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Supplementary Information for

Forest and woodland replacement patterns following drought-related mortality.

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This PDF file includes:

Figures S1 to S15

Other supplementary materials for this manuscript include the following:

Datasets: D1, D2 and D3

Supporting information

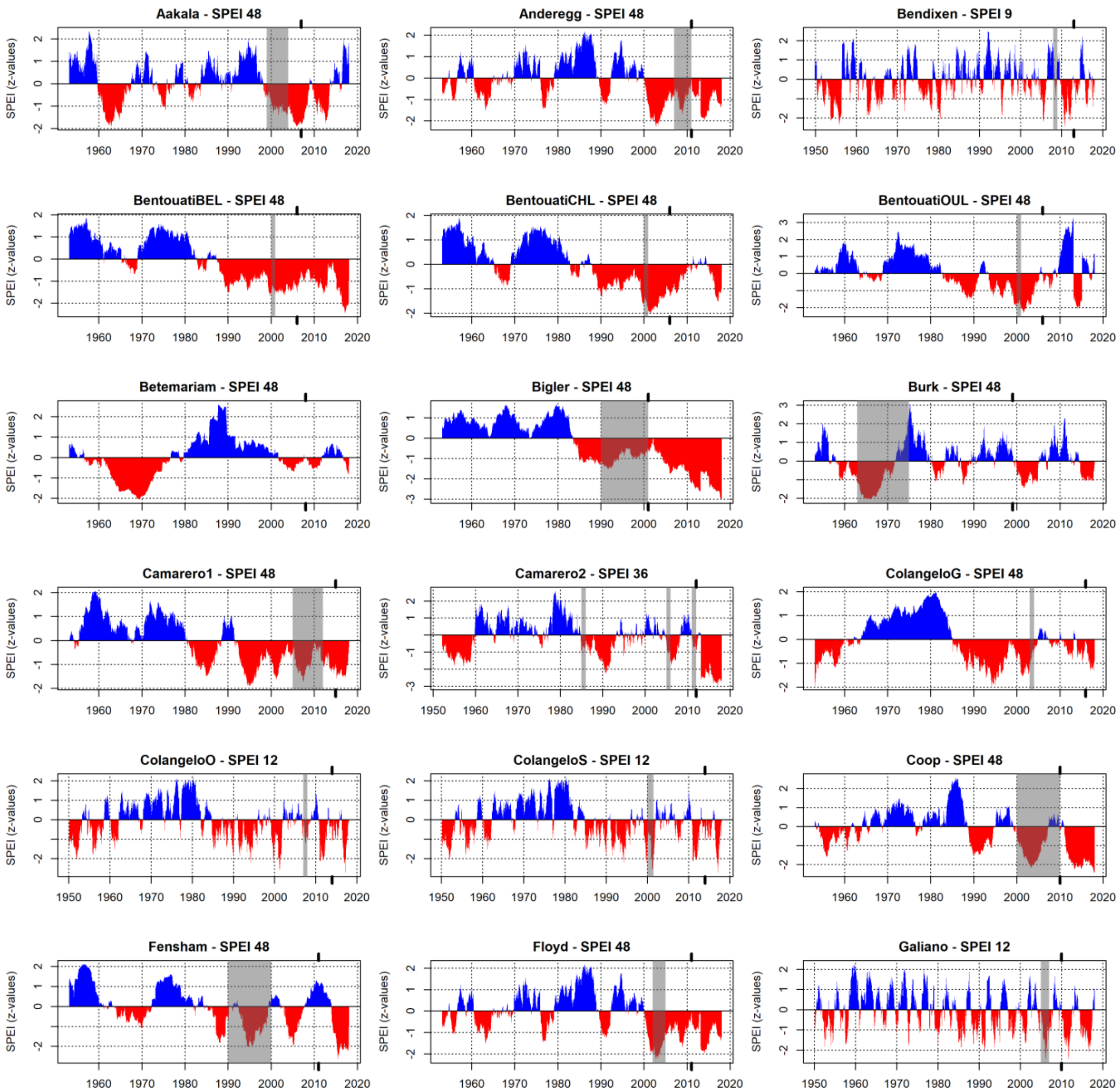


Fig. S1. Temporal series of the Standardized Precipitation-Evapotranspiration Index (SPEI) in the 131 field sites included in this study. For each site (identified with *Dataset* D1 'CODE'), the forest mortality event is depicted by the grey shading (excepting in Betemariam where mortality date is unknown) and the sampling date to assess forest replacement patterns is depicted by the black, wide ticks (in both the upper and lower x-axes of each plot). SPEI is a multi-scalar index, so in each site it is indicated the time scale (e.g., 9, 24, 36 or 48 months) over which water deficit accumulation was considered in order to show the temporal series of drought intensity. SPEI temporal scale matched the period of drought-induced mortality as described by the individual study authors. Note that the Y scale is variable among plots, and that similar to the Standardized Precipitation Index (SPI), values of SPEI between -1.5 and -1.99 represents very dry conditions and values < -2 correspond to extremely dry periods. Given the spatial resolution of the used SPEI data set, note that for some forests a representative site is used for several sites (i.e., Matusick, Veblen, VilaCabrera; *please see also Dataset* D1).

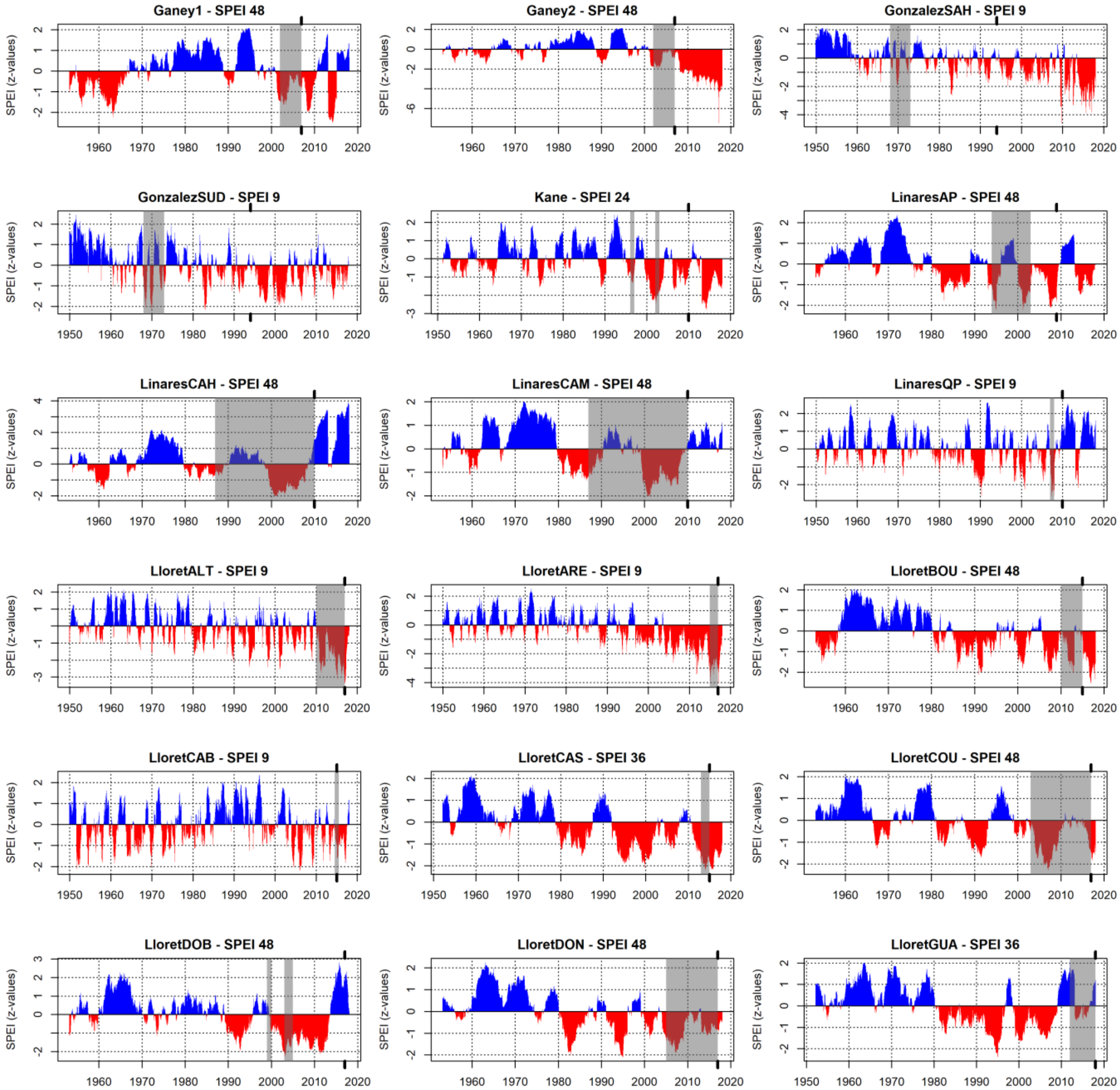
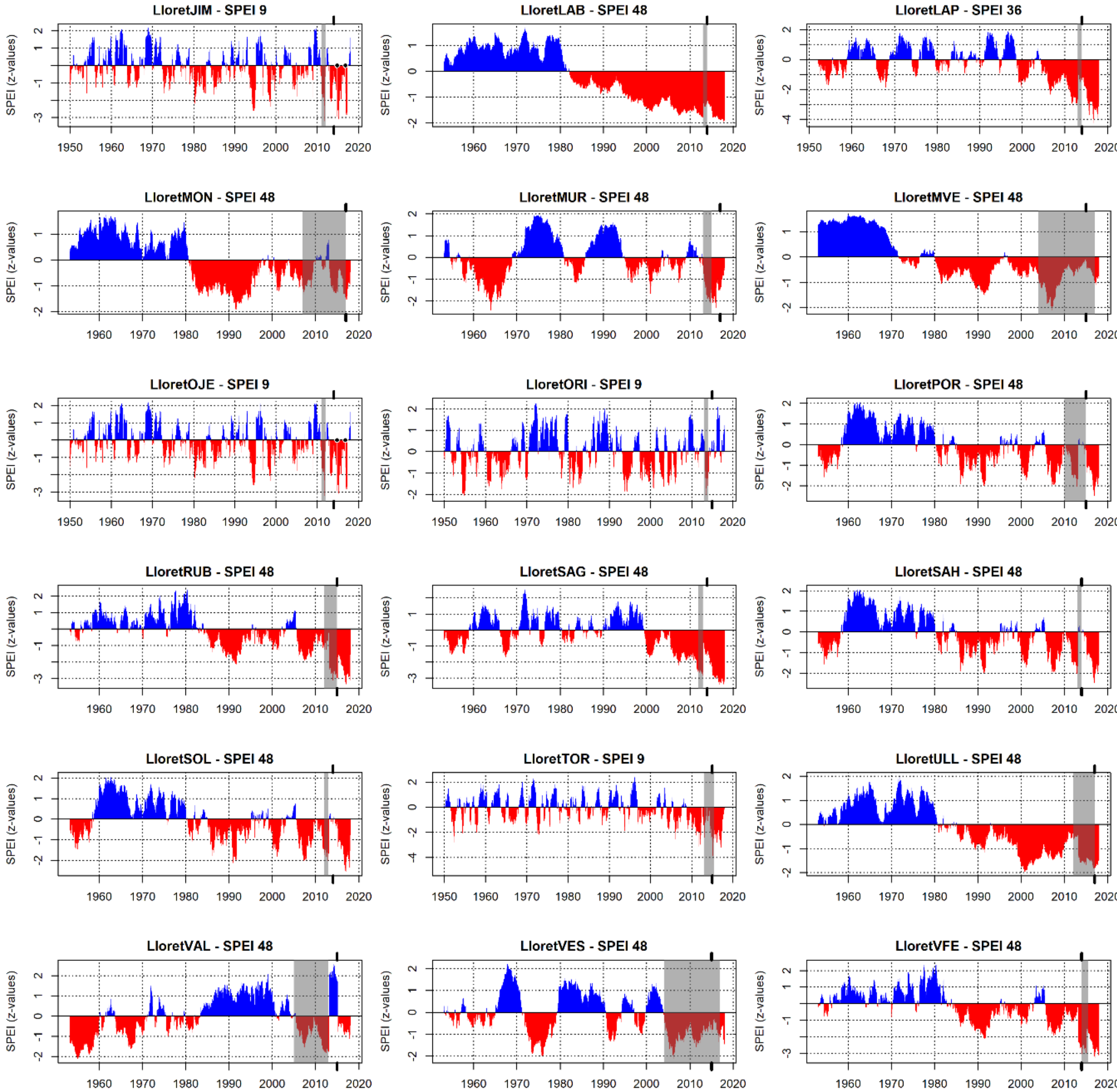


Fig. S1. *continued*



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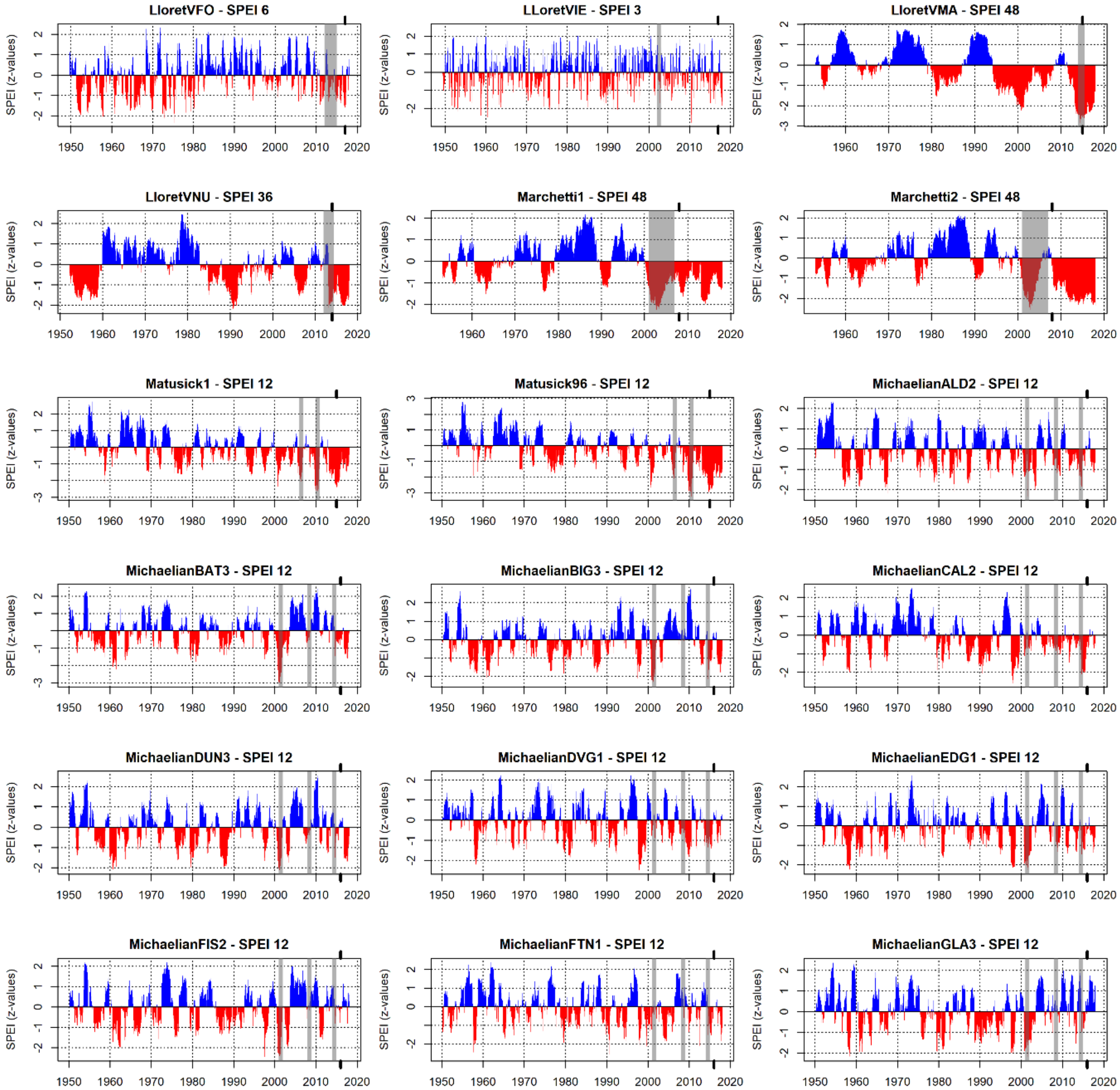

Fig. S1. *continued*

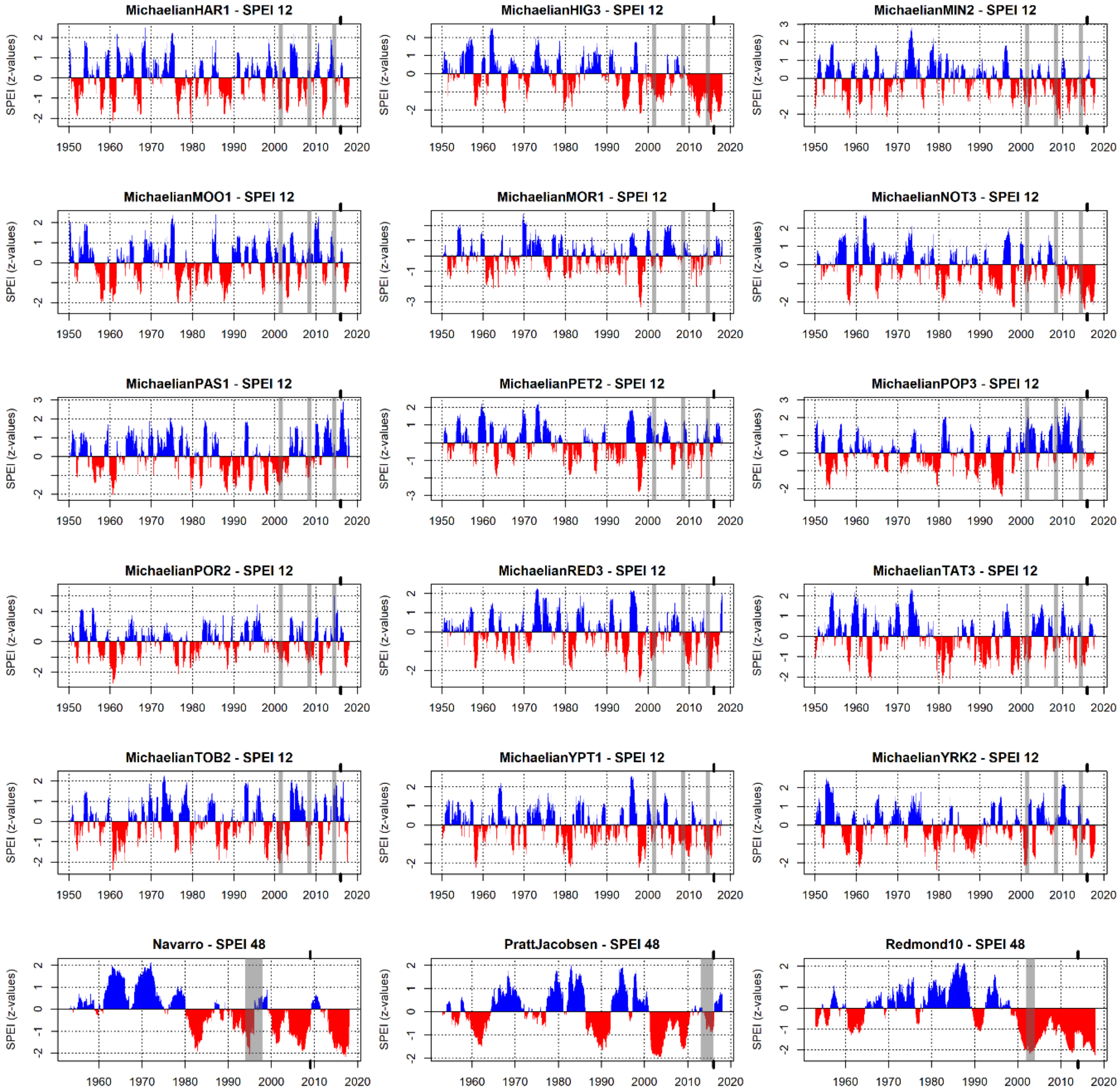

Fig. S1. *continued*

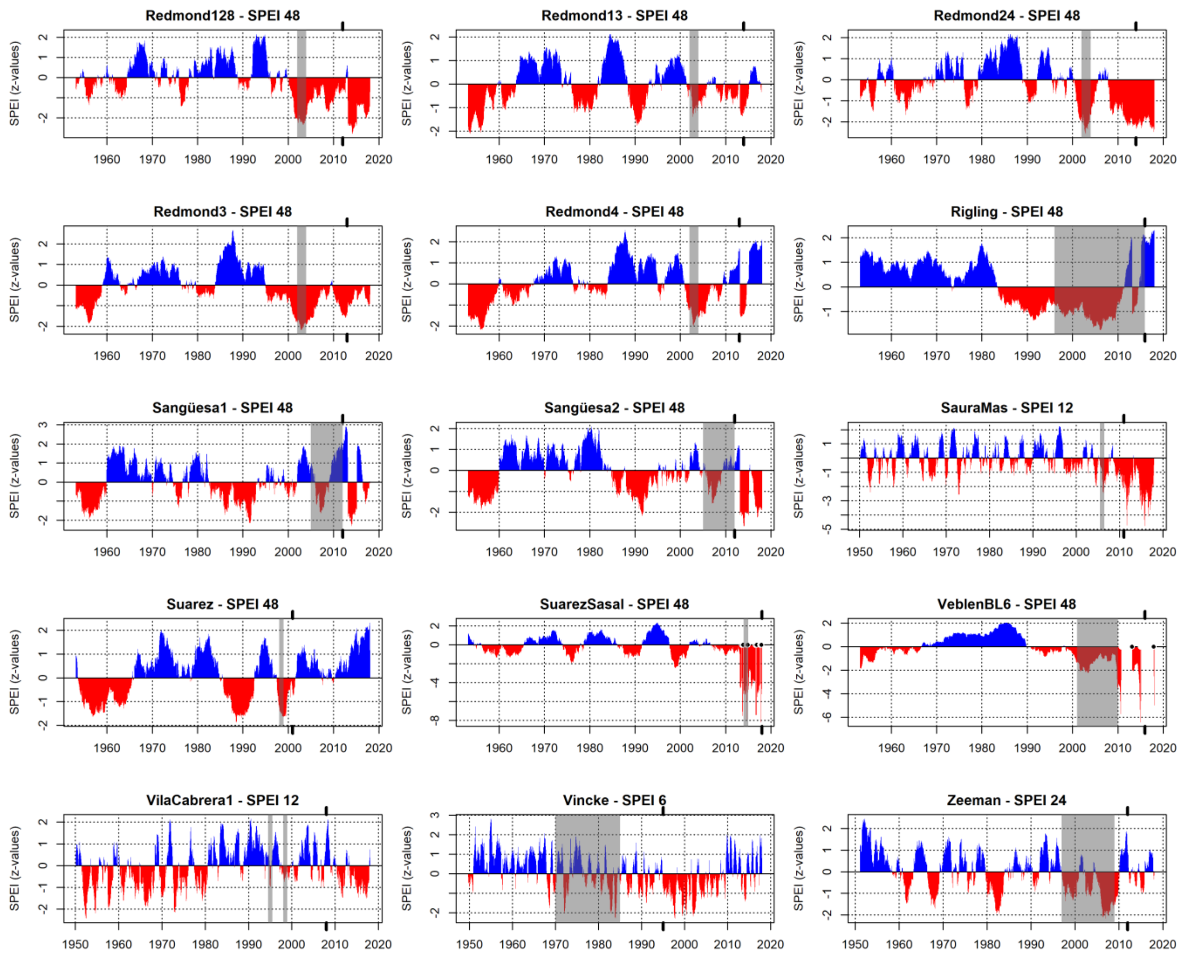

Fig. S1. *Continued*

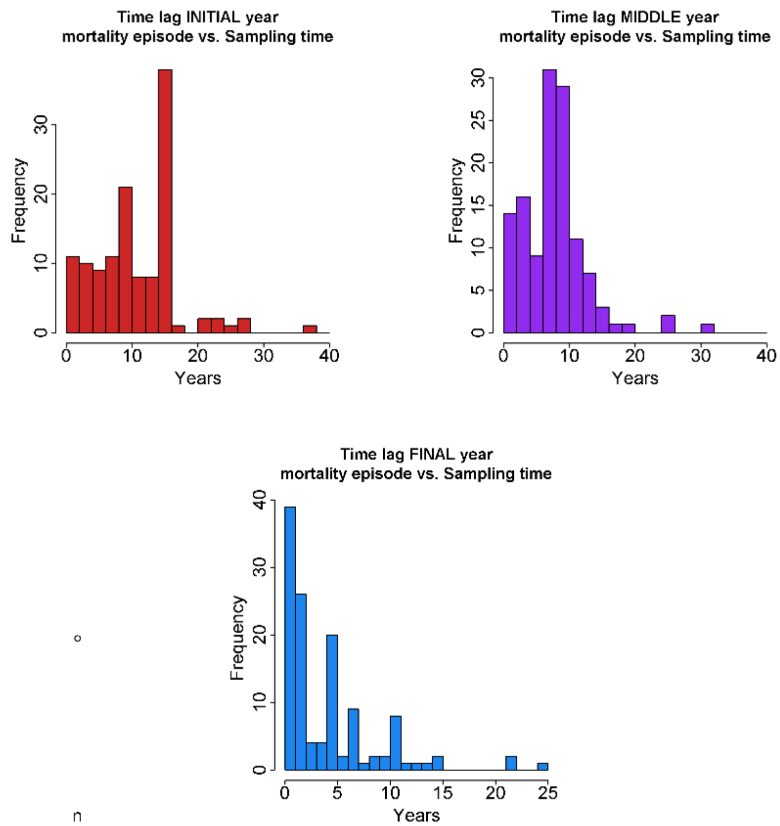

Fig. S2. Frequency distributions of the temporal lag in years between the drought event and assessment of replacement patterns (i.e., how long after drought field measurements were made) in each study site (*Dataset* D1). The lag between initial (top-left), middle (top-right), and last (bottom) year of tree mortality is depicted.

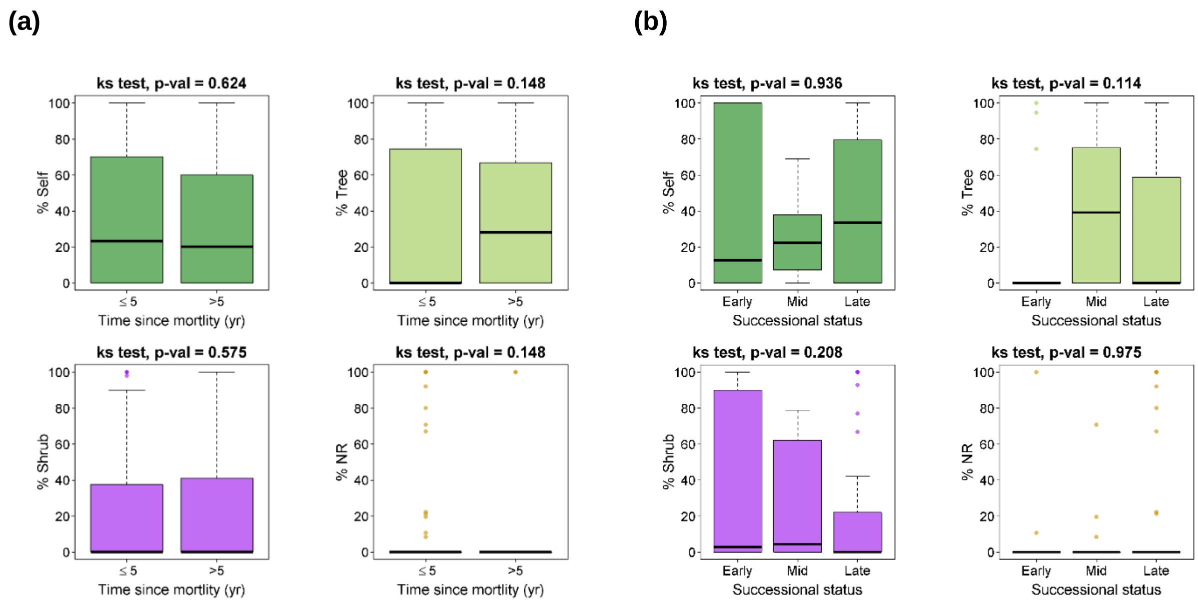

Fig. S3. Replacement patterns in relation to (a) 'recovery time' or the lag between the observed mortality and sampling time and (b) the successional state (*Dataset* D1 and D3) of the assessed forest and woodlands. In (a) boxplots display the proportion of: '%Self' - self-replacement (i.e., replacement of dominant tree species with itself), '%Tree' and '%Shrub' - replacement by other woody species including trees and shrubs, respectively, or '%NR' - lack of replacement by woody vegetation in sites sampled ≤ 5 years and > 5 years after drought-induced tree mortality. In (b) boxplots display the proportion of: '%Self', '%Tree', '%Shrub', and '%NR' in sites within Early, Mid or Late successional state, that is whether forests are in compositional equilibrium and represent stable, self-reproducing populations (i.e., late) or transitional forests types (i.e., early, mid). The significance of Kruskal-Wallis rank sum tests is presented for each case, indicating that no significant differences exist among the groups of study sites.

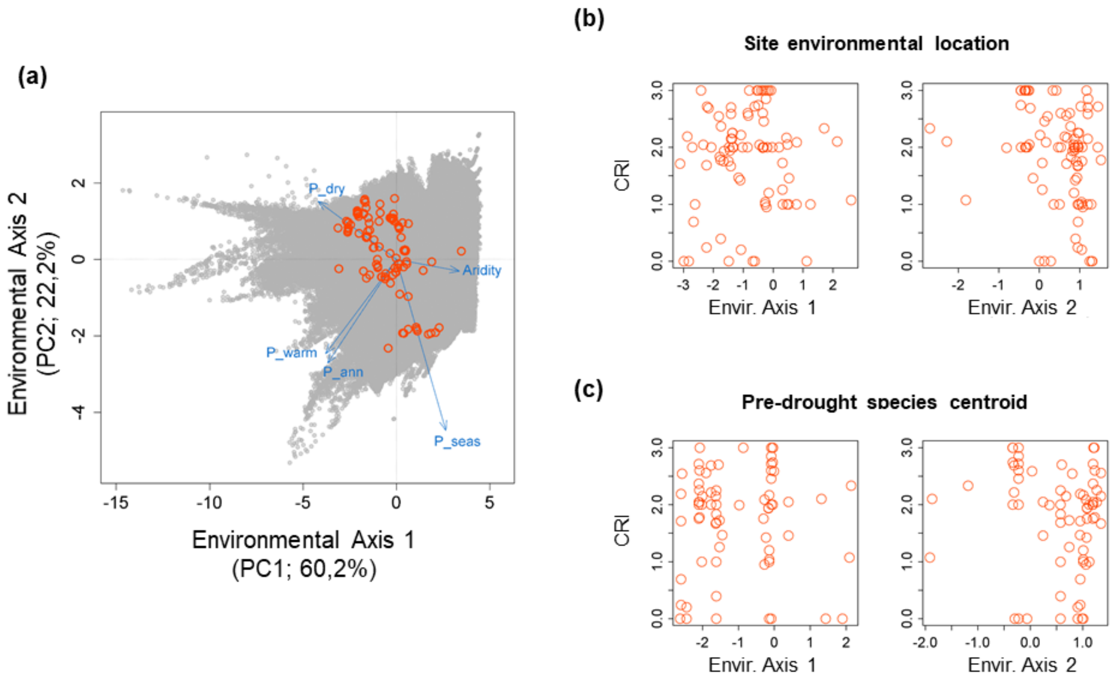

Fig. S4. (a) Environmental space used to characterize the bioclimatic characteristics of the species and reporting sites. Each grey dot corresponds to all 10 × 10 km pixels within the forested biomes included in our analysis (see Fig. 1 within the main text) and the orange circles depict the field sites included in our analyses. Right panels show replacement patterns, characterized by means of the joint compositional and structural community resemblance index CRI, in relation to (b) the bioclimatic characteristics of the study sites and (c) the environmental centroids of the dominant (pre-drought) species at each site. The environmental space (a) was defined through Principal Component Analysis (PCA) on the basis of four precipitation regime variables plus the aridity index at the global scale (excluding species-rich tropical biomes, following Olson *et al*. 2001 biome classification; *Bioscience* **51**, 933–938 (2001)); P_seas – precipitation seasonality, P_dry – precipitation of the driest quarter, P_warm – precipitation of the warmest quarter, P_ann – annual precipitation, and Aridity – Aridity Index expressed as 1- aridity. Precipitation data for baseline conditions were obtained from WorldClim Version 2.0 at a 10 × 10 km resolution (http://www.worldclim.org/) and the aridity index from CGIAR-CSI website (http://www.cgiar-csi.org). The bioclimatic optima or environmental centroids of all species within the study sites (orange circles) were defined as the density centroid (center of mass of the point distribution within the environmental space) of the 95% density distribution kernel of the species observations (i.e., presence data) as obtained from the Global Biodiversity Information Facility (GBIF; https://www.gbif.org/). In (b) mapped PCA loadings represented in graph (a) were used to extract the principal components PC1 and PC2 values at the x-y coordinates of the sites. In (c) the environmental centroid of each site was computed as the weighted mean (based on species abundance) of the environmental centroids of the dominant (pre-drought) tree species.

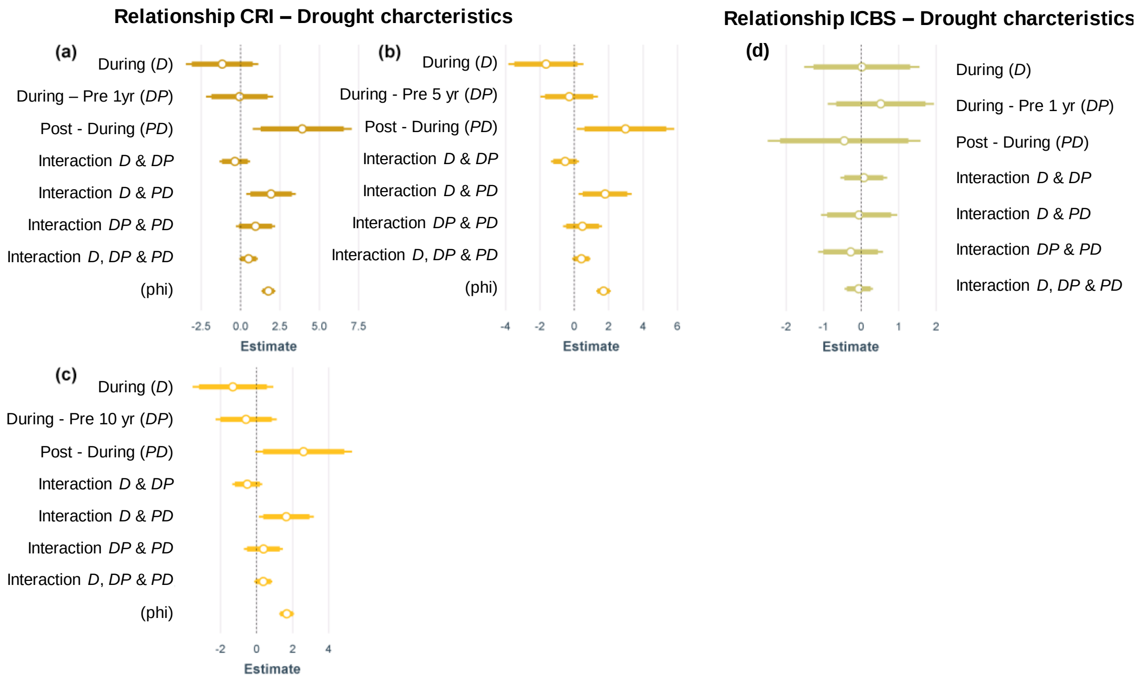

Fig. S5. (a) – (c) Coefficient estimates of the beta regression models assessing the relationship between replacement patterns (included in the model as the community resemblance index, CRI) and drought conditions before, during, and after tree mortality. In panels (a), (b) and (c), Pre 1 yr, Pre 5 yr and Pre 10 yr correspond to pre-mortality drought conditions averaged over 1yr, 5yr and 10yr temporal windows before the year of tree mortality, respectively. (d) Coefficient estimates of the generalized linear model assessing the relationship between community-level bioclimatic change (included in the model as site-level community bioclimatic shift index ICBS) and drought conditions before, during, and after tree mortality. Models pseudo R^2 = 0.274, 0.242, 0.228, and 0.11, respectively.

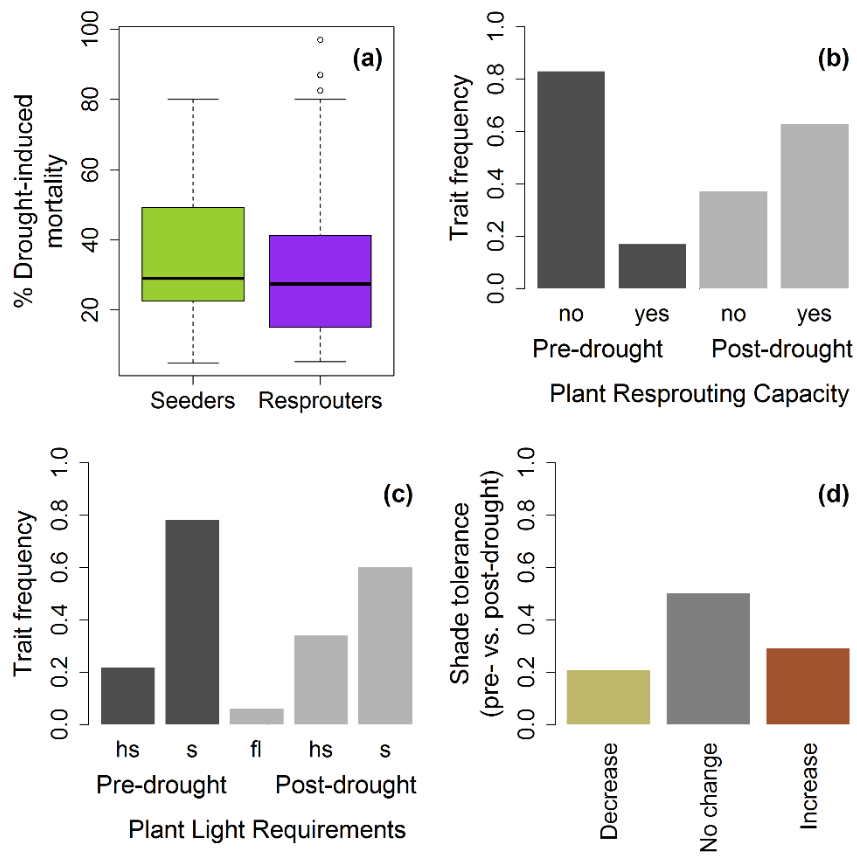

Fig. S6. (a) Level of drought-induced mortality (proportion of tree death) in relation to plant resprouting capacity (PRC) in the 131 field sites included in our analysis; (b) frequency of the community-level plant resprouting capacity; (c) frequency of plant light requirements (PLR) before and after the drought-induced mortality event. The PRC graph shows the proportion of resprouting and non-resprouting (seeders) woody species across all sites, and the PLR graph depicts the proportion of species in each of the following species' light requirements classes: fl – full light, hs – half-shadowy, s – shadowy (*following the TRY database notation*). In both plots, dark grey represents the pre-drought trait frequency of dominant tree species whereas light grey depicts the trait frequency of replacing woody species independent of vegetation-type replacement. The composition (species presence) of the pre- and post-drought woody communities were used to compute trait frequencies before and after drought-induced mortality. Graph (d) shows the community-level change in shade tolerance assessed as the difference in plant light requirements between pre-drought dominant and post-drought replacing species. Species-specific traits were obtained from the publicly available, open access TRY database (J. Kattge, *et al.*, TRY - a global database of plant traits. *Glob. Chang. Biol.* **17**, 2905–2935 (2011)). Please see *Material and Methods* description above for additional details about imputation of missing trait values.

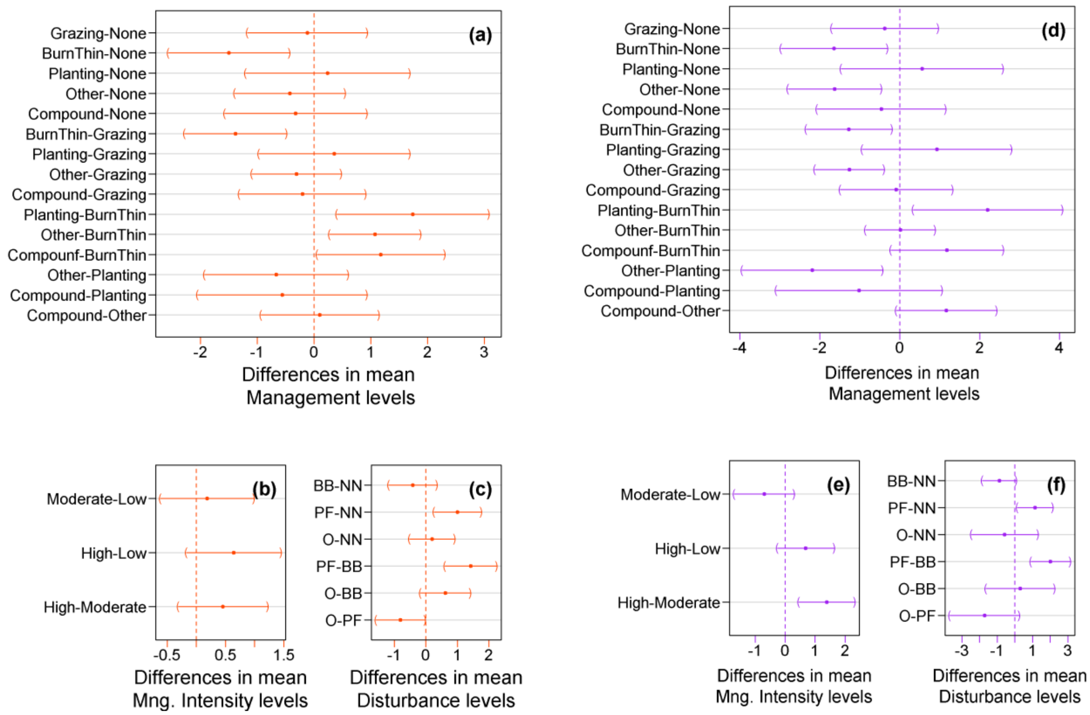

Fig. S7. Pairwise differences in mean levels of management (a, d), management intensity (b, e) and biotic disturbances (c, d) as inferred from Tukey Honest Significant Differences performed on the results of beta regression models for community resemblance index (CRI; orange color) and proportion of replacement by shrubs (purple color) under each condition, respectively. Beta regression models were performed in R (function '`betareg`') and pairwise differences with the package `multcomp`. Note that models for shrublands proportion were performed after rescaling proportions of shrub replacement to 0-1.

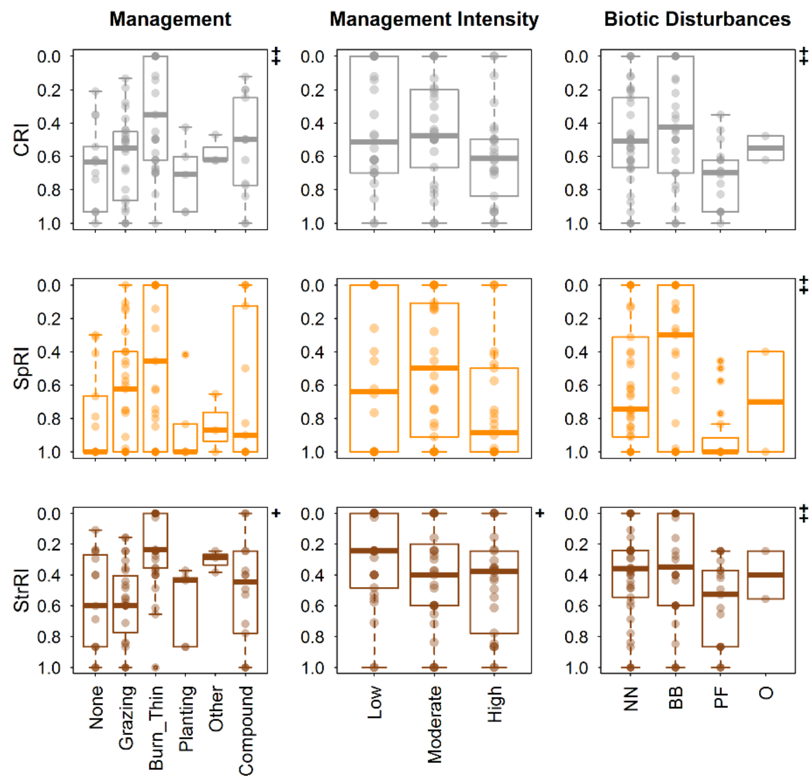

Fig. S8. Replacement patterns in relation to management, management intensity, and biotic disturbances within the 131 filed sites included in our analysis. From top to bottom, CRI – join compositional and structural resemblance index, SpRI – compositional resemblance index, StrRI – structural resemblance index are displayed. CRI corresponds to a measure of community resemblance of the pre-drought and post-drought vegetation in terms of composition and structure, computed as the mean of dissimilarity indices of composition (SpRI) and structure (StrRI). Compositonal and structural indices were computed by means of the functions '`vegdist`' and '`vegdiststruct`' of the R packages `vegan` *(52)* and `vegclust` *(51)*. In all cases, 0 indicates no change and 1 indicates complete change. Please see *Methods* description in the main text for additional details about assessment of composition and structural differences.

(a) **(b)**

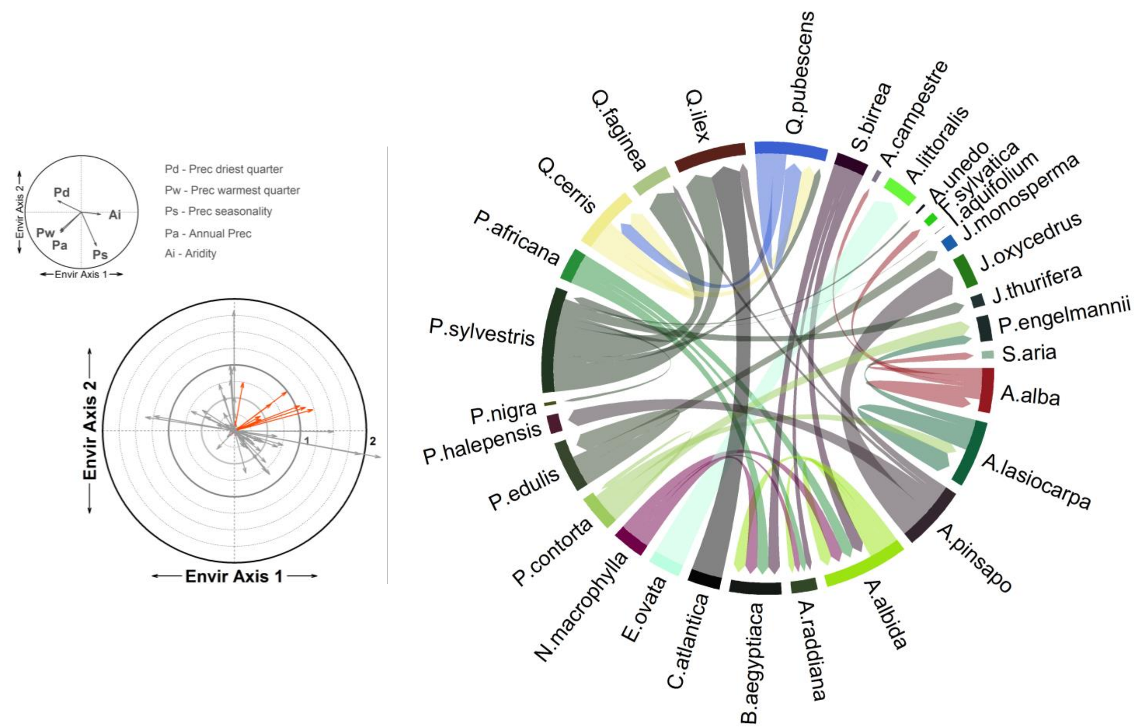

Fig. S9. (a)Relative change in the environmental space of those forest sites in which the bioclimatic optimum of the replacing community derived in a shift towards drier conditions: lower precipitation of the warmest quarter, lower annual precipitation, and increased aridity. (b) Replacement patterns at the species level in these sites. The inner, top plot in panel (a) depicts the contribution of the five climate variables used to characterize the environmental space through principal component analysis. Note that the bioclimatic shifts were assessed by means of the weighted community values of the bioclimatic optima of all dominant (pre-drought) and replacing species at a given site. Therefore, some species-specific relationships (drier versus wetter optima) may not match the overall community level shift.

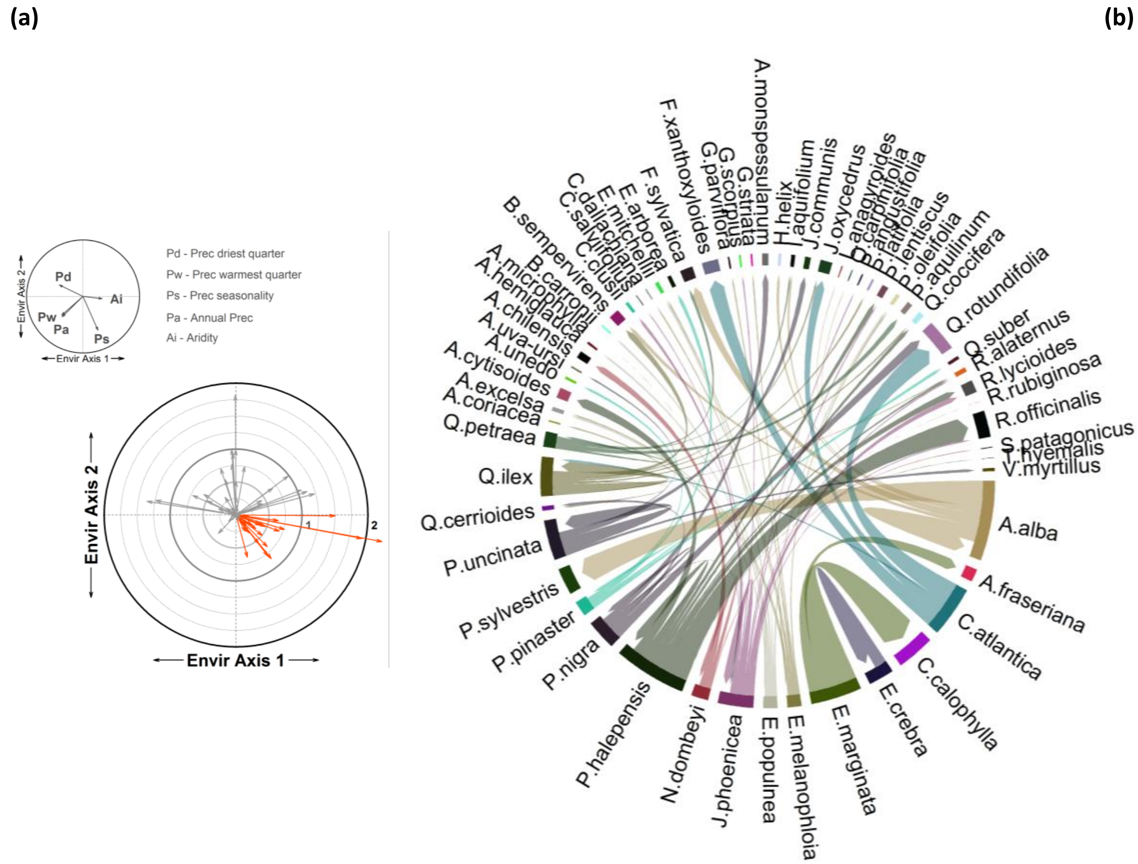

Fig. S10. (a) Relative change in the environmental space of those forest sites in which the bioclimatic optimum of the replacing community derived in a shift towards increased precipitation seasonality, lower precipitation of the driest quarter, and increased aridity. (b) Replacement patterns at the species level in these sites. The inner, top plot in panel (a) depicts the contribution of the five climate variables used to characterize the environmental space through principal component analysis. Note that the bioclimatic shifts were assessed by means of the weighted community values of the bioclimatic optima of all dominant (pre-drought) and replacing species at a given site. Therefore, some species-specific relationships (drier versus wetter optima) may not match the overall community level shift.

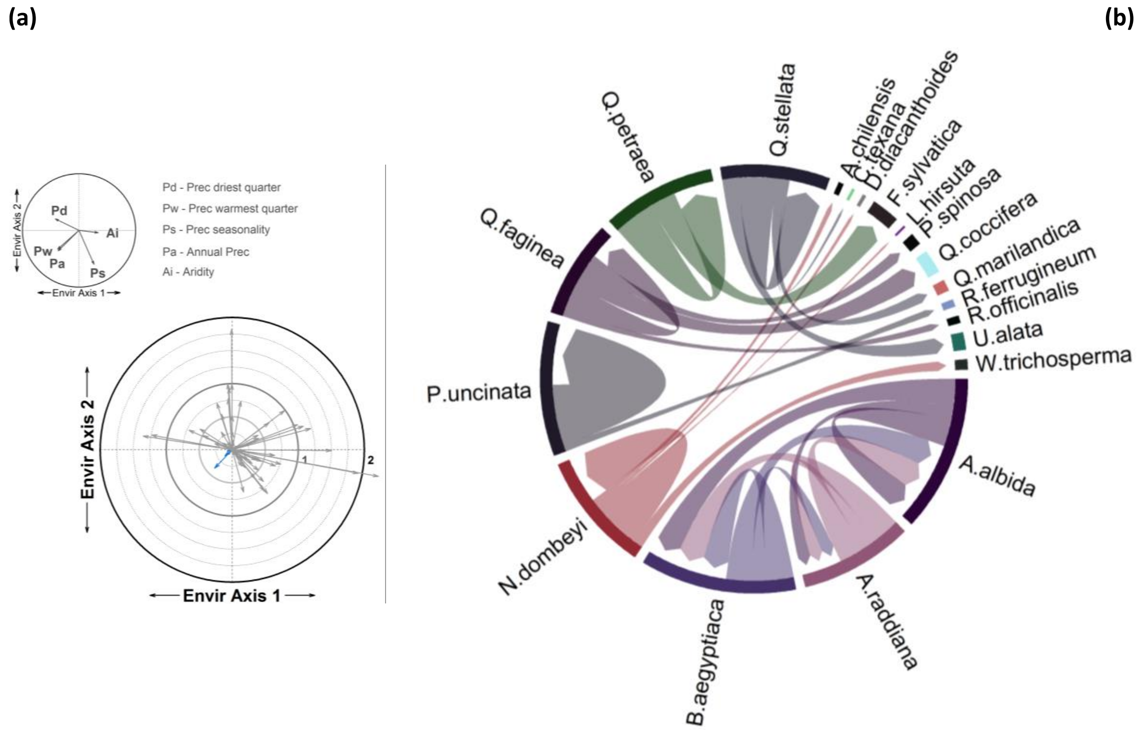

Fig. S11. (a) Relative change in the environmental space of those forest sites in which the bioclimatic optimum of the replacing community derived in a shift towards moister conditions: higher precipitation of the warmest quarter, higher annual precipitation, and decreased aridity. (b) Replacement patterns at the species level in these sites. The inner, top plot in panel (a) depicts the contribution of the five climate variables used to characterize the environmental space through principal component analysis. Note that the bioclimatic shifts were assessed by means of the weighted community values of the bioclimatic optima of all dominant (pre-drought) and replacing species at a given site. Therefore, some species-specific relationships (drier versus wetter optima) may not match the overall community level shift.

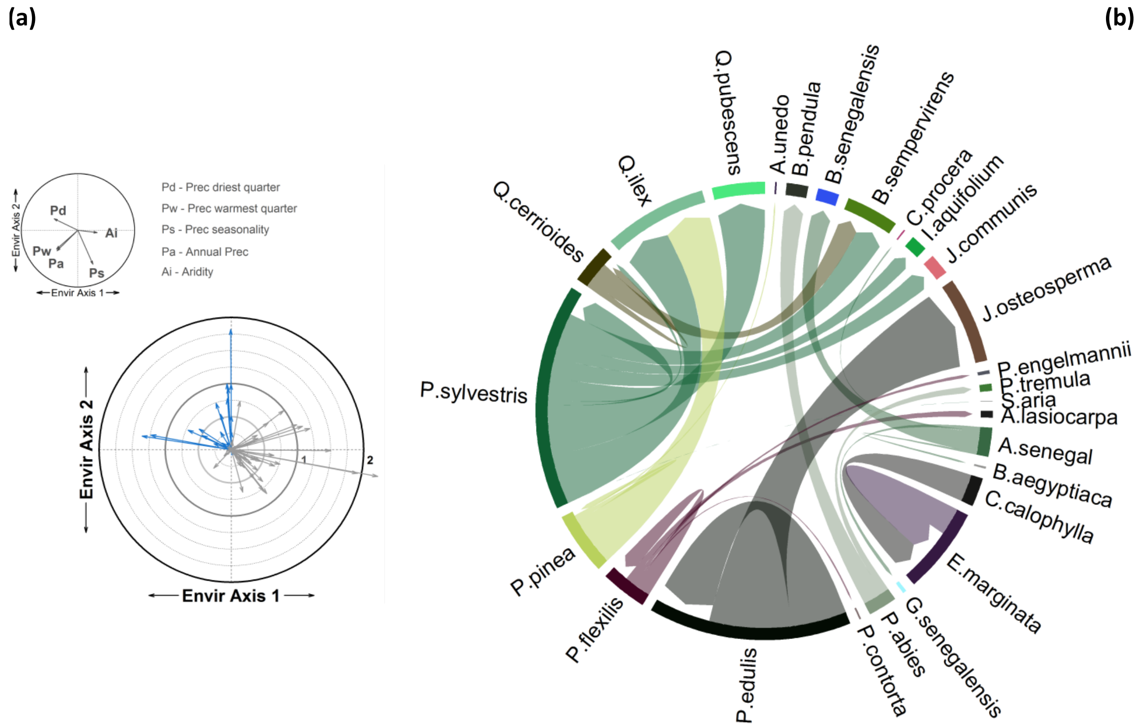

Fig. S12. (a) Relative change in the environmental space of those forest sites in which the bioclimatic optimum of the replacing community derived in a shift towards decreased precipitation seasonality, increased precipitation of the driest quarter, and decreased aridity. (b) Replacement patterns at the species level in these sites. The inner, top plot in panel (a) depicts the contribution of the five climate variables used to characterize the environmental space through principal component analysis. Note that the bioclimatic shifts were assessed by means of the weighted community values of the bioclimatic optima of all dominant (pre-drought) and replacing species at a given site. Therefore, some species-specific relationships (drier versus wetter optima) may not match the overall community level shift.

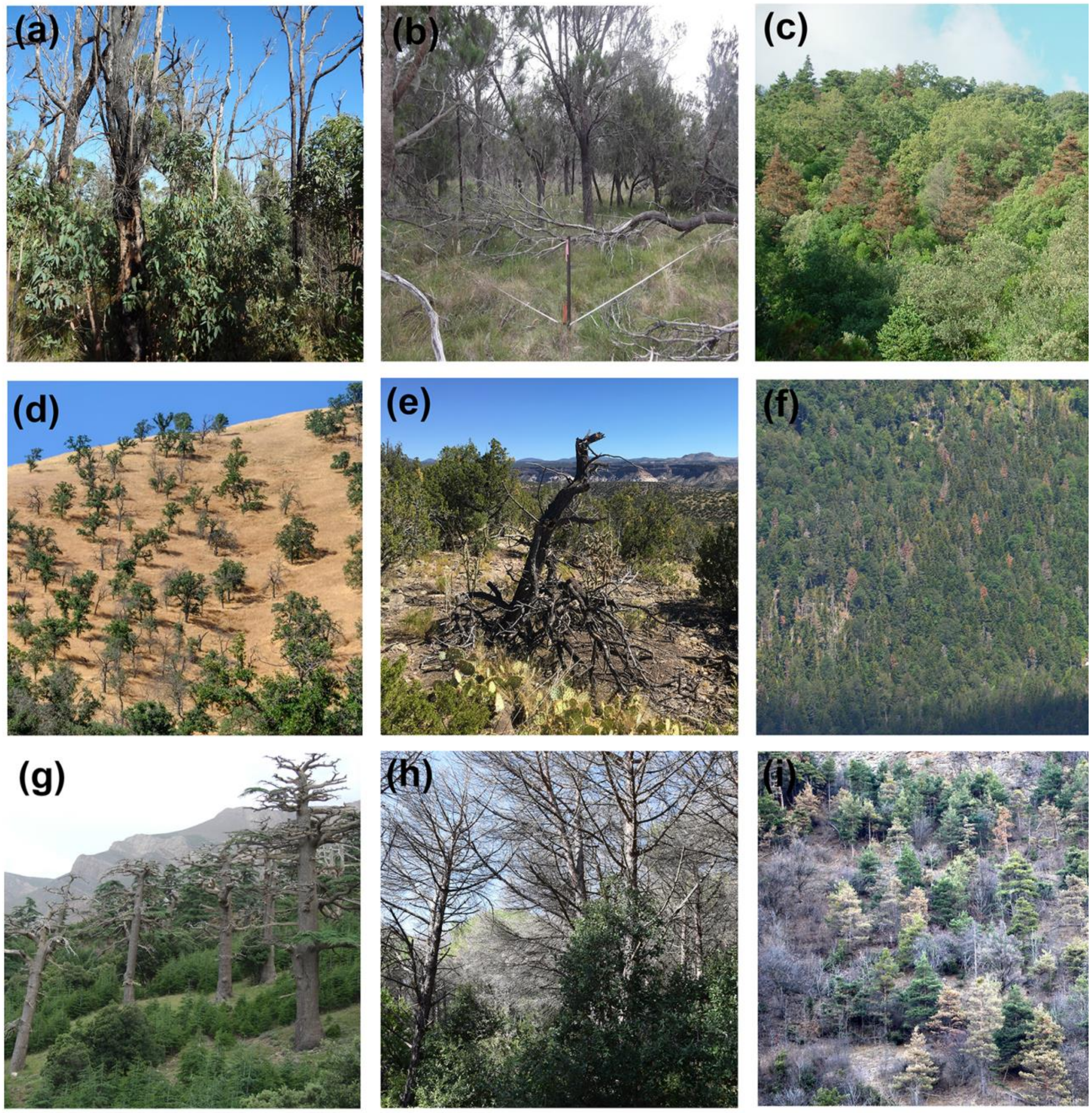

Fig. S13. (a) Self-replacement, *Eucalyptus marginata*, Northern Jarrah Forest, SW Australia (George Matusick); (b) tree replacement, *Eucalyptus ovata* replacement by *Allocasuarina littoralis*, temperate coastal woodland, SE Australia (Ben Zeeman); (c) tree replacement, *Abies pinsapo* replacement by *Quercus ilex* and *Q. faginea*, Sierra de las Nieves, Spain (Juan Carlos Linares); (d) lack of woody replacement, *Quercus douglasii*, California (Brandon Pratt); (e) lack of replacement, *Pinus edulis*, New Mexico, USA (Miranda Redmond); (f) tree replacement, *Abies alba* replacement by *Pinus sylvestris* and *Fagus sylvativa*, Central Pyrenees, Spain (Gabriel Sangüesa-Barreda); (g) self-replacement, *Cedrus atlantica*, Middle Atlas, Morocco (Jun Carlos Linares), (h) tree replacement, *Pinus pinea* replacement by *Quercus ilex*, NE Spain (Francisco Lloret), (i) tree replacement, *Pinus sylvestris* replacement by *Quercus pubescens*, Valais, Switzerland (Andreas Rigling).

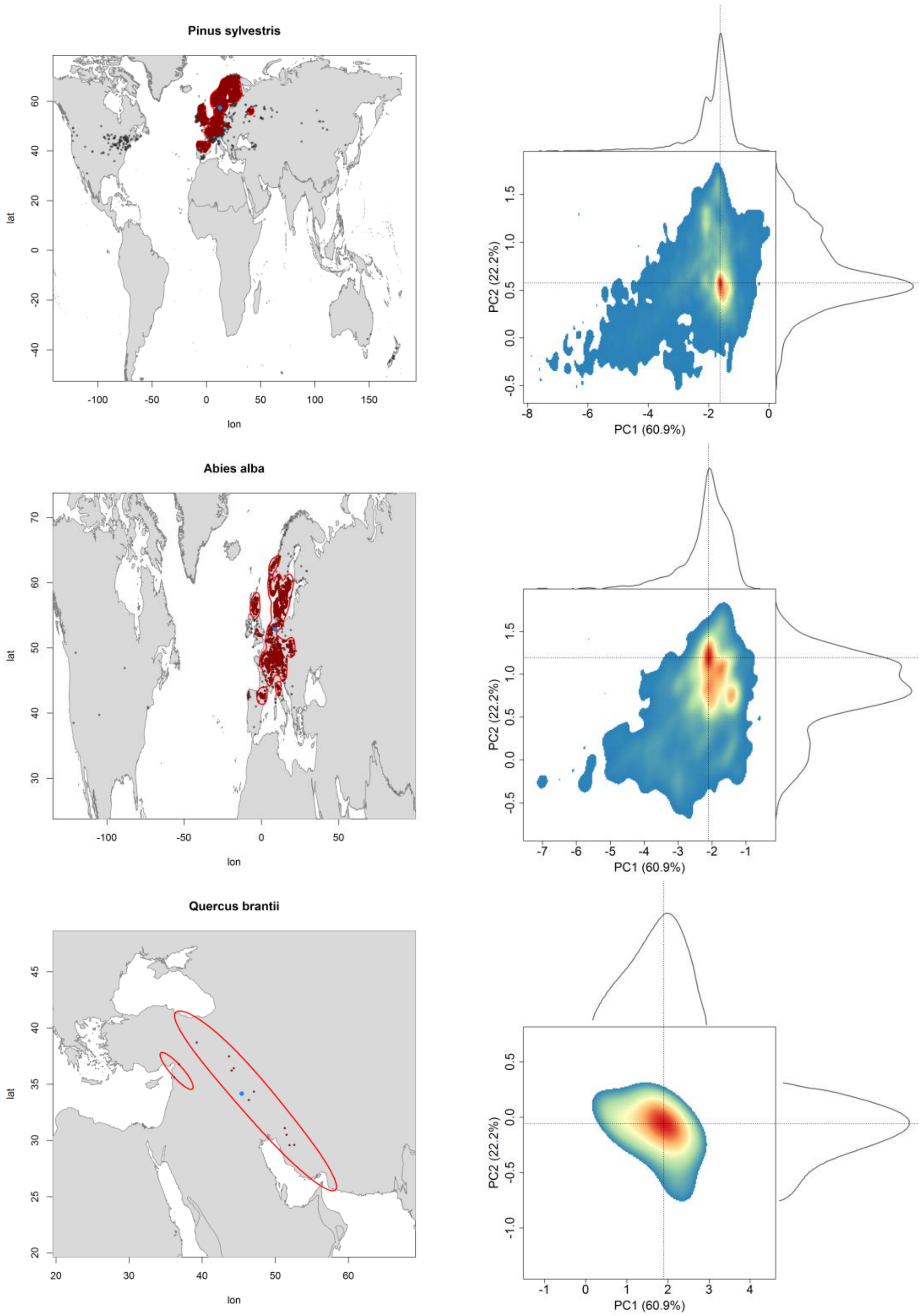

Fig. S14. Species occurrence data in geographic space (left) and its correspondence within the environmental space (right) that was used to define the bioclimatic niche (*see* Fig. S4). Original GBIF occurrence data (grey dots) were filtered using the 95% distribution kernel (red line) to define the bioclimatic niche of each species from the correspondence of geographic occurrence and position within the environmental space. From top to bottom, examples of species with wider and smaller distribution ranges (*Pinus sylvestris*, *Abies alba*, *Quercus brantii*).

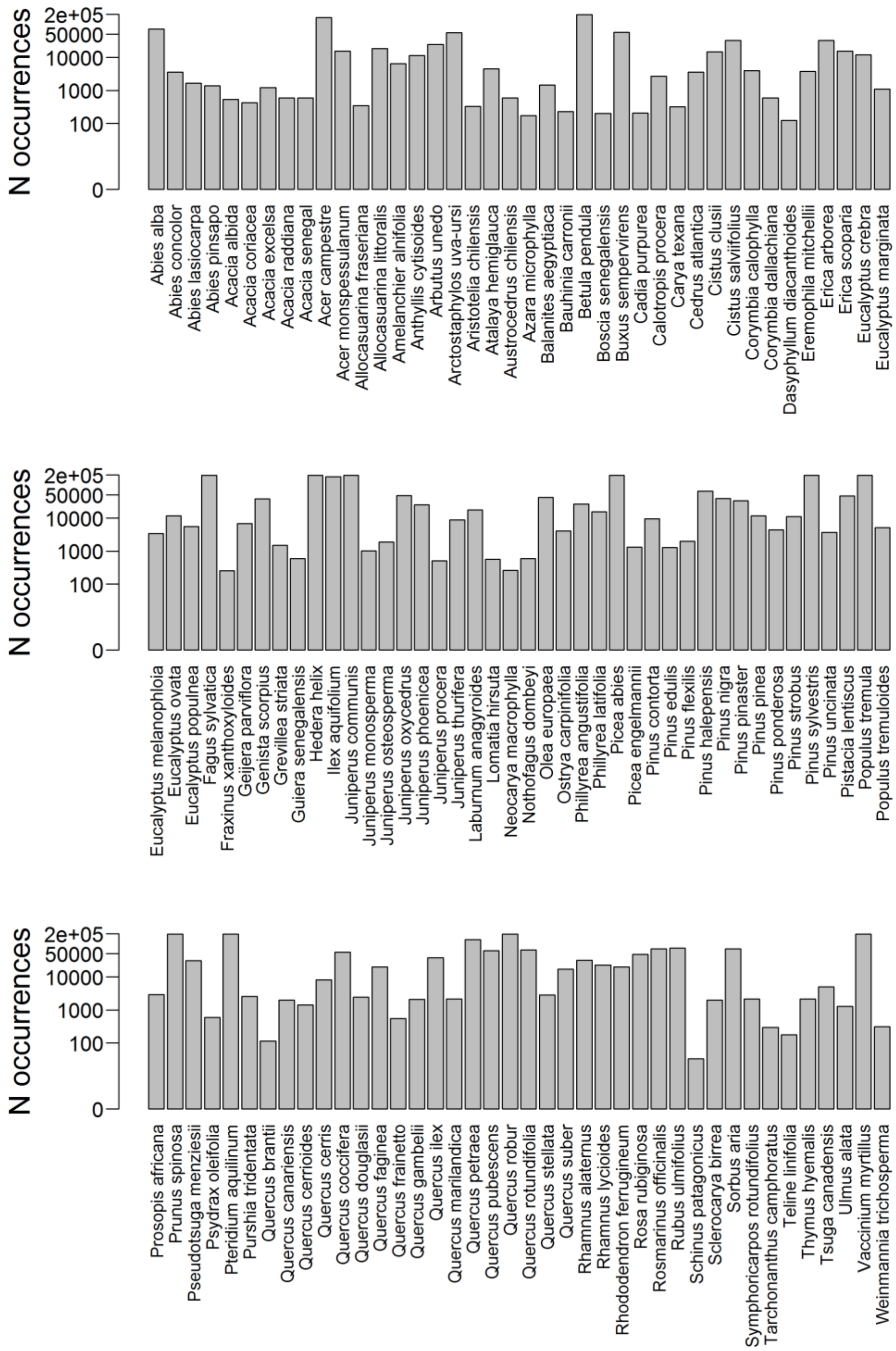

Fig. S15. Number of occurrences for all woody species (N = 122) that formed the basis of the replacement assessment, and for which the bioclimatic niche was estimated. Occurrence data were obtained from GBIF (http://www.gbif.org) in 19-21 January 2018.