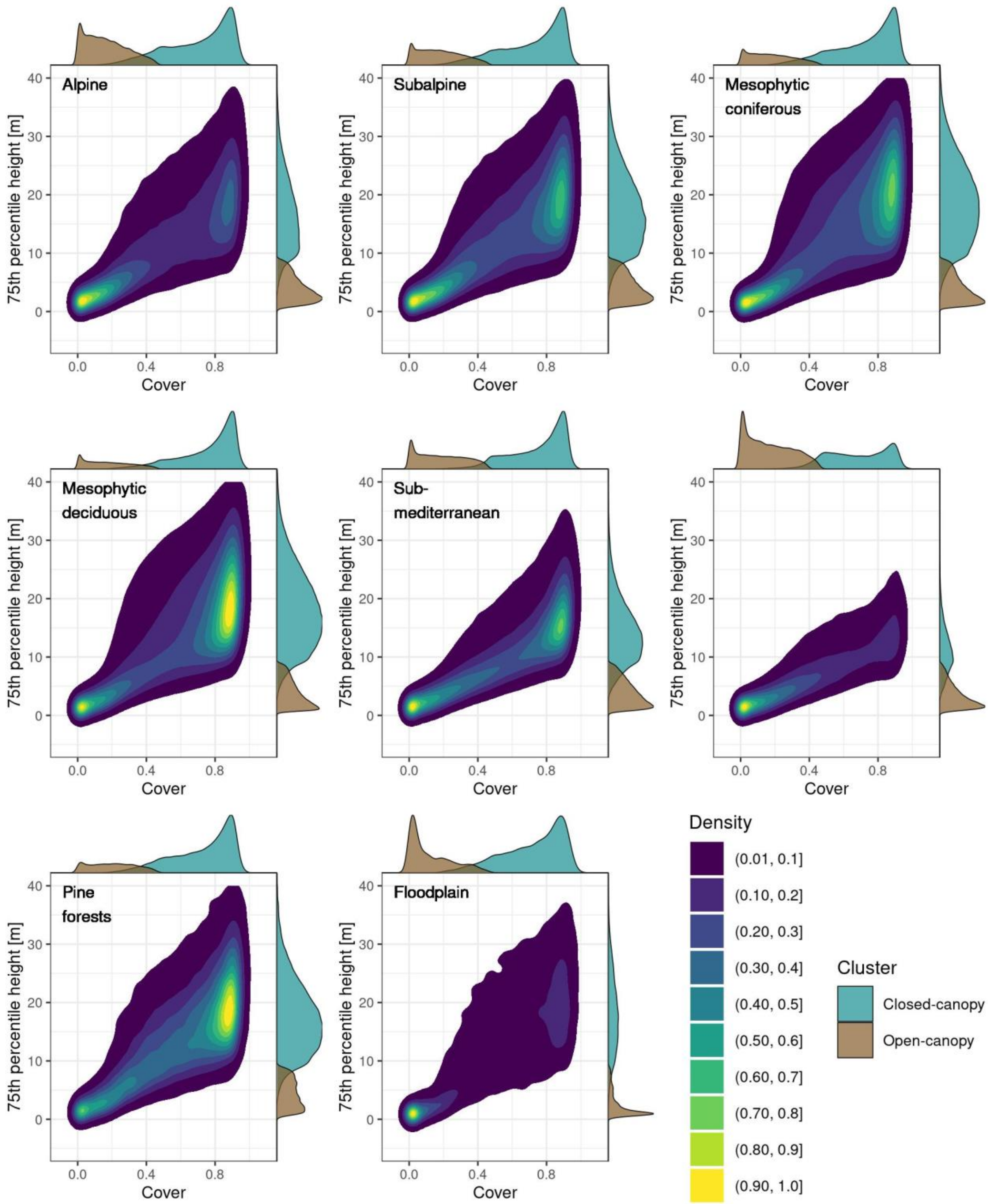

Figure S3: Distribution of GEDI points in a space defined by canopy cover and relative height (75th percentile) for all the main potential natural vegetation (Bohn, 2004) types in the Alps. Marginal distributions show the distributions of each variable for the two clusters identified with a Gaussian mixture model, where cluster 1 represents closed forests with a higher canopy and cluster 2 represents open forests.

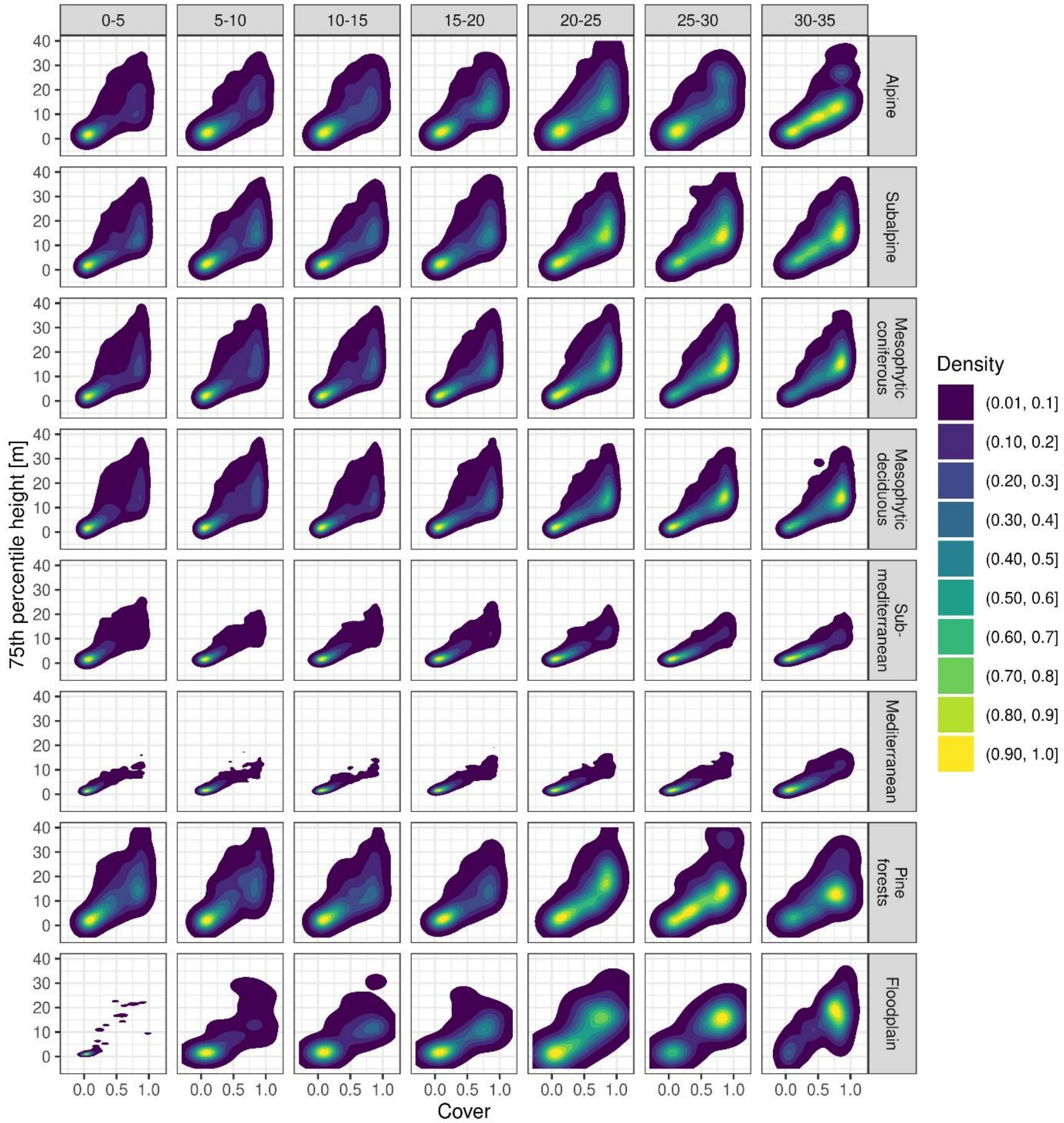

Figure S4: Distribution of disturbed GEDI footprints in a space defined by canopy cover and relative height (75th percentile) over time after disturbance for the main potential natural vegetation types in the Alps.

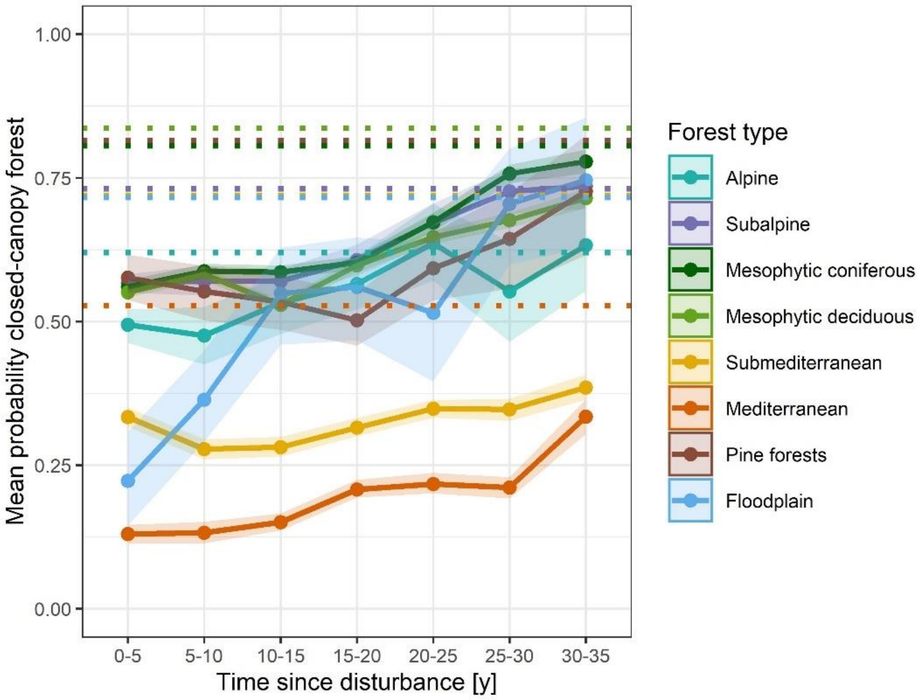

Figure S5: Mean probability of points belonging to the closed-canopy cluster over time after disturbance for the main potential natural vegetation types in the Alps. The ribbon indicates the 95 % interval of the mean probability obtained by 500-fold bootstrap resampling of the points (with replacement). The dotted line shows the mean probability of points belonging to the closed-canopy cluster in undisturbed forests.

2 Dynamics of individual structural metrics

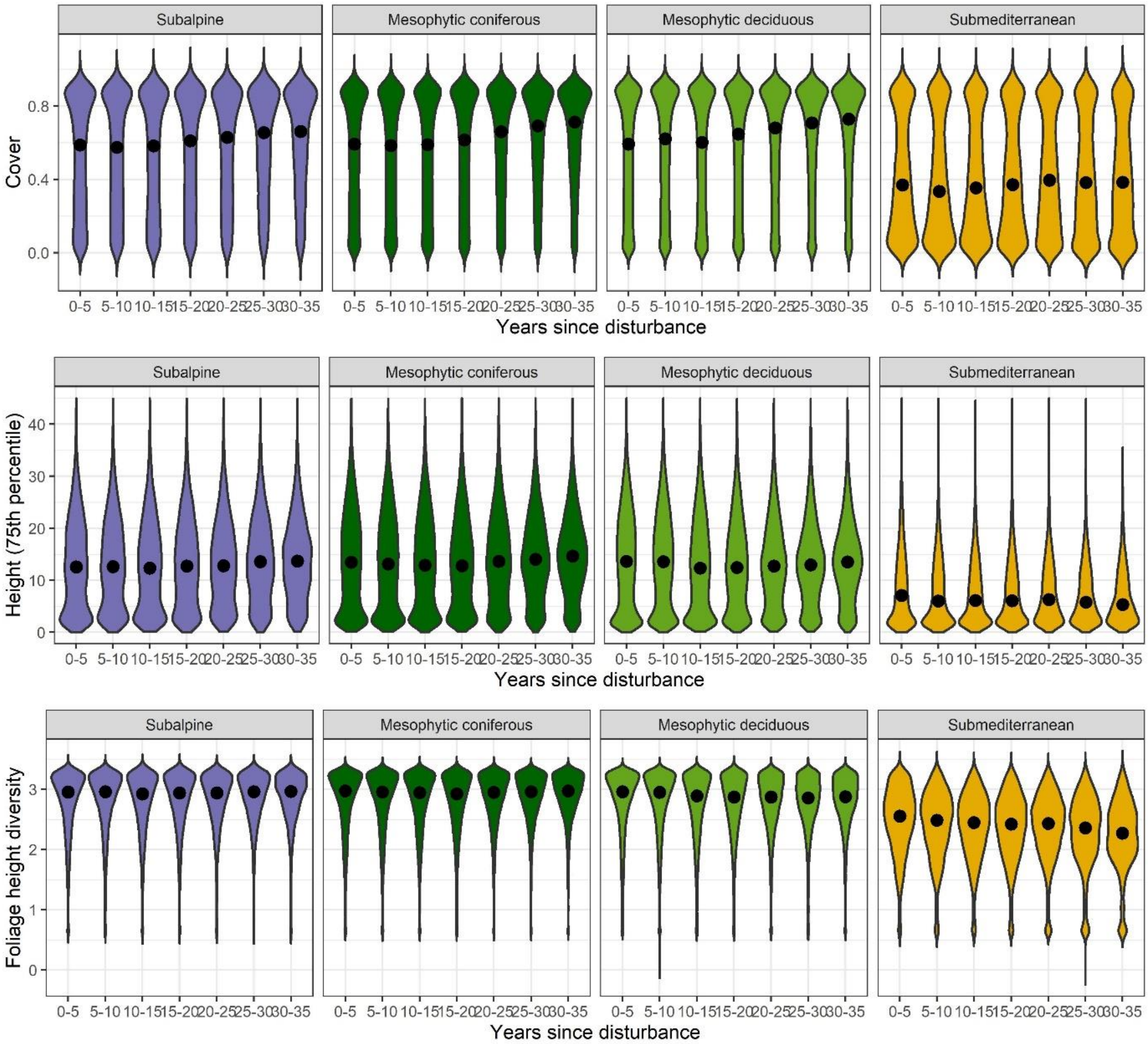

Figure S6: Distributions of three structural metrics (canopy cover,75th percentile of canopy height, foliage height diversity) over time after disturbance for the four main potential natural vegetation types in the Alps, with the dot indicating the median value. We see an increase in canopy cover and height, which is less pronounced in submediterranean forests. Foliage height diversity shows no clear trend over time.

3 Alternative stable states and their drivers

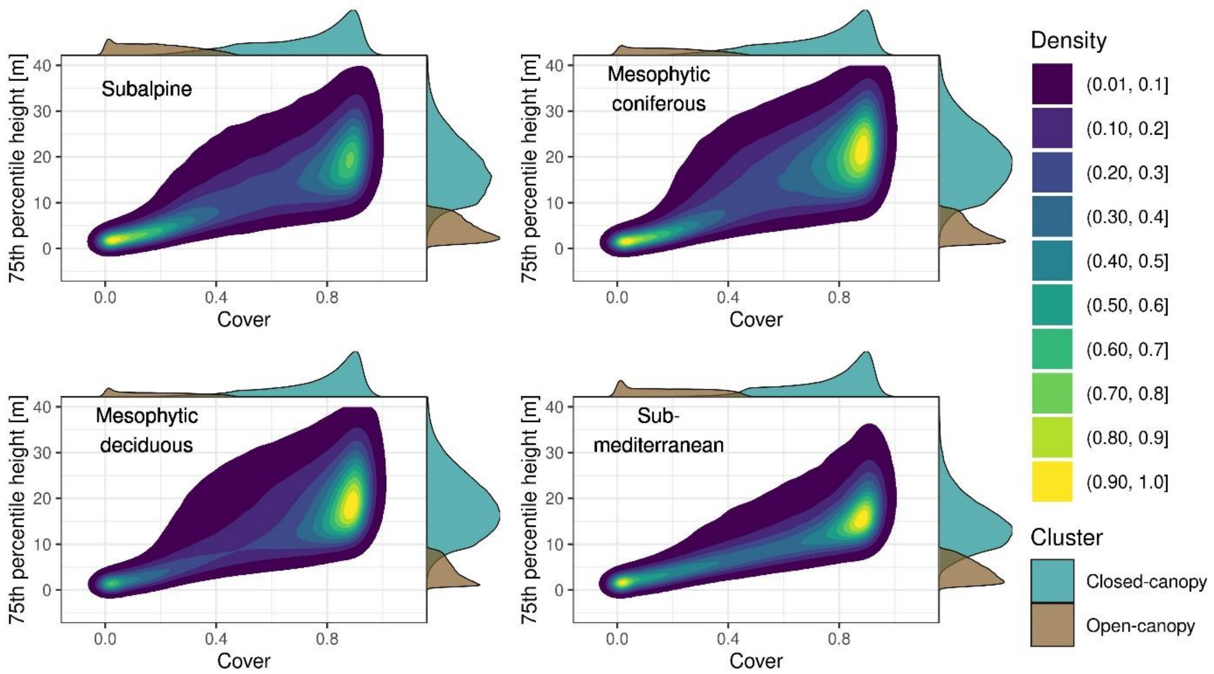

Figure S7: Distribution of undisturbed GEDI footprints in a space defined by canopy cover and relative height (75th percentile) for four of the main potential natural vegetation types in the Alps (following Bohn et al. 2004). Marginal distributions show the distributions of each variable for the two clusters identified with a Gaussian mixture model, where one cluster represents tall, closed-canopy forests and the second cluster represents short, open-canopy forests. The pattern of two clusters (alternative states) emerges also when considering only footprints that have not been disturbed since 1986.

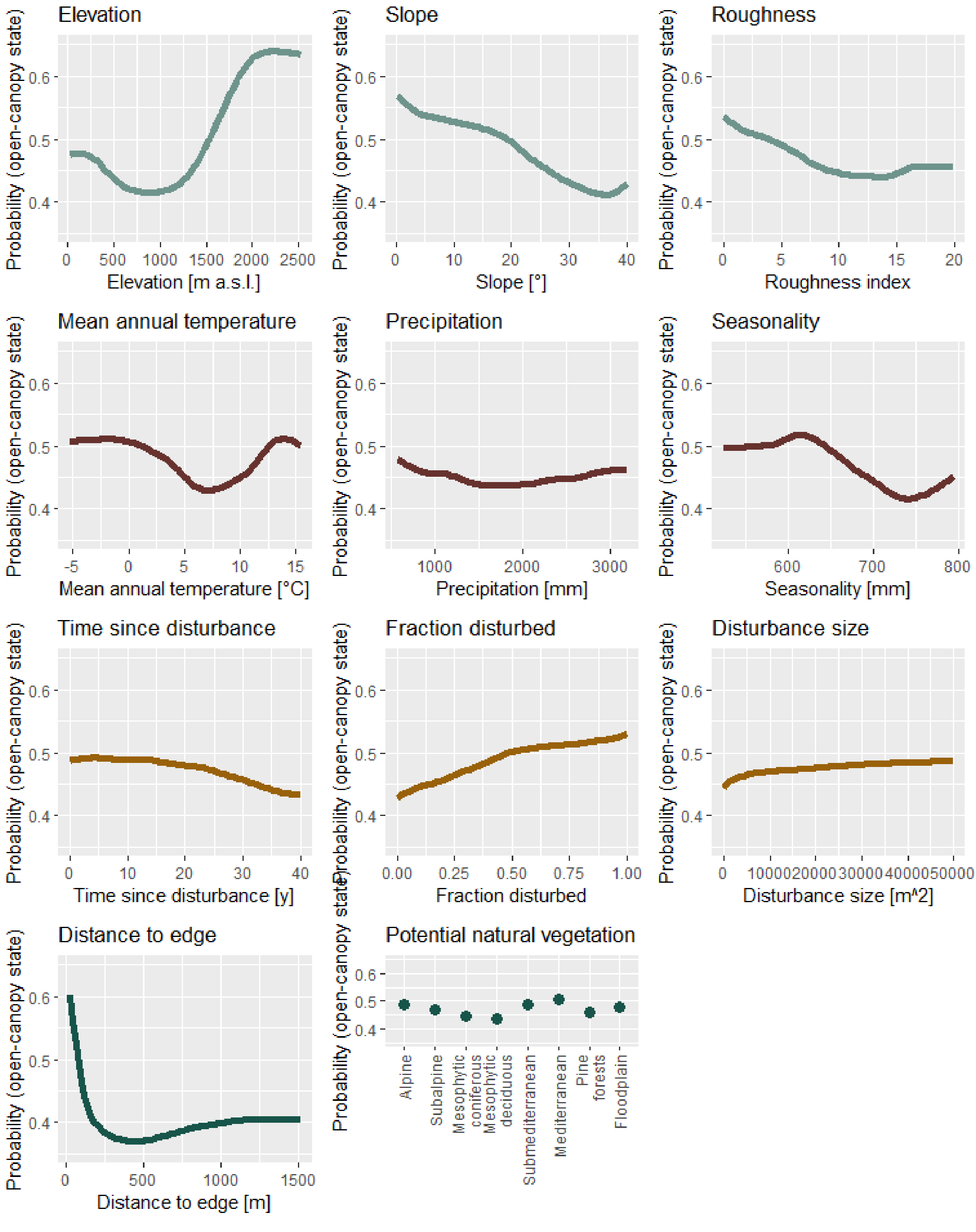

Figure S8: Partial dependence plots based on the random forest model, showing the probability of open-canopy forests (cluster 2) based on predictors describing topography, climate, disturbance history, and forest configuration and composition.

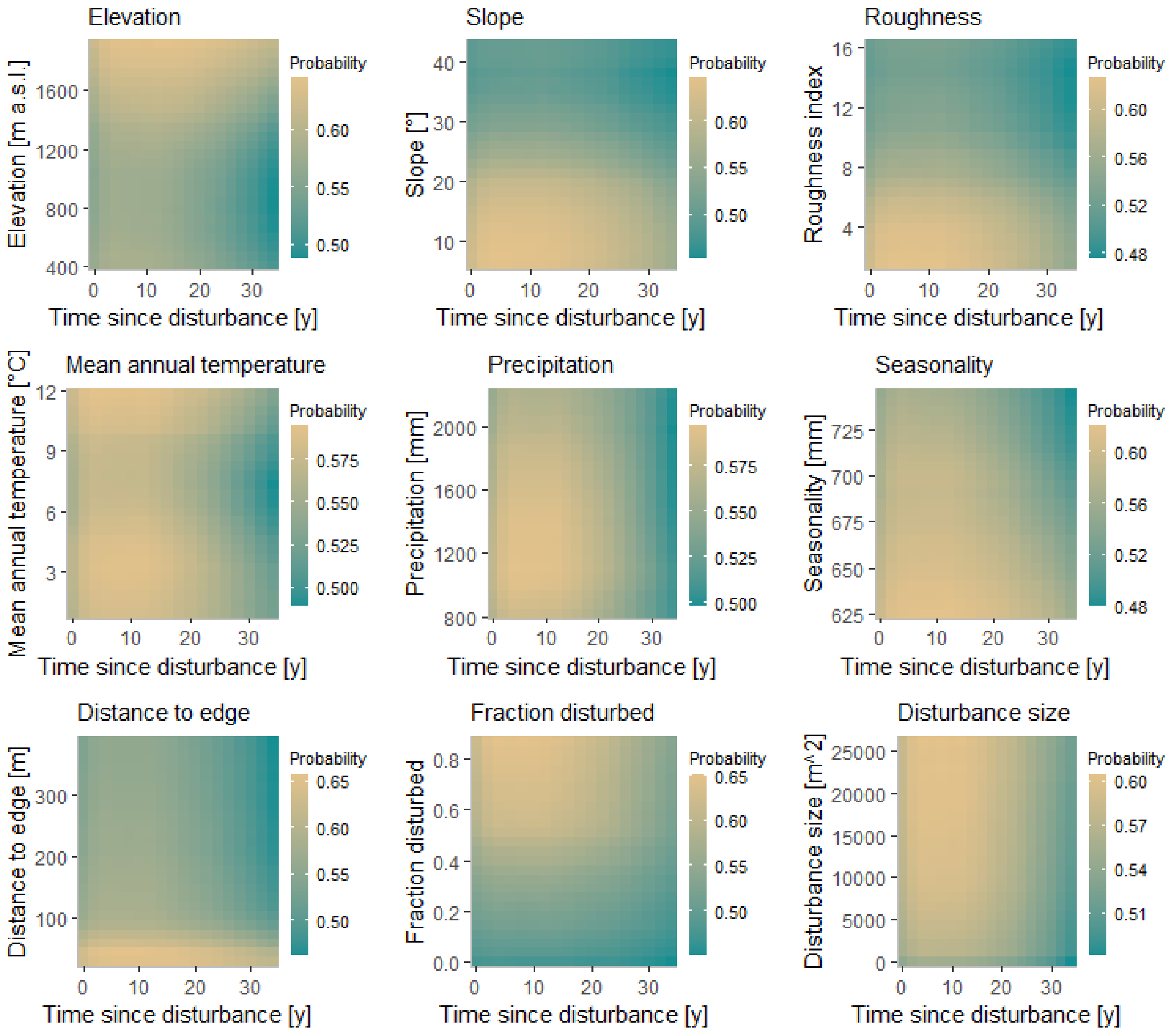

Figure S9: Partial dependence plots based on the random forest model, showing the probability of open-canopy forests depending on interactions between time since disturbance and other predictors. Note that the color scales are different in each plot for better visibility of the interactions.

4 The effect of slope on GEDI

When checking the effect of topography on variable distributions, we found that on steeper slopes, the distribution of GEDI metrics (including cover and height) shifts towards higher values. This effect is more pronounced when using the ground-detection algorithm no. 2, which is the default selected algorithm on most of the points within the Alps.

To avoid artefacts resulting from the slope effect in our analysis, we tried using either only the ground-detection algorithm 1, or the slope-adaptive metrics approach (Wang et al., 2019). Both approaches reduced the slope-related increase in cover (see Figure S10). We then performed a comparison of each approach with reference ALS data from Berchtesgaden National Park (Mandl et al., under review), where we found that none of the approaches consistently performed better than the default (see Table S2). With algorithm 1, cover and heights tend to be underestimated more than with the default algorithm.

We performed the analysis of post-disturbance dynamics using the default metrics and the slope adaptive approach (see Figure S12). Based on the slope-adaptive approach, more forests are classified as open (cluster 2), but the overall pattern of recovery remains similar. Forests on steeper slopes are more likely to be classified as "closed" due to higher cover and height values, and this effect is not removed when using slope-adaptive metrics. Therefore, we decided to use the default metrics for the main analysis.

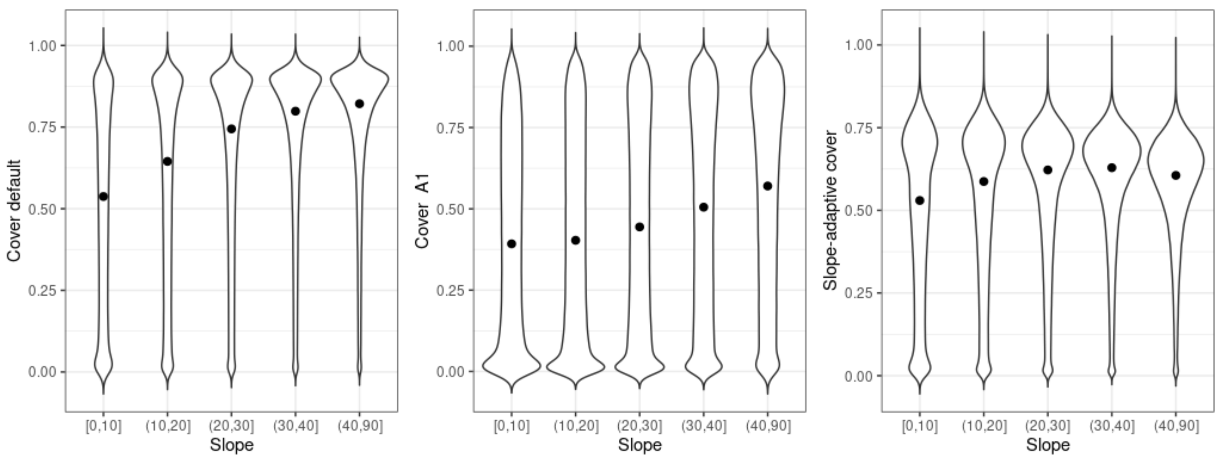

Figure S10: Distributions of canopy cover across slope classes, derived from the default GEDI product (left), using algorithm settings 1 (A1) for ground detection (middle) and the slope-adaptive approach (right).

Table S2: Comparison of GEDI metrics calculated with different approaches (default algorithm, algorithm 1, the slope-adaptive approach, and a combination of the slope-adaptive approach and algorithm 1) with ALS data in Berchtesgaden National Park (N = 3351).

	Cover			RH50			RH98		
	Correlation	RMSE	Bias	Correlation	RMSE	Bias	Correlation	RMSE	Bias
Default algorithm	0.48	0.31	-0.15	0.51	7.11	-1.53	0.50	9.84	2.22
Algorithm 1	0.47	0.40	-0.29	0.53	7.46	-3.66	0.48	9.49	-0.88
Slope-adaptive	0.50	0.32	-0.23	0.47	7.01	1.33	0.47	10.14	3.09
Slope-adaptive (A1)	0.47	0.41	-0.34	0.45	6.64	-1.21	0.44	9.60	0.01

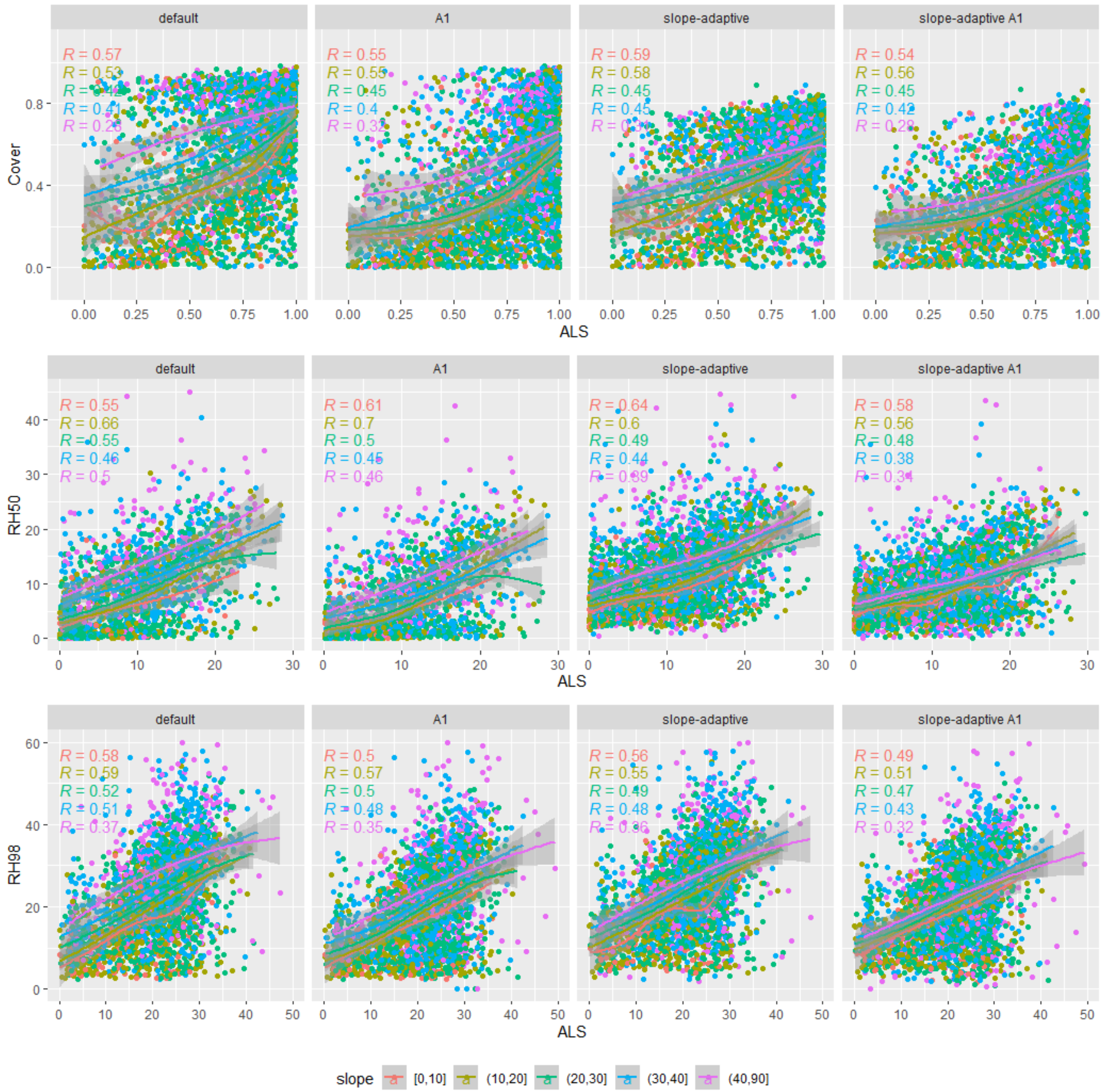

Figure S11: Comparison of structural metrics from GEDI with ALS in Berchtesgaden National Park (Mandl et al, in prep.), for four versions of GEDI data processing (default ground-detection algorithm, algorithm settings no. 1 (A1), slope-adaptive metrics, and a combination of both), across different slope categories.

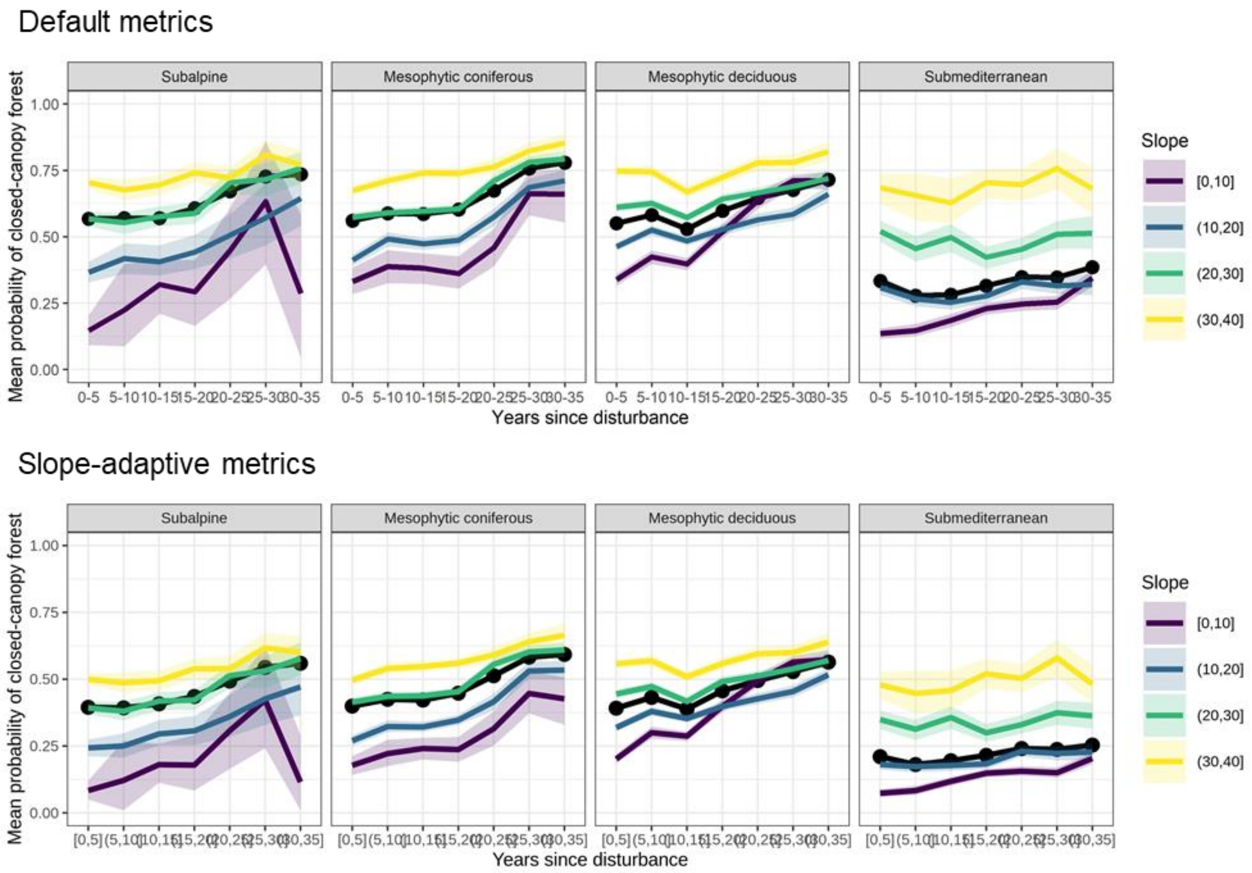

Figure S12: Mean probability of points belonging to the "closed forest" cluster over time after disturbance for different slope classes, calculated based on default GEDI metrics (above) and using the slope-adaptive approach (below). The ribbon indicates the 95 % interval of the mean probability obtained by 500-fold bootstrap resampling of the points (with replacement). Overall, forests on steeper slopes are more likely to be classified as "closed" (upper cluster) due to higher cover and height values, and this effect is not removed when using slope-adaptive metrics.

5 Ordination – analysis with multiple variables

To evaluate the sensitivity of the analysis to the selection of specific GEDI metrics, we performed a PCA analysis using a wider range of metrics (relative heights at 10, 50, 75 and 95 %, cover, plant area index, and foliage height diversity).

The ordination shows one main axis explaining a large part of the variability (80 %) among GEDI points (see Figure S13), with a high correlation among the different variables. The bimodal distribution of points remains clearly visible along this axis (see Figure S14).

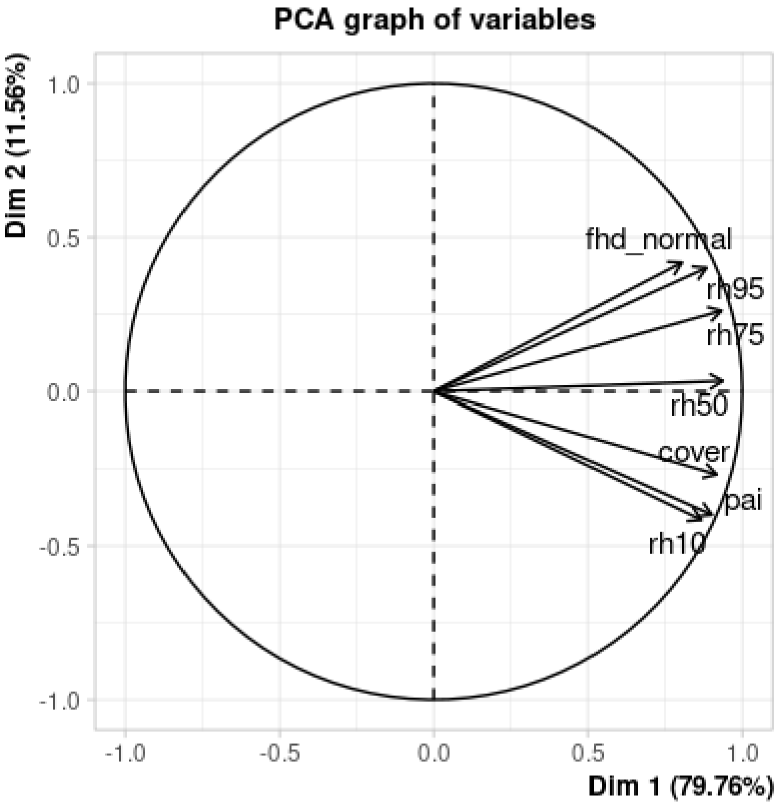

Figure S13: Ordination of GEDI points based on the variables: relative heights (rh) at 10, 50, 75 and 95 %, cover, plant area index (pai), and foliage height diversity (fhd_normal).

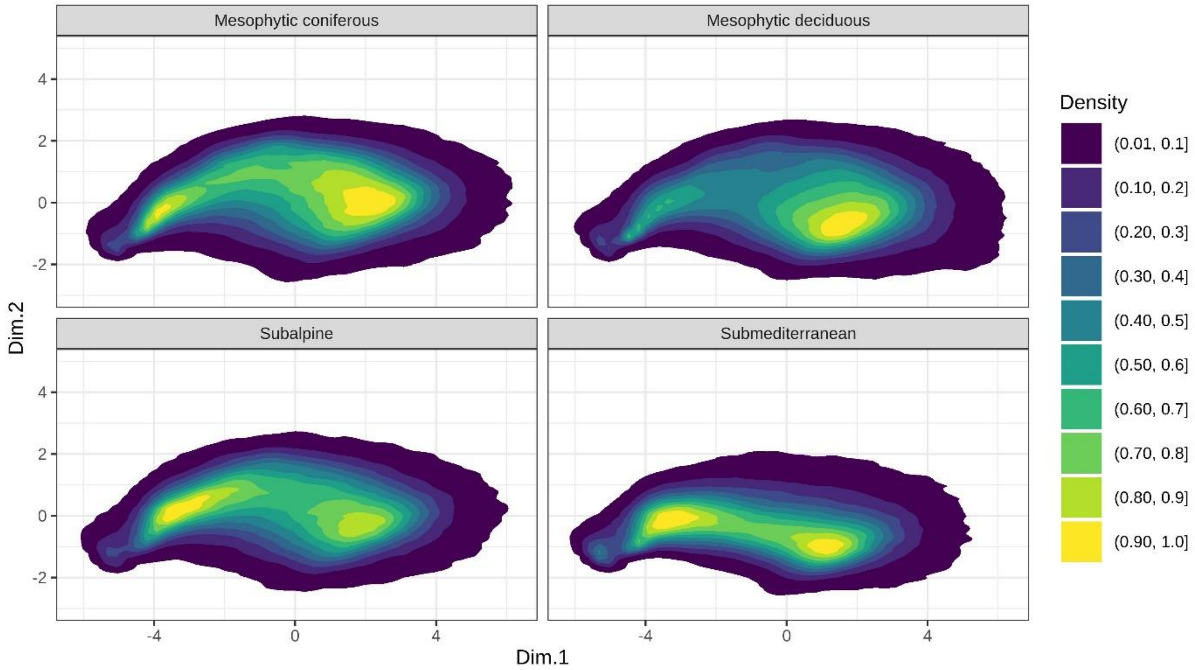

Figure S14: Distribution of GEDI footprints in the ordination space defined by the PCA.