Supplementary material for:

C_4 trees have broader niches than their close C_3 relatives

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SUPPLEMENTARY FIGURES

Figure S1

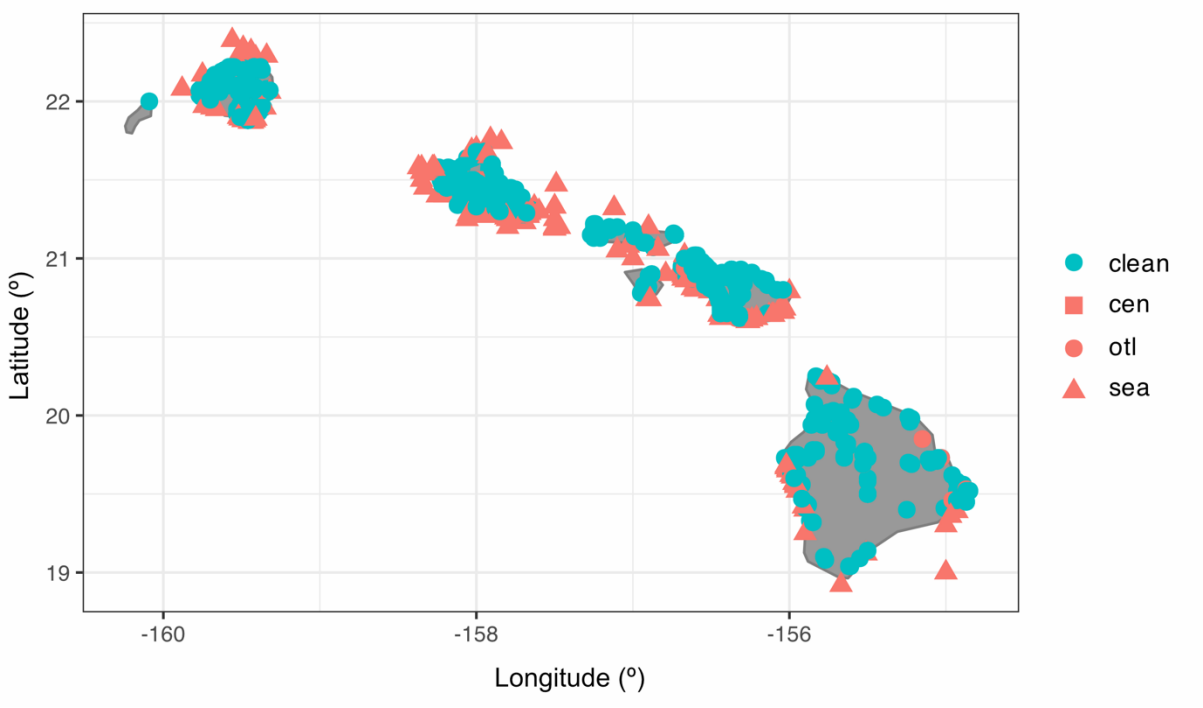

Fig S1. **Map of occurrence data flagged by CoordinateCleaner.** Occurrence data for species in Euphorbiaceae on the Hawaiian Islands were processed using the CoordinateCleaner package in R. 277 coordinates were flagged (pink) including those located on country centroids (cen, n = 1, squares), species outliers (otl, n = 22, circles), or in the sea (sea, n = 262, triangles), and removed prior to further analysis. Remaining coordinates (n = 1091) are designated as 'clean' (blue circles).

Figure S2

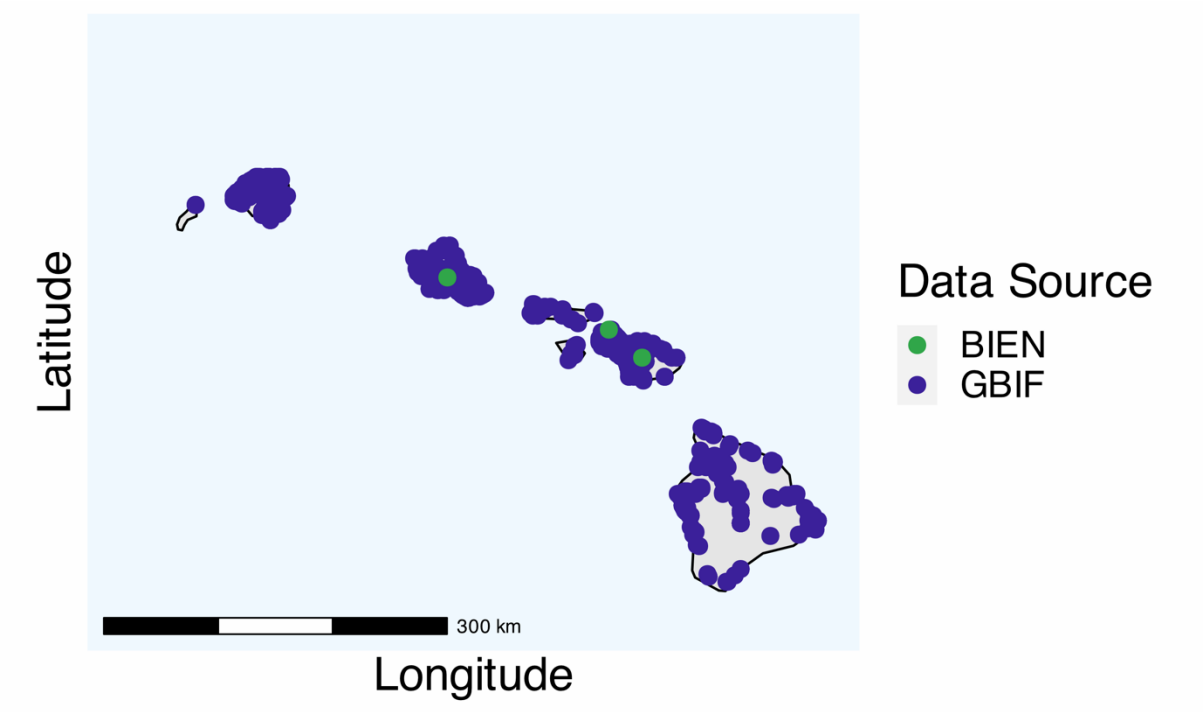

Fig S2. **Map of occurrence data by data source.** Cleaned occurrence data are shown for species in Euphorbiaceae that were obtained from either the Botanical Information and Ecology Network (BIEN, n = 3, green) or the Global Biodiversity Information Facility (GBIF, n = 687, blue). Duplicate records (*i.e.* those that appeared in both datasets, or twice in one dataset) have been removed.

Figure S3

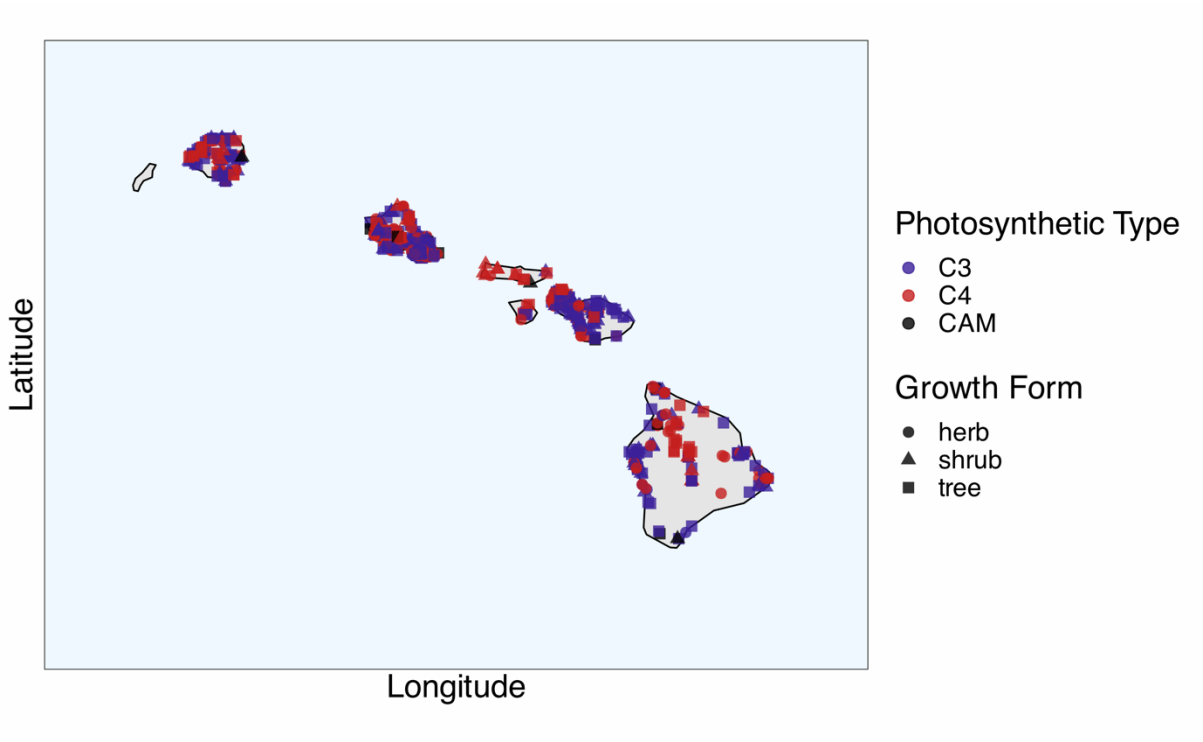

Fig S3. **Map of distributions of Hawaiian herbs, shrubs and trees by photosynthetic type.** Occurrence data for herbs (n = 199, representing 9 species, circles), shrubs (n = 170, representing 18 species, triangles) and trees (n = 283, representing 25 species, squares) in Euphorbiaceae are shown on a map of the Hawaiian Islands. Points are coloured according to the photosynthetic type assigned to each species: C_3 (blue), C_4 (red) or CAM (black).

Figure S4

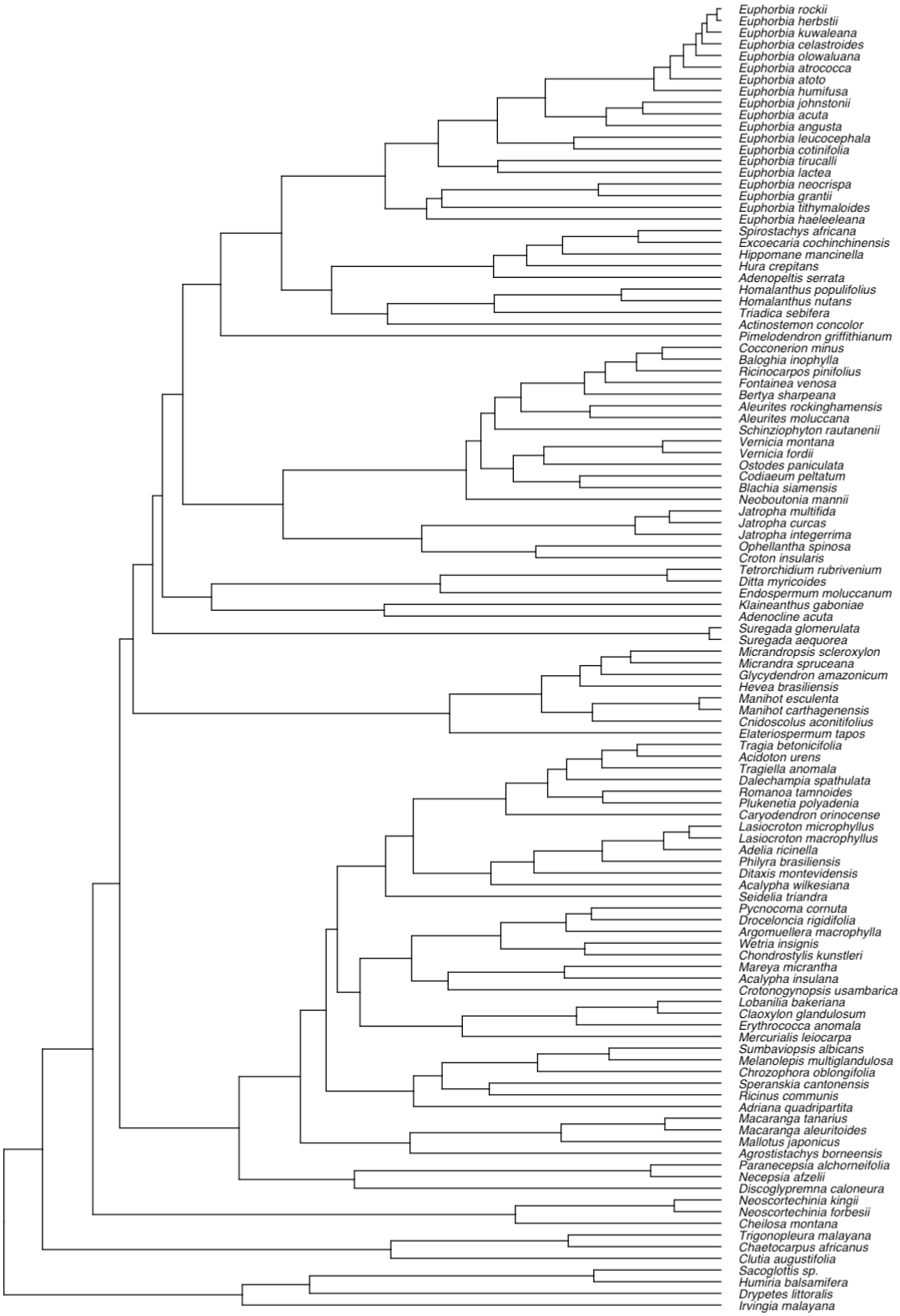

***Fig S4*. Complete phylogeny of all species whose data was obtained in this study.** Phylogenetic tree generated using previously published data for 112 species in Euphorbiaceae.

Figure S5

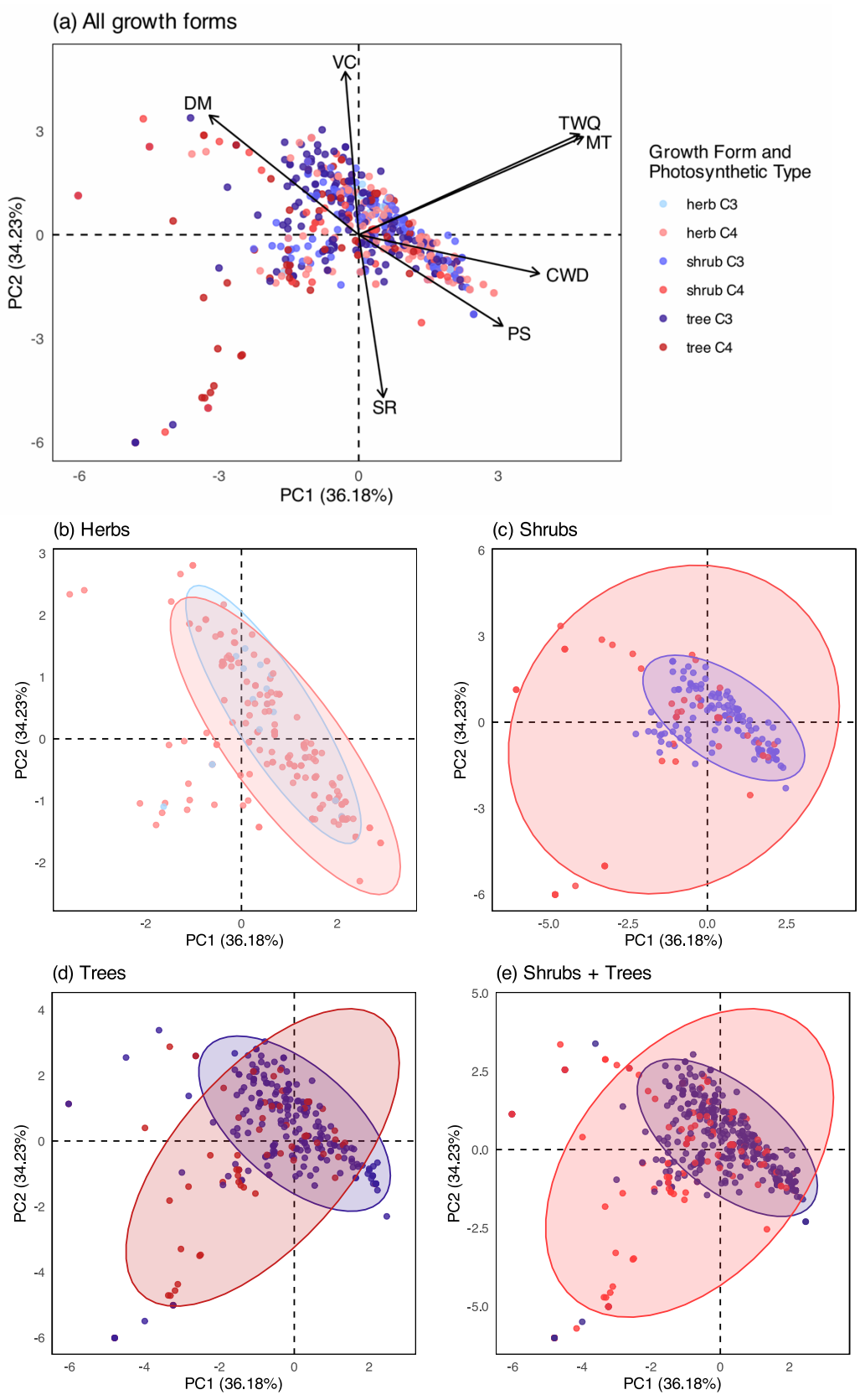
(a) All growth forms
VC
DM
TWQ
MT
CWD
PS
SR
PC2 (34.23%)
PC1 (36.18%)
Growth Form and Photosynthetic Type
herb C3
herb C4
shrub C3
shrub C4
tree C3
tree C4
(b) Herbs
(c) Shrubs
(d) Trees
(e) Shrubs + Trees

Fig S5. **Principal components 1 and 2 of a Principal Component Analysis (PCA) of environmental variables for all growth forms.** (a) PCA plot showing C_3 (blue) and C_4 (red) herb, shrub, and tree species in Euphorbiaceae. Arrows show the loading of each of the 7 environmental variables used in the PCA. Abbreviations are as follows: MT=minimum temperature of the coldest month, TWQ= temperature of the wettest quarter, DM=precipitation of the driest month, PS=precipitation seasonality, SR=solar radiation, VC=vegetation cover, CWD=climatic water deficit. Data are also shown on individual plots separated by growth form, with 95% confidence ellipses calculated for each group. (b) C_3 (n = 21) and C_4 (n = 178) herbaceous species, (c) C_3 (n = 119) and C_4 (n = 47) shrub species, C_3 (n = 202) and C_4 (n = 66) tree species, and (e) C_3 (n = 331) and C_4 (n = 113) woody (herb and shrub) species.

Figure S6

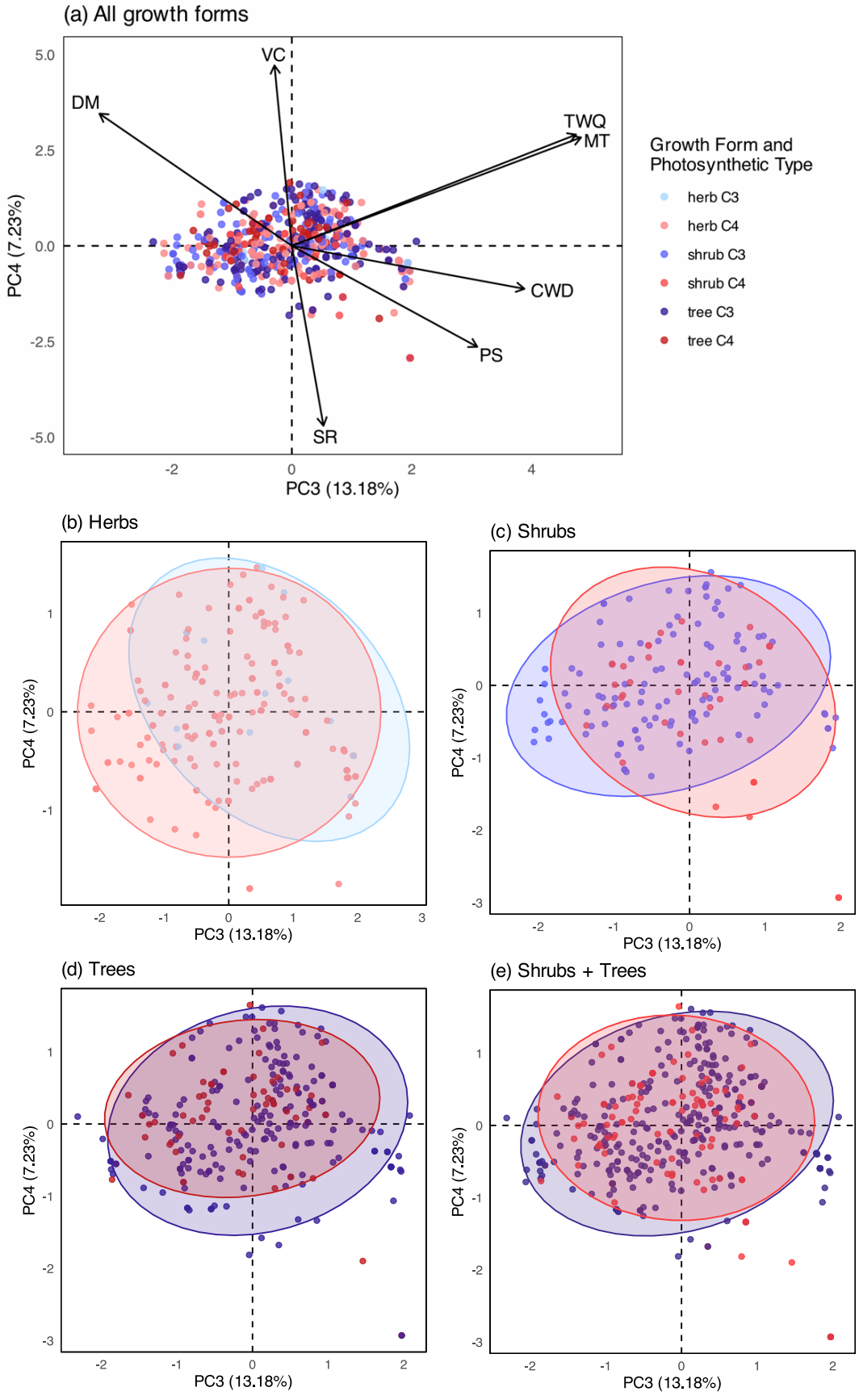
(a) All growth forms
VC
DM
TWQ
MT
CWD
PS
SR
PC4 (7.23%)
PC3 (13.18%)
Growth Form and Photosynthetic Type
herb C3
herb C4
shrub C3
shrub C4
tree C3
tree C4
(b) Herbs
(c) Shrubs
(d) Trees
(e) Shrubs + Trees

***Fig S6*. Principal components 3 and 4 of a Principal Component Analysis (PCA) of environmental variables for all growth forms.** (a) PCA plot showing C_3 (blue) and C_4 (red) herb, shrub, and tree species in Euphorbiaceae. Arrows show the loading of each of the 7 environmental variables used in the PCA. Abbreviations are as follows: MT=minimum temperature of the coldest month, TWQ= temperature of the wettest quarter, DM=precipitation of the driest month, PS=precipitation seasonality, SR=solar radiation, VC=vegetation cover, CWD=climatic water deficit. Data are also shown on individual plots separated by growth form, with 95% confidence ellipses calculated for each group. (b) C_3 (n = 21) and C_4 (n = 178) herbaceous species, (c) C_3 (n = 119) and C_4 (n = 47) shrub species, C_3 (n = 202) and C_4 (n = 66) tree species, and (e) C_3 (n = 331) and C_4 (n = 113) woody (herb and shrub) species.

Figure S7

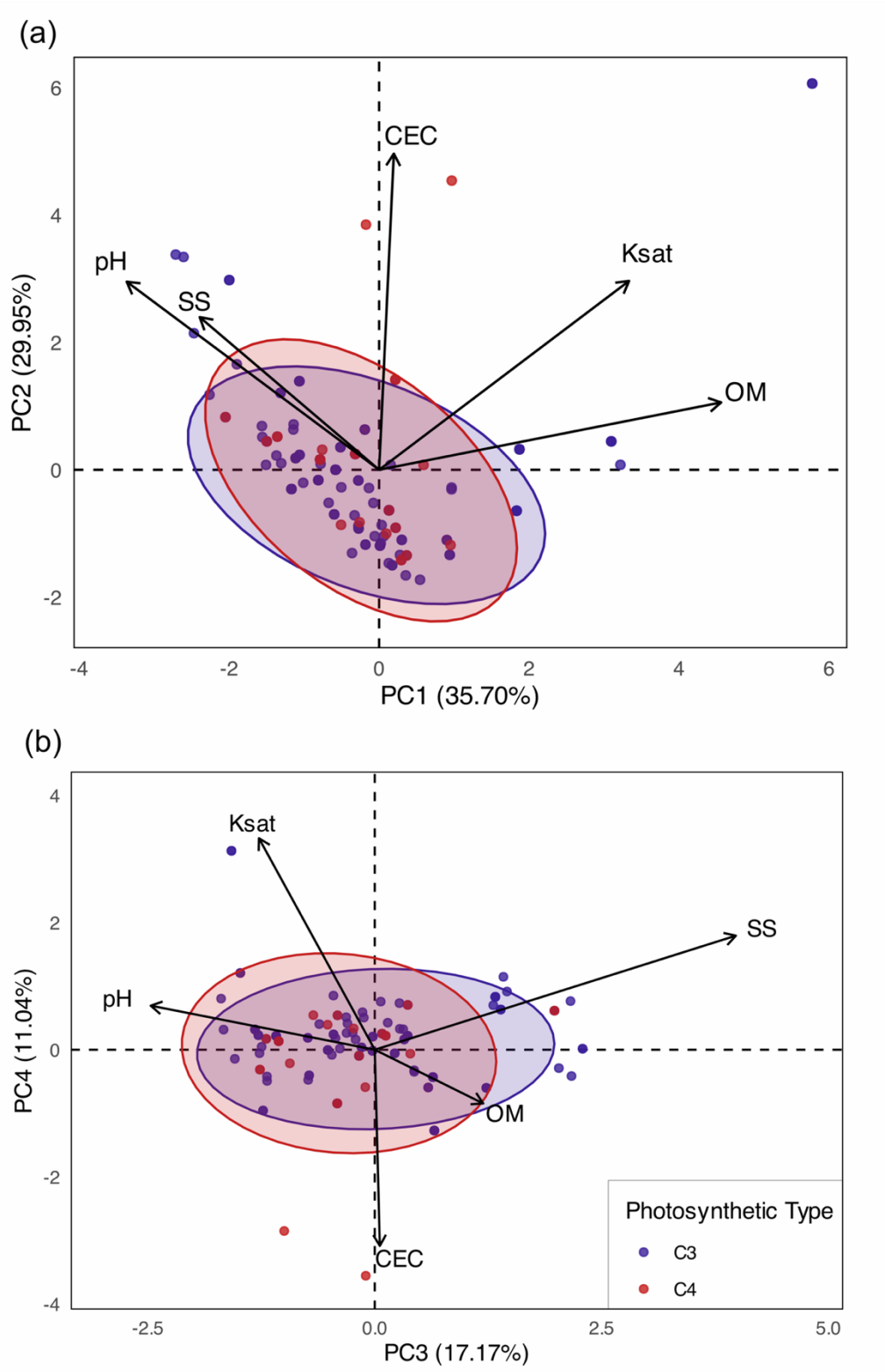

***Fig S7*. Principal component analysis (PCA) of soil variables for C_3 and C_4 trees.** (a) Principal Components (PCs) 1 and 2, and, (b) PCs 3 and 4 of a PCA conducted on 5 soil variables for C_3 (blue) and C_4 (red) trees. Arrows show the loading of each of the 5 variables. Abbreviations are as follows: CEC = cation exchange capacity, Ksat = water permeability, SS = shrink-swell potential (soil stability), OM = organic matter. 95% confidence ellipses were calculated for each group.

Figure S8

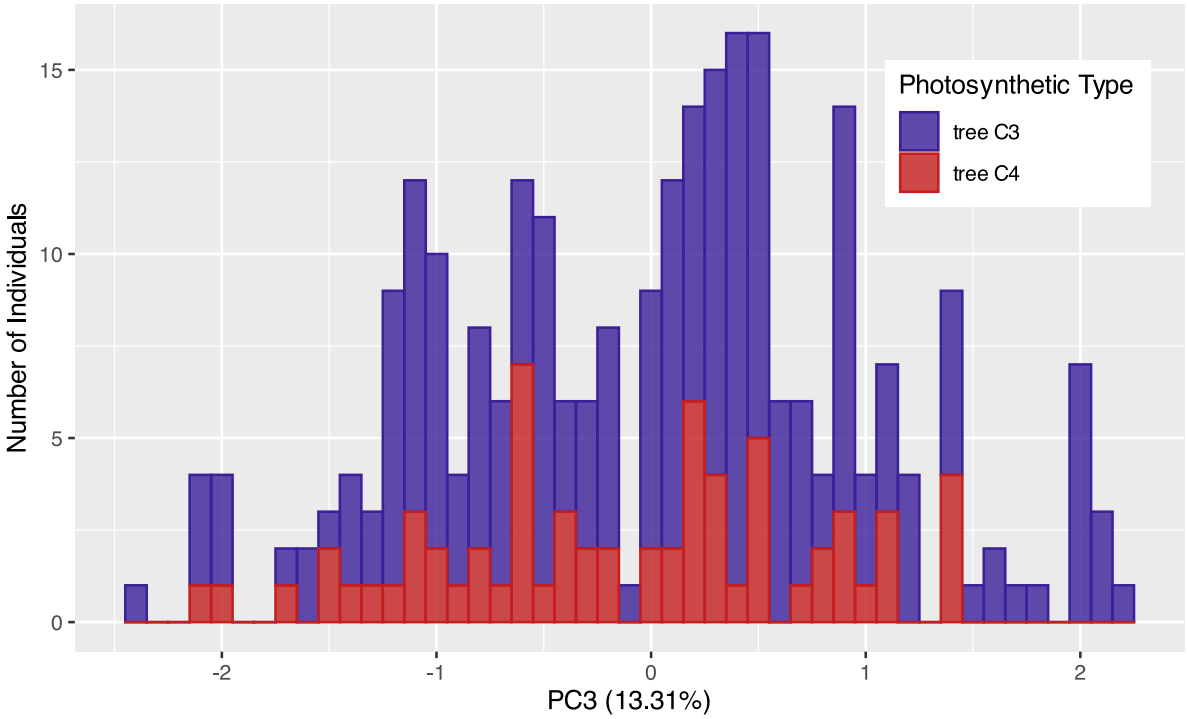

***Fig S8*. Histogram of Principal Component 3 of a Principal Component Analysis (PCA) of environmental variables for C_3 and C_4 trees.** Histogram showing C_3 (blue, n = 202) and C_4 (red, n = 66) tree species in Euphorbiaceae.

Figure S9

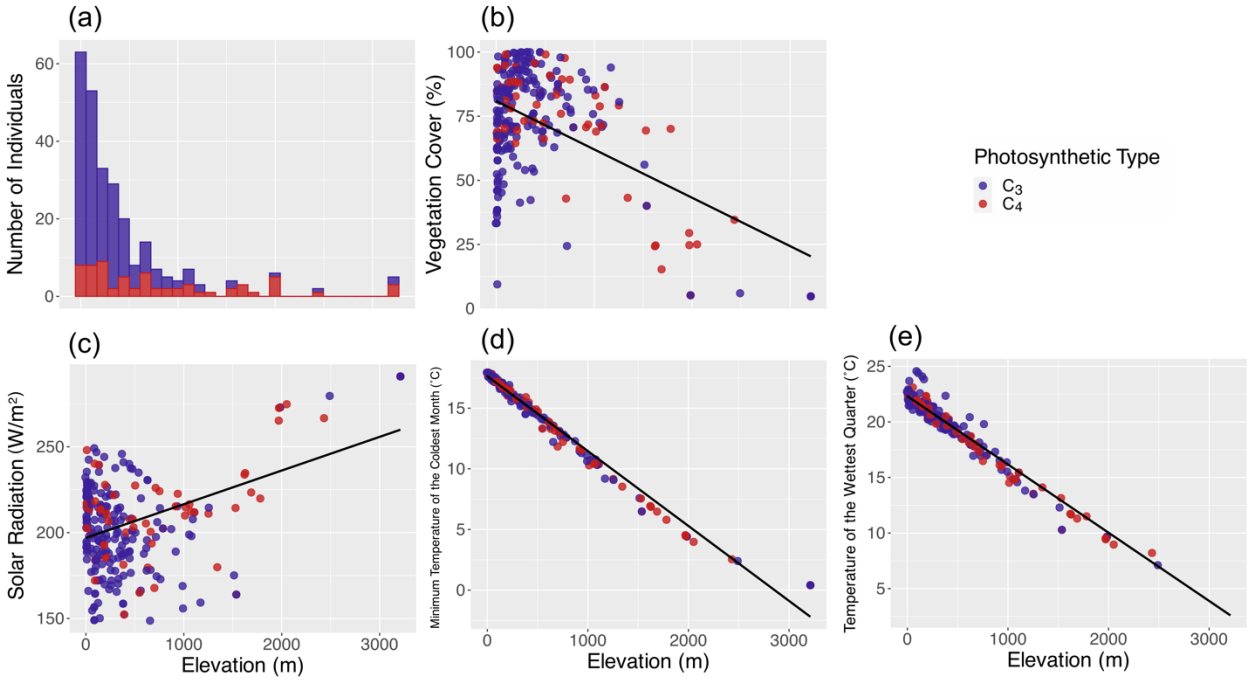

***Fig S9*. Distribution of C_3 and C_4 trees by elevation, and environmental variables correlated with elevation.** (a) Histogram of the distribution of C_3 (blue) and C_4 (red) trees by elevation. Scatterplots of the relationship between elevation and 4 environmental variables are shown: (b) vegetation cover, (c) solar radiation, (d) minimum temperature of the coldest month and (e) temperature of the wettest quarter. Linear regression lines (black) were fitted to the data in plots b-e.

SUPPLEMENTARY TABLES

Table S1. **Issues identified by GBIF which resulted in a record being removed from this analysis**

code	issue	description	type
conti	CONTINENT_INVALID	Uninterpretable continent values found.	occurrence
cucdmis	COUNTRY_COORDINATE_MISMATCH	The interpreted occurrence coordinates fall outside of the indicated country.	occurrence
cuiv	COUNTRY_INVALID	Uninterpretable country values found.	occurrence
cum	COUNTRY_MISMATCH	Interpreted country for dwc:country and dwc:countryCode contradict each other.	occurrence
preneglat	PRESUMED_NEGATED_LATITUDE	Latitude appears to be negated, e.g. 32.3 instead of -32.3	occurrence
preneglon	PRESUMED_NEGATED_LONGITUDE	Longitude appears to be negated, e.g. 32.3 instead of -32.3	occurrence
preswcd	PRESUMED_SWAPPED_COORDINATE	Latitude and longitude appear to be swapped.	occurrence
txmatfuz	TAXON_MATCH_FUZZY	Matching to the taxonomic backbone can only be done using a fuzzy, non-exact match.	occurrence
cdpi	COORDINATE_PRECISION_INVALID	Indicates an invalid or very unlikely coordinatePrecision	occurrence

Table S2. summary of sequence data used and accession numbers

	rbcL		matK		trnL		
Species	**Length (bp)**	**Accession**	**Length (bp)**	**Accession**	**Length (bp)**	**Accession**	**Total (bp)**
Acalypha_insulana	1331	AB233854	1203	AB233750	0	-	2534
Acalypha_wilkesiana	599	KU243027	0	-	0	-	599
Acidoton_urens	1321	AB267913	1194	AB268017	0	-	2515
Actinostemon_concolor	1324	AB233883	1203	AB233779	0	-	2527
Adelia_ricinella	1315	AB267914	1203	AB268018	1016	AY794737	3534
Adenocline_acuta	1325	AB233874	1197	AB233770	0	-	2522
Adenopeltis_serrata	1324	AB267954	1203	AB268058	791	AY794633	3318
Adriana_quadripartita	1325	AB233855	1206	AB233751	0	-	2531
Agrostistachys_borneensis	1331	AB233856	1203	AB233752	0	-	2534
Aleurites_moluccana	1321	AY794883	1218	LK021377	904	AY794709	3443
Aleurites_rockinghamensis	0	-	0	-	743	KC428437	743
Argomuellera_macrophylla	1325	AB267915	1203	AB268019	986	AY794769	3514
Baloghia_inophylla	1331	AB233875	1203	AB233771	899	AY794707	3433
Bertya_sharpeana	1324	AB267935	1215	AB268039	0	-	2539
Blachia_siamensis	1324	AB267936	1203	AB268040	873	AY794727	3400
Caryodendron_orinocense	1325	AB233857	1203	AB233753	997	AY794760	3525
Chaetocarpus_africanus	1325	AB233858	1191	AB233754	854	AY794809	3370
Cheilosa_montana	1331	AB267910	1203	AB268014	0	-	2534
Chondrostylis_kunstleri	1331	AB233859	1203	AB233755	0	-	2534
Chrozophora_oblongifolia	1325	AB233860	1203	AB233756	0	-	2528
Claoxylon_glandulosum	0	-	1209	LK021406	998	HG971843	2207
Clutia_augustifolia	1321	AB233861	1191	AB233757	0	-	2512
Cnidoscolus_aconitifolius	1325	AB267937	1203	AB268041	946	MH935283	3474
Cocconerion_minus	1323	AB267938	1203	AB268042	0	-	2526
Codiaeum_peltatum	1331	AB233876	1203	AB233772	0	-	2534
Croton_insularis	1331	AB233877	1203	AB233773	697	AY971308	3231
Crotonogynopsis_usambarica	1331	AB233862	1209	AB233758	1008	HG971853	3548
Dalechampia_spathulata	1331	AB233863	1188	AB233759	1080	Y794754	3599
Discoglypremna_caloneura	1324	AB267916	1209	AB268020	1095	AY794802	3628
Ditaxis_montevidensis	1324	AB233865	1203	AB233761	0	-	2527
Ditta_myricoides	1311	AB267939	1212	AB268043	1006	AY794675	3529
Droceloncia_rigidifolia	1318	AB267917	1203	AB268021	0	-	2521
Drypetes_littoralis	1331	AB233926	1203	AB233822	0	-	2534
Elateriospermum_tapos	1322	AB267940	1203	AB268044	964	AY794678	3489
Endospermum_moluccanum	1331	AB267941	1206	AB268045	976	AY794671	3513
Erythrococca_anomala	1324	AB267918	1215	AB268022	0	-	2539
Euphorbia_acuta	1300	JN249261	1203	HQ645674	982	JN249596	3485
Euphorbia_angusta	0	-	1203	HQ645678	381	HQ645528	1584
Euphorbia_atoto	1331	AB267955	1203	AB268059	402	HQ645536	2936

	rbcL		matK		trnL		
Species	**Length (bp)**	**Accession**	**Length (bp)**	**Accession**	**Length (bp)**	**Accession**	**Total (bp)**
Euphorbia_atrococca	0	-	0	-	1031	MH490365	1031
Euphorbia_celastroides	1106	JN249280	1203	HQ645698	1053	JN249615	3362
Euphorbia_grantii	1331	AB233888	1200	AB233784	1032	JN249654	3563
Euphorbia_haeleeleana	0	-	1221	KC019490	0	-	1221
Euphorbia_herbstii	0	-	0	-	1036	MH490446	1036
Euphorbia_humifusa	1331	AB233884	1203	AB233780	406	HQ645587	2940
Euphorbia_johnstonii	0	-	1203	HQ645742	386	HQ645592	1589
Euphorbia_kuwaleana	0	-	1203	HQ645743	1048	MH490361	2251
Euphorbia_leucocephala	1300	JN249340	637	GU214862	978	JN249672	2915
Euphorbia_neocrispa	1324	AB267958	1224	AB268062	0	-	2548
Euphorbia_olowaluana	0	-	1203	HQ645766	1042	MH490363	2245
Euphorbia_rockii	0	-	1004	HQ645791	1022	MH490489	2026
Euphorbia_tithymaloides	1331	AB267959	1203	AB268063	0	-	2534
Excoecaria_cochinchinensis	1331	AB233885	1203	AB233781	959	AY794619	3493
Fontainea_venosa	1324	AB233878	1203	AB233774	872	AY794708	3399
Glycydendron_amazonicum	1324	AB267942	1209	AB268046	964	AY794681	3497
Hevea_brasiliensis	1316	NC_15308	1197	NC_15308	988	NC_15308	3501
Hippomane_mancinella	1324	AB267956	1203	AB268060	983	AY794616	3510
Homalanthus_nutans	1331	AB267957	1203	AB268061	961	JN249590	3495
Homalanthus_populifolius	572	KM392269	757	KM392242	0	-	1329
Humiria_balsamifera	1324	AB233889	1197	AB233785	0	-	2521
Hura_crepitans	1331	AB233886	1203	AB233782	984	AY794636	3518
Irvingia_malayana	1331	AB233892	1195	AB233788	0	-	2526
Jatropha_integerrima	1331	AB233879	1215	AB233775	1034	AY794685	3580
Jatropha_multifida	687	KP898357	749	LC461834	937	KP868720	2373
Jatropha_curcas	1315	NC_12224	1212	NC_12224	1024	NC_12224	3551
Klaineanthus_gaboniae	1331	AB267944	1203	AB268048	887	AY794668	3421
Lasiocroton_macrophyllus	1324	AB267919	1203	AB268023	0	-	2527
Lasiocroton_microphyllus	1320	AB267920	1203	AB268024	990	HG971893	3513
Lobanilia_bakeriana	1324	AB267921	1209	AB268025	1022	AY794779	3555
Macaranga_aleuritoides	1331	AB267922	1203	AB268026	988	Q899191	3522
Macaranga_tanarius	1331	MW297079	1203	MW297079	994	MW297079	3528
Mallotus_japonicus	1309	MW244068	1203	MW244068	990	MW244068	3502
Manihot_carthagenensis	1331	MK430314.1	0	-	964	EU518901	2295
Manihot_esculenta	1313	NC_10433	1209	NC_10433	1000	NC_10433	3522
Mareya_micrantha	1324	AB267924	1197	AB268028	1026	AY794774	3547
Melanolepis_multiglandulosa	1331	AB267925	1203	AB268029	988	AY794733	3522
Mercurialis_leiocarpa	1331	AB233867	1203	AB233763	0	-	2534
Micrandra_spruceana	1323	AB267945	1212	AB268049	0	-	2535

	rbcL		matK		trnL		
Species	**Length (bp)**	**Accession**	**Length (bp)**	**Accession**	**Length (bp)**	**Accession**	**Total (bp)**
Micrandropsis_scleroxylon	1321	AB267946	1206	AB268050	0	-	2527
Necepsia_afzelii	1324	AB233868	1203	AB233764	986	DQ991514	3513
Neoboutonia_mannii	1324	AB233881	1215	AB233777	889	AY794723	3428
Neoscortechinia_forbesii	1322	AB267911	1197	AB268015	0	-	2519
Neoscortechinia_kingii	1322	AB267912	1203	AB268016	971	AY794806	3496
Ophellantha_spinosa	1324	AB267947	1209	AB268051	685	AY971344	3218
Ostodes_paniculata	1322	AB267948	1215	AB268052	881	AY794725	3418
Paranecepsia_alchorneifolia	1315	AB267926	1203	AB268030	0	-	2518
Philyra_brasiliensis	1324	AB267927	1209	AB268031	1001	AY794740	3534
Pimelodendron_griffithianum	1331	AB233887	1187	AB233783	0	-	2518
Plukenetia_polyadenia	1324	AB267928	1194	AB268032	0	-	2518
Pycnocoma_cornuta	1324	AB233870	1203	AB233766	0	-	2527
Ricinocarpos_pinifolius	1324	AB267949	1212	AB268053	0	-	2536
Ricinus_communis	1331	NC_16736	1203	NC_16736	981	NC_16736	3515
Romanoa_tamnoides	1320	AB233872	1194	AB233768	1037	Y794757	3551
Sacoglottis_sp.	1323	AB233890	1197	AB233786	0	-	2520
Schinziophyton_rautanenii	1324	AB233882	1215	AB233778	0	-	2539
Seidelia_triandra	1324	AB267929	1203	AB268033	983	AY794762	3510
Speranskia_cantonensis	1326	AB267930	1203	AB268034	1025	AY794735	3554
Spirostachys_africana	1324	AB267960	1203	AB268064	977	Y794621	3504
Sumbaviopsis_albicans	1324	AB267931	1209	AB268035	986	Y794732	3519
Suregada_aequorea	1331	AB267950	1203	AB268054	0	-	2534
Suregada_glomerulata	1331	AB267951	1203	AB268055	0	-	2534
Tetrorchidium_rubrivenium	1315	AB267952	1212	AB268056	0	-	2527
Tragia_betonicifolia	1324	AB267932	1194	AB268036	0	-	2518
Tragiella_anomala	1324	AB267933	1194	AB268037	1032	AY794753	3550
Triadica_sebifera	1331	AB267961	1209	AB268065	1021	Y794649	3561
Trigonopleura_malayana	1331	AB233873	1194	AB233769	0	-	2525
Vernicia_montana	1316	MW297080.1	1215	MW297080.1	1049	MW297080	3580
Vernicia_fordii	1301	KY628420	0	-	0	-	1301
Wetria_insignis	1324	AB267934	1203	AB268038	0	-	2527

Table S3. **Environmental variables correlated to PCA axes (trees only)**

	Correlation Coefficient	*p*-value
Dim 1		
Temperature of the Wettest Quarter	0.8690961	2.699026e-83
Minimum Temperature of the Coldest Month	0.8645576	1.826855e-81
Vegetation Cover	0.7552094	1.035758e-50
Precipitation of the Driest Month	0.3539213	2.508441e-09
Climatic Water Deficit	0.2165732	3.551292e-04
Precipitation Seasonality	-0.2360332	9.570400e-05
Solar Radiation	-0.7002899	7.997929e-41
Dim 2		
Precipitation Seasonality	0.7008964	6.400334e-41
Climatic Water Deficit	0.6665530	8.467696e-36
Minimum Temperature of the Coldest Month	0.4632755	1.155631e-15
Temperature of the Wettest Quarter	0.4485016	1.144784e-14
Solar Radiation	0.4037758	6.238385e-12
Vegetation Cover	-0.2841251	2.274431e-06
Precipitation of the Driest Month	-0.7682722	1.856038e-53
Dim 3		
Climatic Water Deficit	0.6439586	8.730307e-33
Precipitation of the Driest Month	0.2994582	5.898452e-07
Solar Radiation	0.2484549	3.904704e-05
Vegetation Cover	-0.2703221	7.171872e-06
Precipitation Seasonality	-0.5406903	9.516836e-22

Table S4. **Environmental variables correlated to PCA axes (all lifeforms)**

	Correlation Coefficient	*p*-value
Dim 1		
Minimum Temperature of the Coldest Month	0.85293675	2.680179e-180
Temperature of the Wettest Quarter	0.83826172	2.393567e-168
Climatic Water Deficit	0.68588944	3.621171e-89
Precipitation Seasonality	0.54686588	1.186145e-50
Solar Radiation	0.09338178	1.877688e-02
Precipitation of the Driest Month	-0.56734656	3.336257e-55
Dim 2		
Vegetation Cover	0.8112428	3.399612e-149
Precipitation of the Driest Month	0.5943777	1.014873e-61
Temperature of the Wettest Quarter	0.5000729	2.339880e-41
Minimum Temperature of the Coldest Month	0.4872993	4.629512e-39
Climatic Water Deficit	-0.1930343	9.924023e-07
Precipitation Seasonality	-0.4538317	1.745728e-33
Solar Radiation	-0.8088022	1.283092e-147
Dim 3		
Climatic Water Deficit	0.6144706	5.582018e-67
Precipitation of the Driest Month	0.3464571	2.731684e-19
Solar Radiation	0.1234679	1.857199e-03
Vegetation Cover	-0.3262061	3.687601e-17
Precipitation Seasonality	-0.5495276	3.165038e-51
Dim 4		
Solar Radiation	0.51276391	9.761776e-44
Vegetation Cover	0.35460097	3.425228e-20
Climatic Water Deficit	-0.09449286	1.740606e-02
Precipitation of the Driest Month	-0.14115937	3.675769e-04
Precipitation Seasonality	-0.28336754	3.738228e-13

Table S5. **Soil variables correlated to PCA axes (trees only)**

	Correlation Coefficient	*p*-value
Dim 1		
Organic Matter	0.8703556	2.11E-51
Water Permeability	0.6360706	7.30E-20
Shrink-Swell Potential	-0.4565908	9.02E-10
pH	-0.6425377	2.35E-20
Dim 2		
Cation Exchange Capacity	0.8675693	1.04E-50
Water Permeability	0.5182415	1.39E-12
pH	0.5162413	1.75E-12
Shrink-Swell Potential	0.418833	2.63E-08
Organic Matter	0.1848592	1.82E-02
Dim 3		
Shrink-Swell Potential	0.7374708	3.06E-29
Organic Matter	0.2214541	4.50E-03
Water Permeability	-0.2365187	2.37E-03
pH	-0.4576132	8.18E-10
Dim 4		
Water Permeability	0.494389	1.98E-11
Shrink-Swell Potential	0.2666742	5.80E-04
Cation Exchange Capacity	-0.4585921	7.45E-10