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Supplementary information

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Global functional shifts in trees driven by alien naturalization and native extinction

In the format provided by the authors and unedited

Supplementary materials to

Global Functional Shifts in Trees Driven by Alien Naturalization and Native Extinction

Table S1 Description of the 8 traits and 49 environmental ranges included in this study. Data for species traits and their environmental ranges, respectively, were extracted from Guo *et al*. (2022) and Kindt (2023).

Category	Sub-category	Abbreviation	Percentage of species with measured trait values	Description
Species traits	Leaf trait	LA	19.55%	Leaf area (in case of compound leaves: leaflet, petiole and rachis excluded)
		SLA	19.49%	specific leaf area (Leaf area per leaf dry mass, 1/LMA)
		LDMC	6.67%	Leaf dry matter content
		leafN	15.67%	Leaf nitrogen (N) content per leaf dry mass
		leafP	10.33%	Leaf phosphorus (P) content per leaf dry mass
	Seed trait	SeedDryMass	21.95%	Seed dry mass
	Whole-plant trait	VegMaxHeight	26.10%	Plant maximum height
		WDensity	21.95%	Stem specific density (SSD)
	Climatic preference	bio01		Annual Mean Temperature
		bio02		Mean Diurnal Range (Mean of monthly (max temp - min temp))
		bio03		Isothermality (BIO2/BIO7) (×100)
		bio04		Temperature Seasonality (standard deviation ×100)
		bio05		Max Temperature of Warmest Month
		bio06		Min Temperature of Coldest Month
		bio07		Temperature Annual Range (BIO5-BIO6)
		bio08		Mean Temperature of Wettest Quarter
		bio09		Mean Temperature of Driest Quarter
		bio10		Mean Temperature of Warmest Quarter
		bio11		Mean Temperature of Coldest Quarter
		bio12		Annual Precipitation

	bio13	Precipitation of Wettest Month
	bio14	Precipitation of Driest Month
	bio15	Precipitation Seasonality (Coefficient of Variation)
	bio16	Precipitation of Wettest Quarter
	bio17	Precipitation of Driest Quarter
	bio18	Precipitation of Warmest Quarter
	bio19	Precipitation of Coldest Quarter
	annualPET	Annual potential evapotranspiration: a measure of the ability of the atmosphere to remove water through evapotranspiration processes, given unlimited moisture
Environmental preference	aridityIndexThornthwaite	Thornthwaite aridity index: index of the degree of water deficit below water need
	climaticMoistureIndex	A metric of relative wetness and aridity
	continentality	Average temp. of warmest month – average temp. of coldest month
	embergerQ	Emberger's pluviothermic quotient: a metric that was designed to differentiate among Mediterranean type climates
	growingDegDays0	Sum of mean monthly temperature for months with mean temperature greater than 0°C multiplied by number of days
	growingDegDays5	Sum of mean monthly temperature for months with mean temperature greater than 5°C multiplied by number of days
	maxTempColdest	Max. temp. of the coldest month
	meanTempColdest	Mean temp. of the coldest month
	meanTempWarmest	Mean temp. of the warmest month
	minTempWarmest	Min Temperature of warmest month
	monthCountByTemp10	Count of the number of months with mean temp greater than 10°C

		PETColdestQuarter	Mean monthly PET of coldest quarter
		PETDriestQuarter	Mean monthly PET of driest quarter
		PETseasonality	Monthly variability in potential evapotranspiration
		PETWarmestQuarter	Mean monthly PET of warmest quarter
		PETWettestQuarter	Mean monthly PET of wettest quarter
		thermicityIndex	Compensated thermicity index: sum of mean annual temp., min. temp. of coldest month, max. temp. of the coldest month, with compensations for better comparability across the globe
		MCWD	Maximum Climatological Water Deficit
		elev	Elevation above sea level (from SRTM)
	soil physio-chemical preference	bdod	Bulk density of the fine earth fraction oven dry
		cec	Capacity of the fine earth fraction to hold exchangeable cations
		nitrogen	Sum of total nitrogen (ammonia, organic and reduced nitrogen) as measured by Kjeldahl digestion plus nitrate–nitrite
		phh2o	Negative common logarithm of the activity of hydronium ions (H+) in water
		clay	Gravimetric contents of sand, silt, and clay in the fine earth fraction of the soil
		sand	Gravimetric contents of sand, silt, and clay in the fine earth fraction of the soil
		silt	Gravimetric contents of sand, silt, and clay in the fine earth fraction of the soil
		soc	Gravimetric content of organic carbon in the fine earth fraction of the soil
		topoWet	SAGA-GIS topographic wetness index
		tri	Terrain roughness index

Table S2 Summary of principal component analysis of species traits and correlations of the 8 traits with the first two principal component axes. Correlations that are equal or larger than 0.75 are in bold.

Summary of PCA		PC1	PC2
Eigenvalue		3.25	1.59
Percentage of variance		40.68	19.82
Cumulative percentage of variance		40.68	60.50
Correlations between variables and PC axes			
Leaf trait	LA	0.34	**0.78**
	SLA	**0.90**	-0.06
	LDMC	**-0.77**	0.02
	Leaf N	**0.86**	0.23
	Leaf P	0.52	-0.60
Seed trait	Seed dry mass	0.09	0.56
Whole-tree trait	Max height	0.42	0.32
	Woody Density	-0.73	0.37

Table S3 Summary of principal component analysis of species' environmental preferences and correlations of the 49 variables with the first two principal component axes. Correlations that are equal or larger than 0.75 are in bold.

Summary of PCA		**PC1**	**PC2**			
Eigenvalue		19.71	12.99			
Percentage of variance		40.23	26.52			
Cumulative percentage of variance		40.23	66.75			
Correlations between variables and PC axes						
		PC1	**PC2**		**PC1**	**PC2**
Climatic preference	bio01	**0.94**	0.31	annualPET	0.70	0.55
	bio02	-0.33	0.59	aridityIndexThornthwaite	-0.24	0.73
	bio03	0.71	-0.28	climaticMoistureIndex	0.42	**-0.80**
	bio04	**-0.77**	0.25	continentality	**-0.77**	0.26
	bio05	0.57	0.71	embergerQ	0.70	-0.62
	bio06	**0.97**	0.00	growingDegDays0	**0.94**	0.31
	bio07	**-0.77**	0.44	growingDegDays5	**0.93**	0.31
	bio08	**0.77**	0.37	maxTempColdest	**0.93**	0.20
	bio09	**0.92**	0.20	meanTempColdest	**0.97**	0.10
	bio10	0.69	0.54	meanTempWarmest	0.65	0.56
	bio11	**0.97**	0.12	minTempWarmest	0.68	0.39
	bio12	0.66	-0.64	monthCountByTemp10	0.72	0.24
	bio13	0.61	-0.43	PETColdestQuarter	**0.85**	0.13
	bio14	0.45	-0.64	PETDriestQuarter	0.63	0.31
	bio15	-0.14	0.59	PETseasonality	-0.70	0.44
	bio16	0.63	-0.45	PETWarmestQuarter	0.13	**0.87**
	bio17	0.48	-0.66	PETWettestQuarter	0.32	0.50
	bio18	0.27	-0.52	thermicityIndex	**0.96**	0.25
	bio19	0.60	-0.49	MCWD	0.24	**-0.83**
	elev	-0.52	-0.39			
Soil physio-chemical preference	bdod	-0.07	**0.85**	phh2o	-0.51	0.57
	cec	-0.40	-0.29	clay	0.52	-0.37
	nitrogen	-0.16	**-0.77**	sand	-0.21	0.64
	topoWet	0.36	0.60	silt	-0.14	-0.59
	tri	-0.38	-0.55	soc	0.18	-0.71

Table S4 Summary of phylogenetic corrected ANOVA of the first two axes of the principal component analysis of functional and environmental spaces. Significant *p* values ($p < 0.05$) were marked in bold.

	Functional space		**Environmental space**	
	PC1	PC2	PC1	PC2
Sum of Squares	536.68	112.56	32443.81	5287.10
Mean Squares	268.34	56.28	16221.91	2643.55
F value	82.89	35.57	869.03	206.13
P value	0.064	0.300	**0.001**	**0.002**
Residual	100293	49011	578296	397302
***p*-values of pairwise comparisons of the first two axes of trait space**				
		naturalized	non-threatened	threatened
PC1	naturalized	1		
	non-threatened	0.204	1	
	threatened	0.101	0.101	1
PC2	naturalized	1		
	non-threatened	0.368	1	
	threatened	0.514	0.368	1
***p*-values of pairwise comparisons of the first two axes of environmental space**				
PC1	naturalized	1		
	non-threatened	**0.002**	1	
	threatened	**0.002**	0.57	1
PC2	naturalized	1		
	non-threatened	0.275	1	
	threatened	**0.045**	**0.003**	1

Table S5 Variable contributions in the discriminant analysis of principal components (DAPC) to identify potential future naturalization.

Variables	**Contribution**
Rates of burned area	0.7371
Rates of cropland expansion	0.1215
Human usage	0.1170
Rates of built-up expansion	0.0158
Rates of deforestation	0.0034
Rates of minimum temperature	0.0021
Rates of maximum temperature	0.0013
Rates of vapor pressure deficit	0.0010
Rates of tree cover decline	0.0006
Rates of precipitation	0.0003

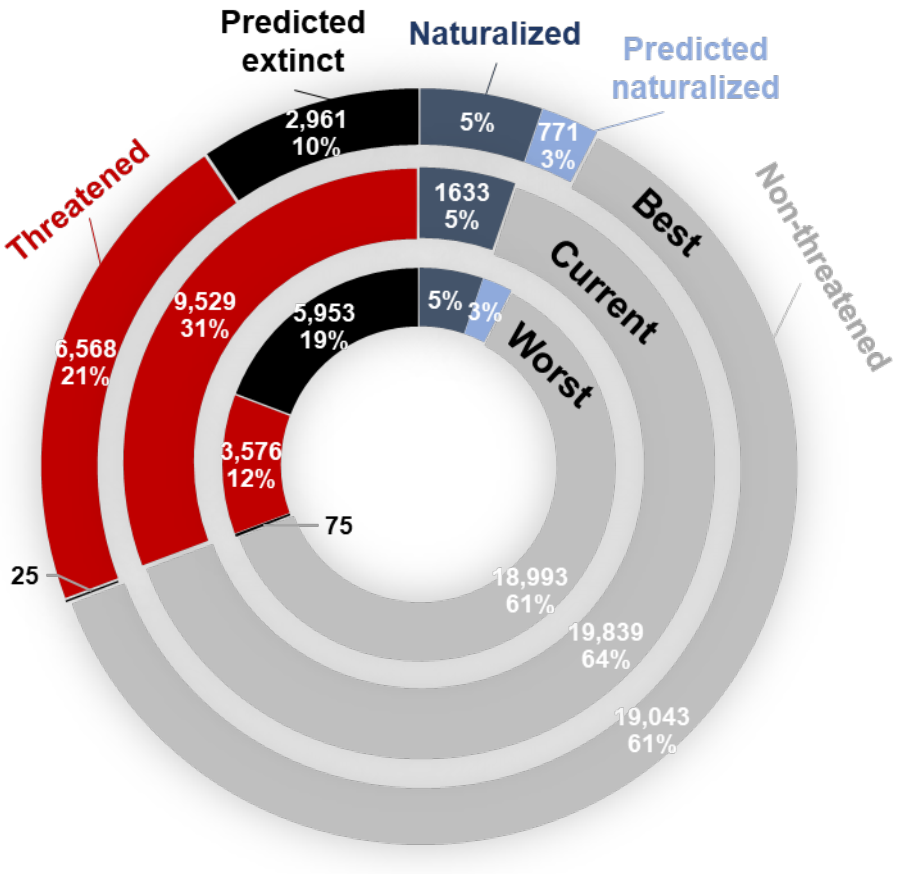

Fig. S1 Numbers/percentages of naturalized, non-threatened, and threatened tree species under current and projected naturalization and extinction (best-case and worst-case) scenarios.

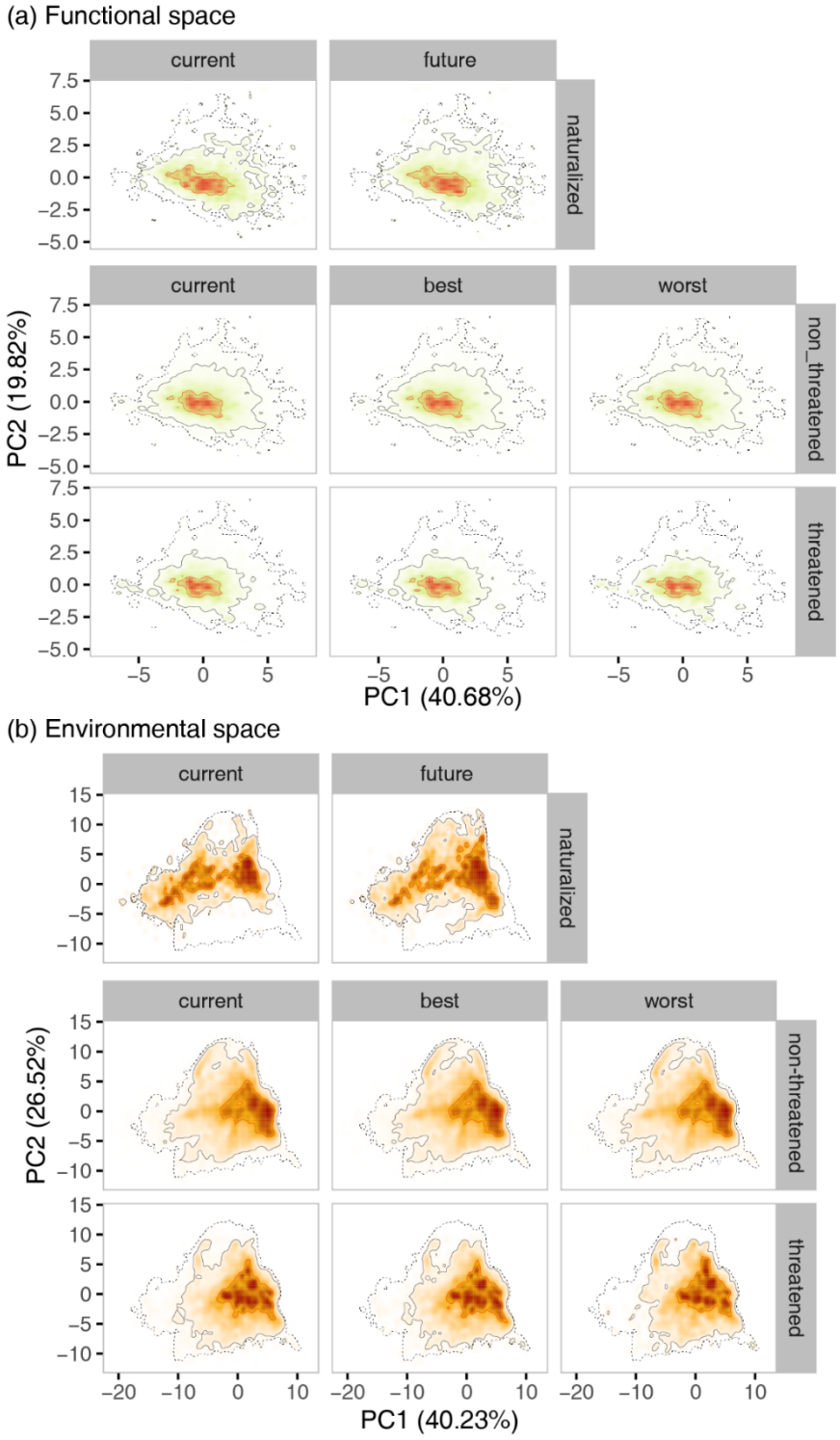

Fig. S2 Current and projected functional and environmental spectra for naturalized, non-threatened, and threatened species, shown as the mean values of the 100-extinction simulation. Dashed contour lines represent the 0.99 quantile of current functional and environmental space, showing the existing trait and environmental boundaries at the global scale, whereas black and red contour lines, respectively, indicate the 0.95 and 0.5 quantile of current functional and environmental space for the three species groups, respectively.

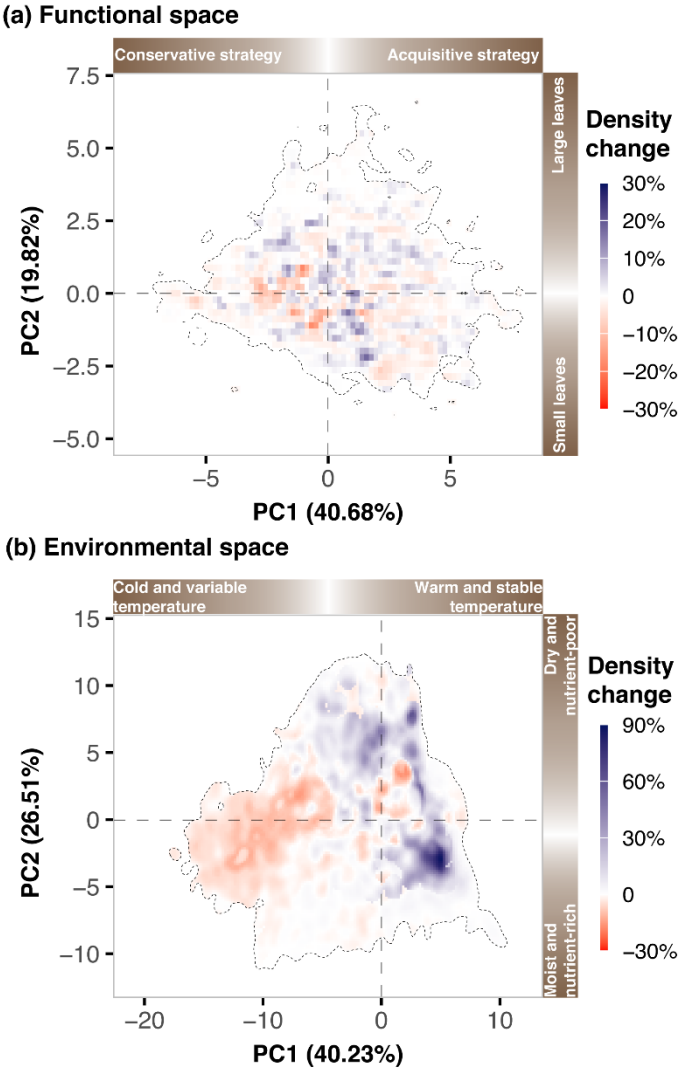

Fig. S3 Shifts in (a) functional and (b) environmental spectras for tree species between the current and the best-case projected future scenario, expressed as changes in kernel density estimates (i.e., trait probability densities, TPD). Red tones indicate regions where TPD values decrease, i.e., those traits or environmental preferences become less frequent in the future, while blue tones indicate areas where TPD values increase, indicating traits or environmental preferences that are expeced to become more prevalent. Dashed contour lines represent the 0.99 quantile of the current functional and environmental space, delineating the existing boundaries of trait and environmental preferences at the global scale. Detailed explainations of each PC are provided in Fig. 2. The best-case projected future scenario was simulated by applying different extinction probabilities to non-threatened and threatened species that were classfied as Data Deficient (DD) and Not Evaluated (NE) by IUCN, that is, non-threatened species were assigned probabilities corresponding to Least Concern (LC), and threatened species were assigned probabilities corresponding to Vulnerable (VU).

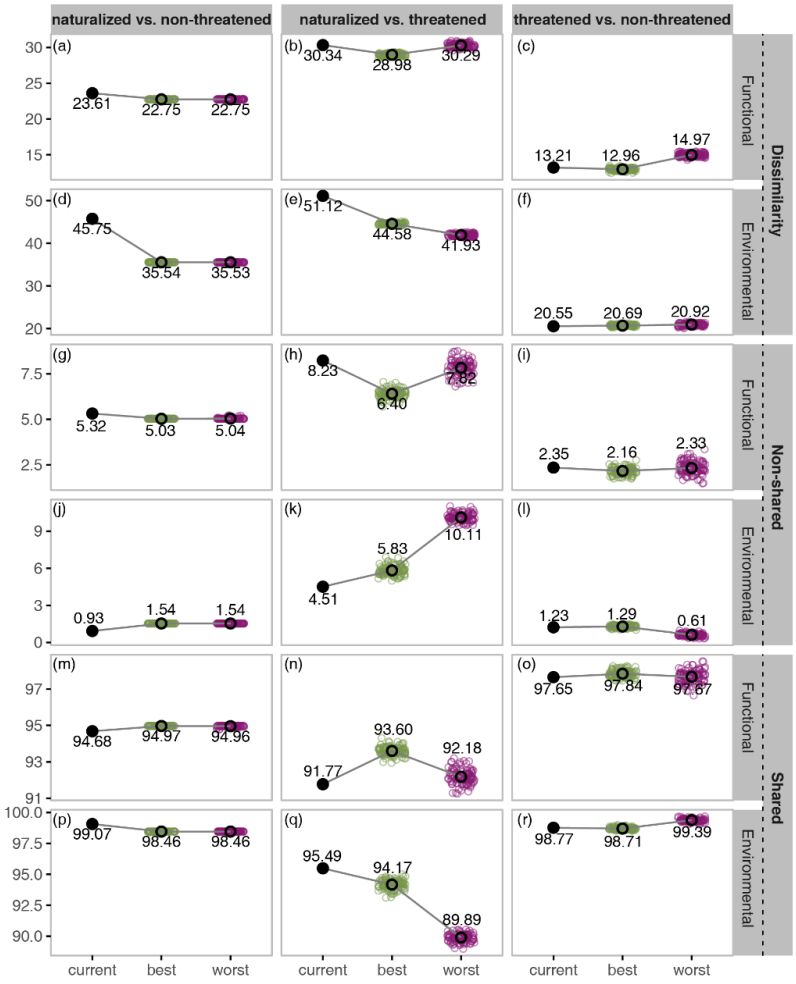

Fig. S4 Shifts in the total dissimilarity and the its decomposition (i.e., non-shared and shared part) of each pair among naturalized, non-threatened, and threatened species within functional and environmental spaces. For best-case and worst-case, points indicate the corresponding value of the 100 extinction simulations, and the open black circles indicate the mean values of the 100 simulations.

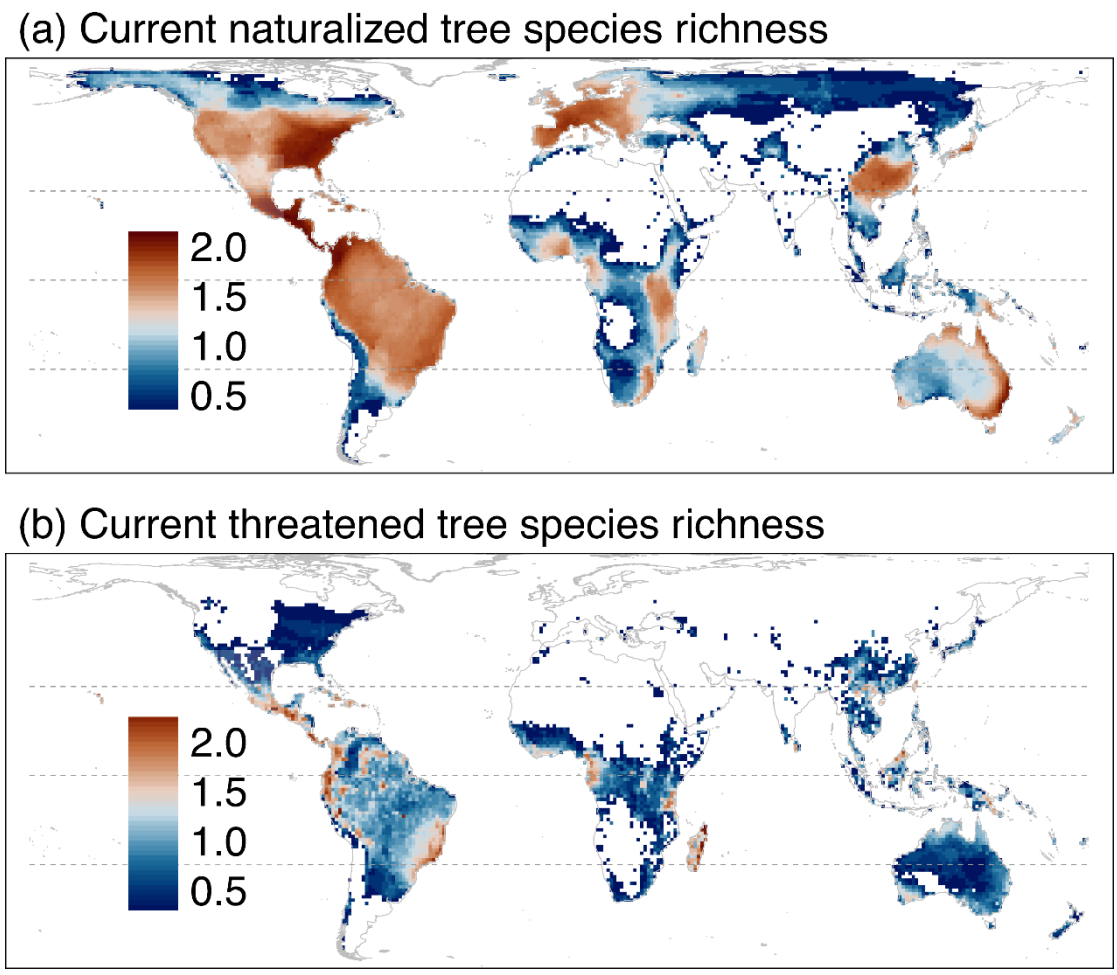

Fig. S5 Species richness per 110 * 110 km grid cell of (a) naturalized and (b) threatened tree species. To improve visualization, data was log10-transformed.

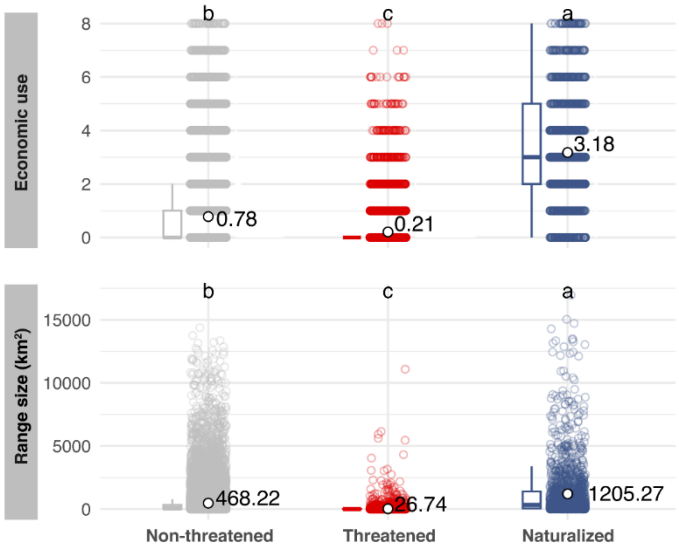

Fig. S6 Plots showing the differences of economic use and range size between non-threatened, threatened and naturalized tree species, with different letters indicating significant differences based on phylogenetically corrected ANOVAs ($p < 0.05$). Tree species' economic use data were extracted from World Checklist of Useful Plant Species (WCUP; Diazgranados *et al*., 2020), and species' range sizes were obtained from (Guo *et al*., 2022).

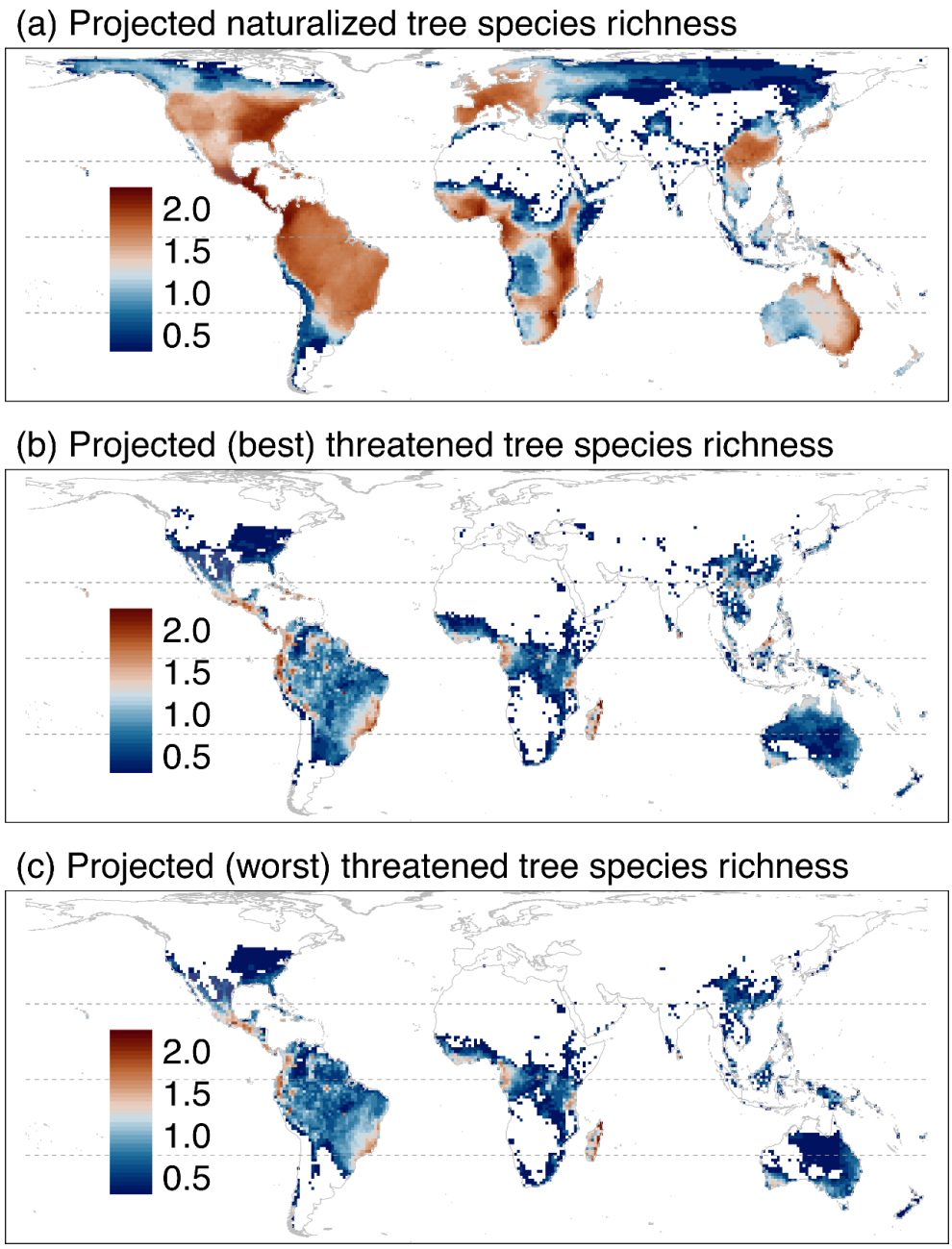

Fig. S7 Projected future species richness per 110 * 110 km grid cell for (a) naturalized, (b) threatened tree species under the best-case scenario, and (c) threatened tree species under the worst-case scenario. For threatened projections, one result was randomly selected from the 100 simulation runs. To improve visualization, data was log10-transformed.

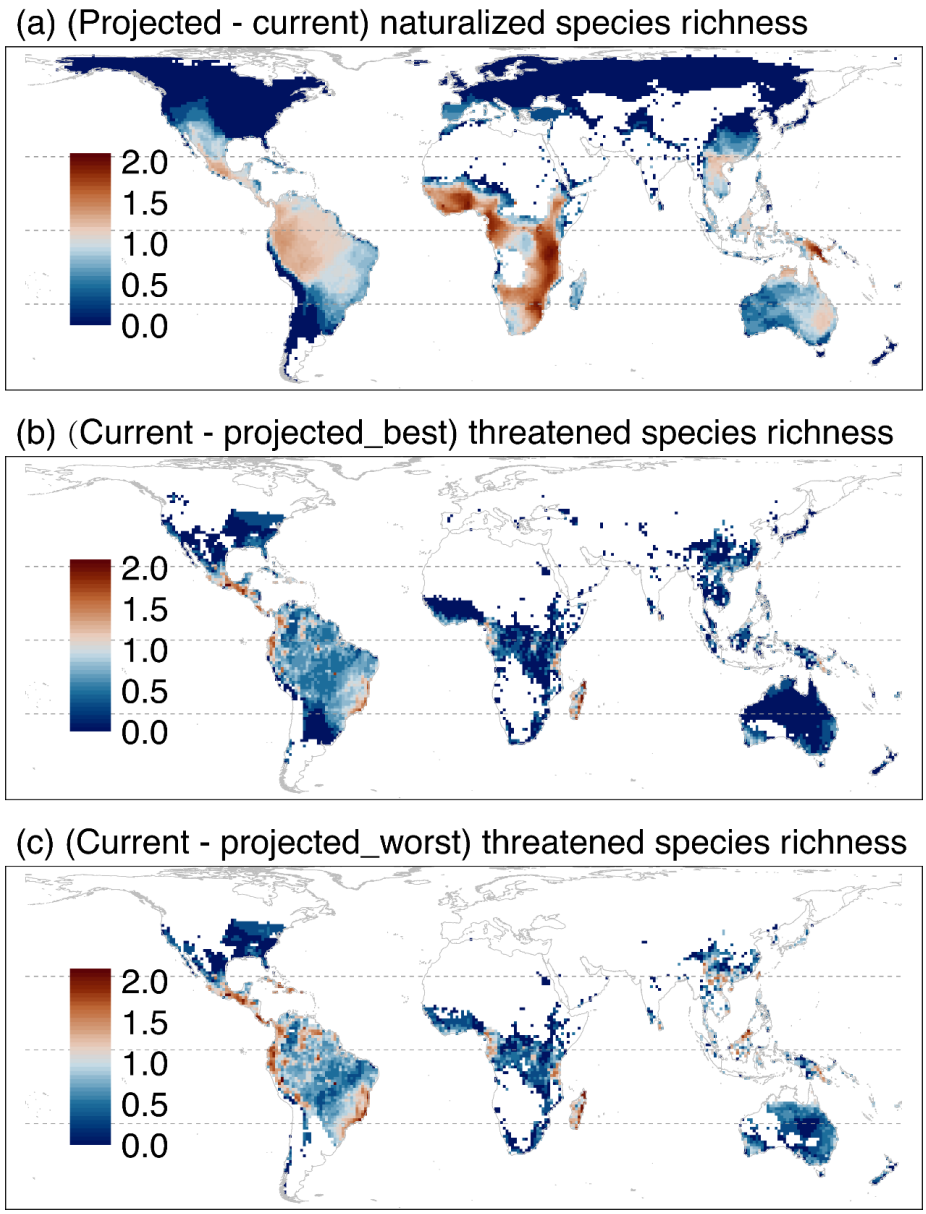

Fig. S8 Differences between current and projected future specie richness per 110*110 km grid cell for (a) naturalized and (b & c) threatened tree species. Panel (a) represents regions most likely to serve as source areas for future naturalized species; while panels (b) and (c) represents areas where tree species extinctions are most likely to occur under the best- and worst-case scenarios, respectively. To improve visualization, data was log10-transformed.

References:

Diazgranados, M. *et al. World checklist of useful plant species*. https://doi.org/10.5063/F1CV4G34 (2020).

Guo, W.-Y. *et al.* High exposure of global tree diversity to human pressure. *Proc. Natl. Acad. Sci. U S A* **119**, e2026733119 (2022).

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