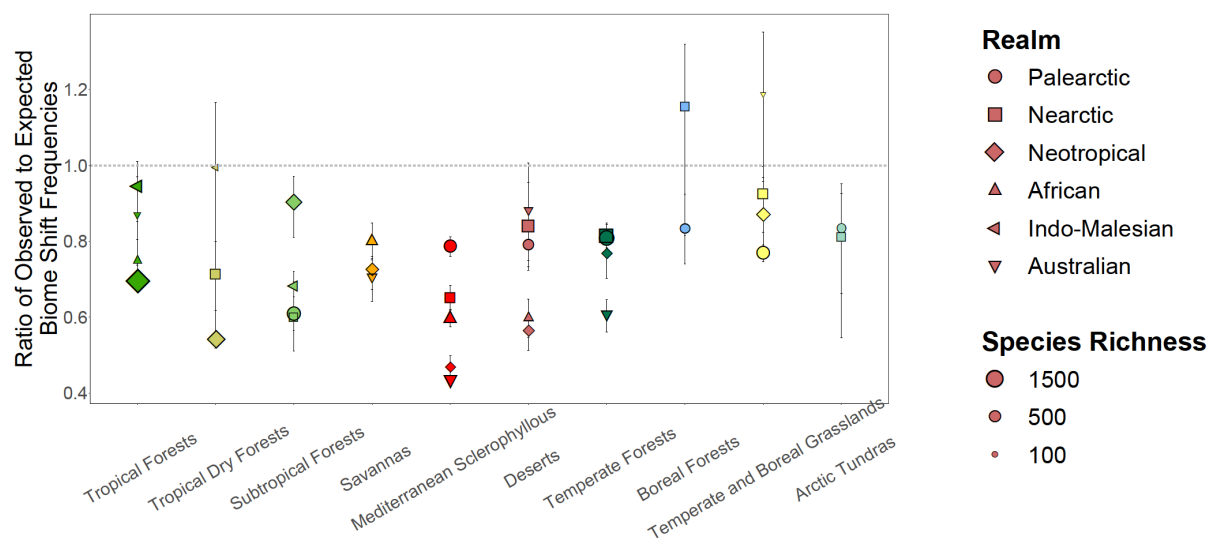


1 **Supplemental information**

2 **Supplemental figures**

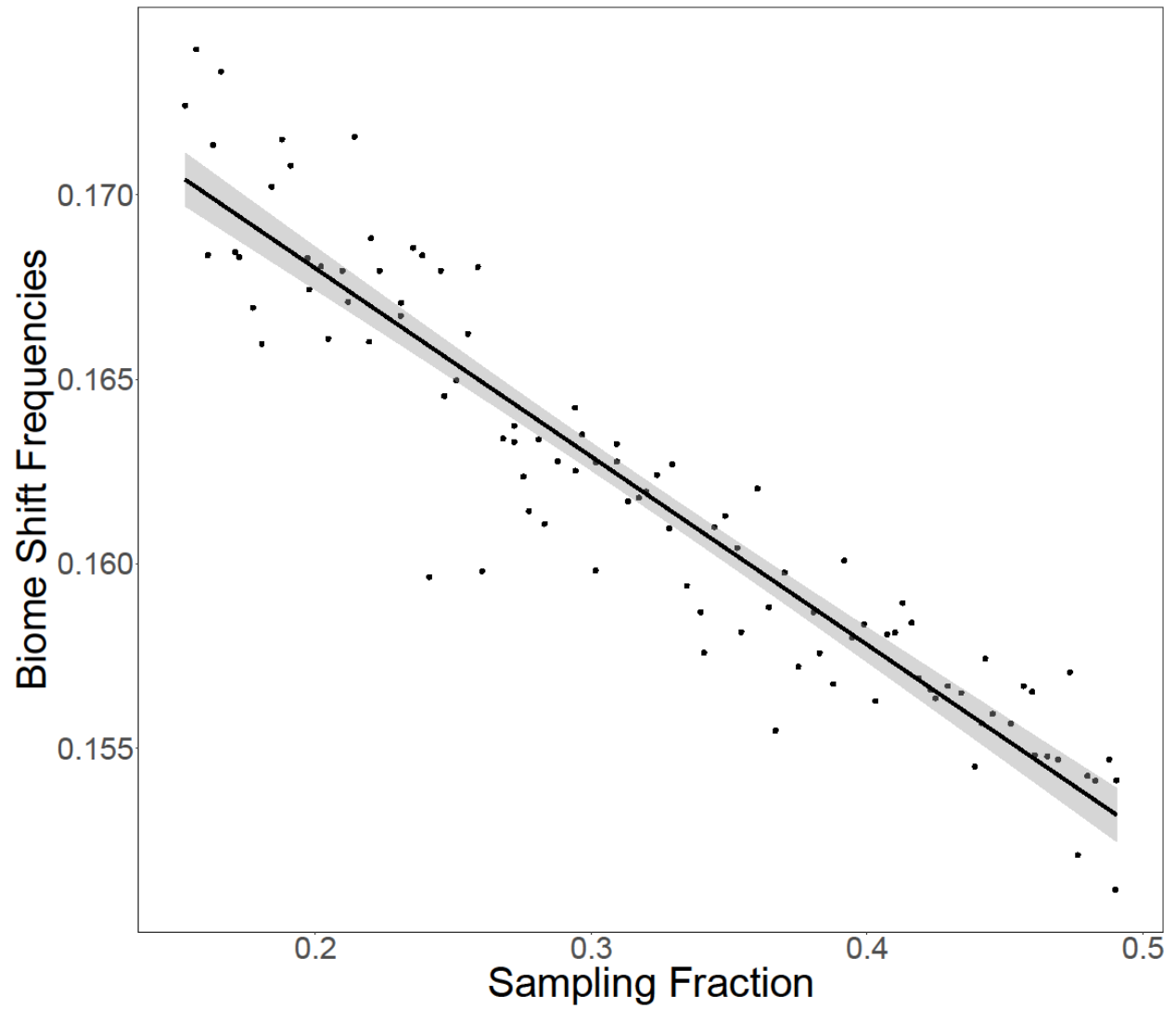
3



4

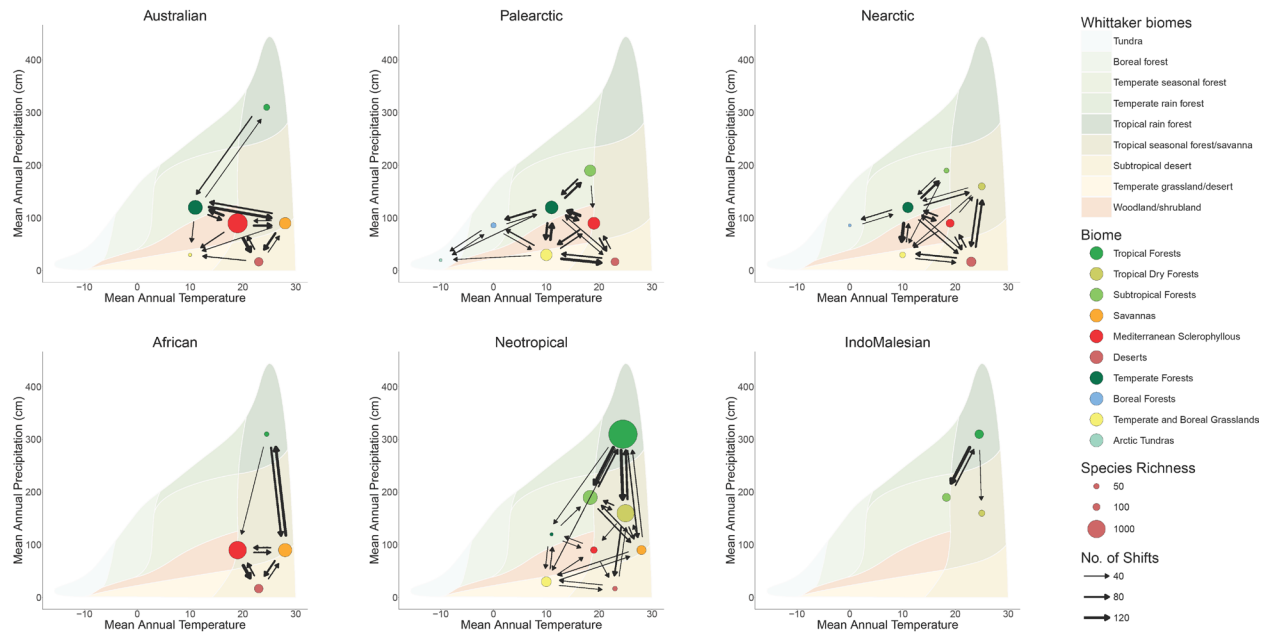
5 **Fig. S1. Comparison of observed and expected biome shift frequencies under null models.**

6 Ratios of observed to expected biome shift frequencies are shown. The grey dotted line indicates
7 a ratio of 1, where observed biome shift frequencies equal null expectations.



8

9 **Fig. S2. Correlation between sampling fraction and estimated biome shift frequencies.**



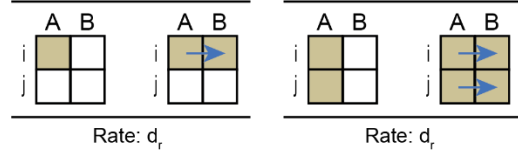
10

11 **Fig. S3. Shifts between biomes within each biogeographic realm projected onto Whittaker's**
 12 **biome framework.** Circle size represents the number of extant species within each biome; arrow
 13 width reflects the number of shifts between two biomes. Very rare shifts (<5) were excluded for
 14 figure clarity.

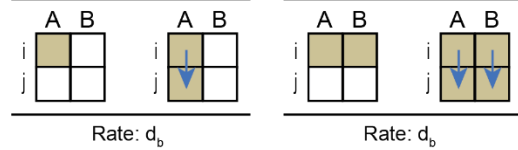
Anagenesis

a. Dispersal

Range Expansion

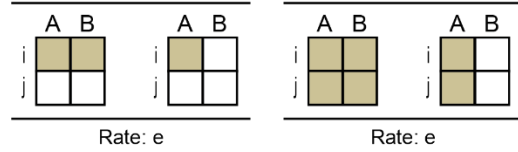


Biome Expansion

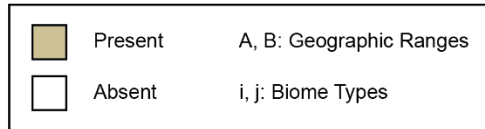
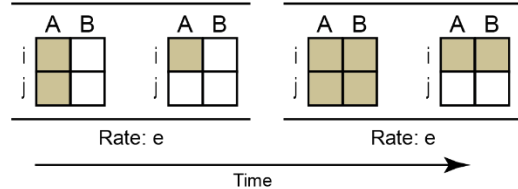


b. Extirpation

Range Contraction

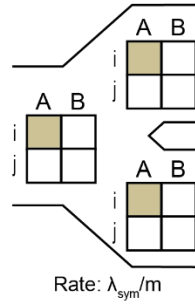


Biome Contraction

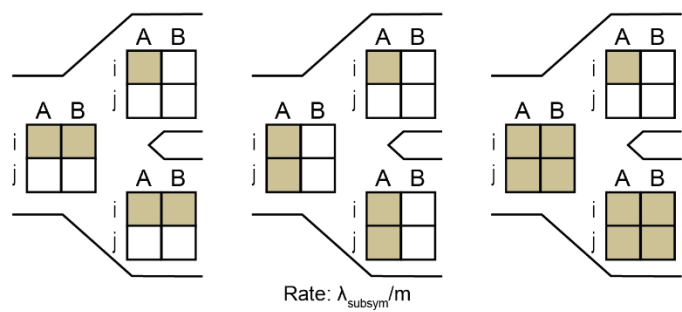


Cladogenesis

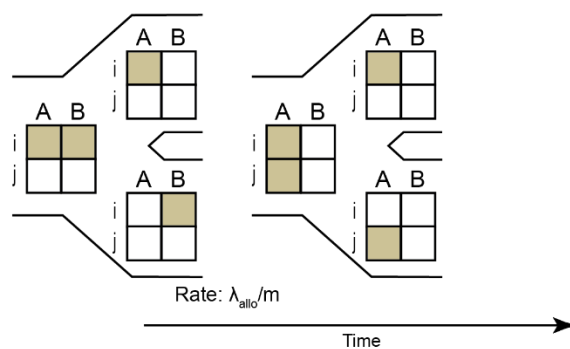
c. Narrow Sympatry



d. Subset Sympatry



e. Allopatry



15

16 **Fig. S4. Illustration of anagenetic and cladogenic events in our model of the joint evolution**

17 **of biome occupancy and geographic ranges.** *A* and *B* denote different geographic ranges, while

18 *i* and *j* different biomes. Time proceeds from left to right. (a) Dispersal: new geographic ranges

19 are colonized at rate d_r , and new biomes are colonized at rate d_b . (b) Extirpation: range

20 contraction and biome contraction occur at rate e . (d) Narrow sympatry: When the ancestral range

21 contains only one area and one biome, both descendental lineages inherit that area and biome. (d)

22 Subset sympatry: When the ancestral range is widespread in geographic ranges or biome

23 occupancy, one descendant inherits the ancestral range, and the other descendant inherits only one

24 geographic range/biome. (e) Allopatry: When the ancestral range is widespread in geographic

25 ranges or biome occupancy, one descendant inherits a single range or biome while the other
26 inherits all remaining ancestral areas. For cladogenetic events, we enumerated the number of
27 possible cladogenetic scenarios and assigned each the rate accordingly.

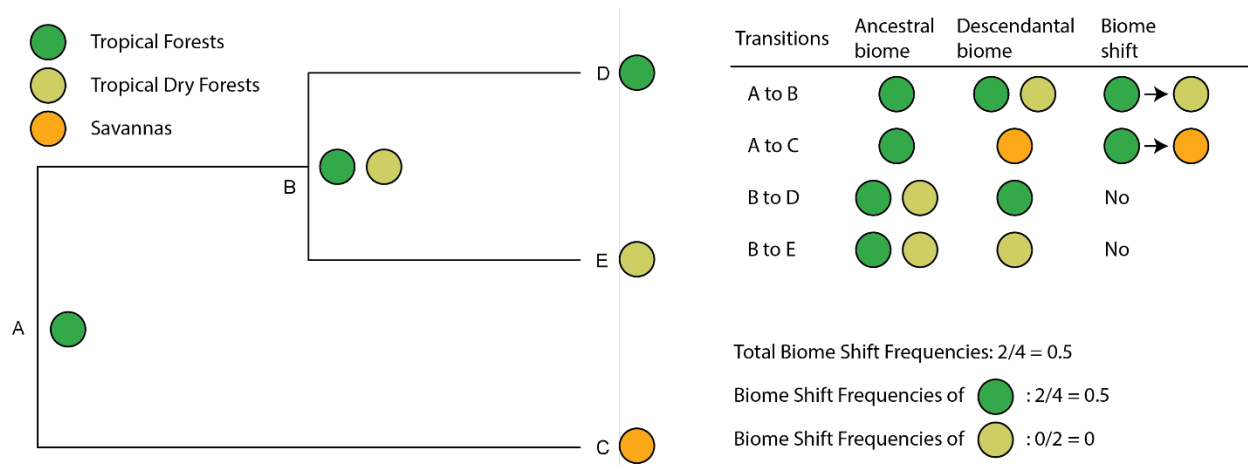


Fig. S5. Conceptual illustration of identifying biome shift events. The phylogeny includes three extant species C, D, and E, with B representing the most recent common ancestor of D and E, and A representing the common ancestor of all three species. Circles in different colors indicate different biomes. Circles next to extant species denote the biomes they currently occupy, while circles at internal nodes (A and B) indicate reconstructed ancestral biome states. For this phylogeny, all four evolutionary transitions are assessed by comparing the biome states of each ancestor–descendant pair. A biome shift is recorded when a descendant occupies a biome not occupied by its ancestor. In this example, transitions from A to B and A to C are identified as biome shifts: A occupies only tropical forests, whereas B also occupies tropical dry forests, and C occupies savannas. Transitions from B to D and B to E are not considered biome shifts because both tropical forests (D) and tropical dry forests (E) are already present in the biome state of the ancestor B. Biome pairs involved in each shift are also specified: A to B represents a shift from tropical forests to tropical dry forests, and A to C represents a shift from tropical forests to savannas. The biome shift frequency is calculated as the ratio of transitions with biome shifts (2: A to B and A to C) to the total number of transitions (4), yielding a frequency of 0.5. Biome-specific shift frequencies are similarly calculated as the ratio of biome shifts to total transitions in which the ancestor occupies that biome. Here, for tropical forests, all four transitions have ancestors occupying this biome, with two involving shifts (frequency = $2/4 = 0.5$). For tropical dry forests, ancestors in two transitions occupy this biome, but none involve shifts (frequency = $0/2 = 0$).

49 **Supplemental tables**

50 **Table S1. Summary of shift events between zonal biomes across globe.** The numbers indicate the medium value of estimated number
51 of shifts, and the brackets indicate the 25%, and 75% quantiles. Row names indicate donor biomes, and column names indicate recipient
52 biomes. (TrF: Tropical Forest, TDF: Tropical Dry Forest, Sav: Savannas, SF: Subtropical Forest, MS: Mediterranean Sclerophyllous
53 Forest, Des: Desert, TpF: Temperate Forest, BF: Boreal Forest, TBG: Temperate and Boreal Grassland, MSG: Montane and Subalpine
54 Grassland, ArT: Arctic Tundra).

55

	TrF	TDF	SF	Sav	MS	Des	TpF	BF	TBG	ArT
TrF		158 (156-163)	186 (182-190)	107 (104-112)	12 (11-14)	7 (6-9)	40 (38-42)		11 (10-12)	
TDF	80 (77-82)		47 (46-50)	33 (31-35)	14 (13-16)	124 (120-128)	14 (12-15)	1 (0-1)	22 (21-24)	
SF	127 (123-130)	32 (30-34)		38 (36-40)	11 (10-13)	5 (4-6)	97 (93-101)	5 (4-6)	25 (24-26)	
Sav	94 (91-97)	23 (22-24)	36 (34-39)		46 (43-50)	99 (96-102)	44 (42-46)		31 (30-34)	
MS	6 (5-7)	13 (12-15)	14 (12-15)	98 (95-101)		254 (250-261)	244 (239-250)	6 (5-7)	104 (102-107)	6 (5-6)
Des	8 (6-9)	79 (76-81)	5 (4-6)	50 (46-52)	131 (128-134)		43 (41-45)	2 (2-3)	134 (131-138)	2 (2-3)
TpF	15 (13-17)	43 (41-44)	178 (173-183)	78 (76-80)	193 (188-197)	51 (48-54)		133 (129-136)	246 (240-250)	49 (47-51)
BF		1 (1-1)	2 (1-3)			3 (2-3)	31 (29-34)		15 (13-16)	47 (44-48)
TBG	1 (1-2)	8 (7-9)	13 (12-14)	17 (15-18)	57 (54-60)	148 (141-152)	161 (157-165)	44 (42-46)		31 (29-33)
ApT					2 (2-3)	5 (5-7)	12 (11-14)	23 (21-26)	10 (9-11)	

56

57 **Table S2. Summary of shift events between zonal biomes in African realm.** The number formats, row names, column names, and
58 abbreviations follow Table S1.

59

	TrF	Sav	MS	Des
TrF		48 (45-52)	6 (5-6)	1 (1-2)
Sav	65 (63-69)		27 (27-29)	40 (38-42)
MS	4 (4-5)	28 (27-30)		79 (77-81)
Des	1 (1-1)	18 (16-20)	29 (28-31)	

60

61 **Table S3. Summary of shift events between zonal biomes in Australian realm.** The number formats, row names, column names, and
62 abbreviations follow Table S1.

63

	TrF	Sav	MS	Des	TpF	TBG
TrF		4 (3-4)	2 (1-3)		20 (18-21)	
Sav	5 (4-5)		12 (10-14)	47 (45-48)	35 (33-36)	9 (8-10)
MS		47 (46-48)		72 (71-74)	60 (58-61)	17 (16-18)
Des		11 (9-12)	26 (24-27)		3 (2-3)	16 (14-17)
TpF	7 (6-8)	61 (59-62)	31 (30-33)	5 (5-6)		12 (11-13)
TBG		2 (2-3)	3 (3-4)	3 (2-4)	2 (1-3)	

64

65 **Table S4. Summary of shift events between zonal biomes in Indo-Malesian realm.** The number formats, row names, column names,
66 and abbreviations follow Table S1.

67

TrF		TDF	SF
TrF		39 (38-41)	52 (49-54)
TDF	2 (2-2)		1 (1-1)
SF	42 (40-45)	3 (2-4)	

68

69 **Table S5. Summary of shift events between zonal biomes in Nearctic realm.** The number formats, row names, column names, and
70 abbreviations follow Table S1.

71

	TDF	SF	Sav	MS	Des	TpF	BF	TBG	ArT
TDF		4 (3-5)	2 (2-3)	3 (3-4)	47 (45-49)	6 (5-7)	1 (0-1)	7 (6-8)	
SF	1 (1-2)		1 (1-2)		3 (2-3)	14 (12-16)	1 (1-1)	6 (5-6)	
Sav	1 (0-1)	1 (1-2)			1 (0-1)	1 (1-2)		1 (1-1)	
MS	6 (5-7)	1 (1-2)	1 (1-2)		26 (24-29)	42 (40-43)	1 (1-1)	16 (14-16)	1 (1-1)
Des	56 (53-57)	3 (2-3)	4 (3-5)	31 (30-33)		14 (12-15)		39 (38-41)	
TpF	29 (27-30)	63 (61-65)	1 (1-2)	48 (46-49)	25 (23-27)		21 (20-23)	98 (96-100)	4 (3-5)
BF					1 (0-1)	7 (6-8)		2 (2-3)	5 (4-6)
TBG	3 (2-3)	2 (1-3)	1 (1-2)	2 (1-3)	20 (18-21)	24 (21-26)	3 (2-3)		4 (3-5)
ApT					1 (0-1)	2 (1-3)	4 (3-5)	1 (1-2)	

72

73 **Table S6. Summary of shift events between zonal biomes in Neotropical realm.** The number formats, row names, column names,
74 and abbreviations follow Table S1.

75

	TrF	TDF	SF	Sav	MS	Des	TpF	TBG
TrF		109 (106-112)	115 (113-118)	34 (32-35)	1 (1-1)	2 (2-3)	7 (6-8)	9 (8-10)
TDF	71 (69-73)		32 (30-34)	26 (25-28)	8 (7-8)	46 (44-47)	3 (2-5)	5 (4-6)
SF	48 (46-50)	18 (17-20)		33 (31-35)	1 (1-2)	1 (1-1)	3 (2-4)	13 (12-14)
Sav	17 (16-19)	16 (15-17)	25 (23-28)		3 (2-3)	4 (3-5)	1 (1-2)	14 (13-16)
MS	1 (1-1)		1 (0-1)	3 (2-3)		10 (10-11)	7 (6-8)	5 (4-6)
Des	3 (2-4)	10 (9-12)	1 (0-1)	3 (3-4)	3 (2-3)			10 (9-12)
TpF	3 (2-4)	3 (3-4)	8 (7-9)	4 (3-4)	6 (5-7)			12 (10-13)
TBG	1 (0-1)	2 (2-3)	5 (4-5)	11 (10-12)	9 (9-10)	10 (9-11)	20 (19-22)	

76

77 **Table S7. Summary of shift events between zonal biomes in Palearctic realm.** The number formats, row names, column names, and
78 abbreviations follow Table S1.

79

	SF	MS	Des	TpF	BF	TBG	ArT
SF		7 (6-8)		57 (54-60)	3 (2-4)	5 (4-6)	
MS	3 (2-4)		56 (53-59)	126 (123-131)	2 (2-3)	56 (54-58)	3 (2-4)
Des	1 (1-2)	27 (25-29)		20 (19-22)		48 (45-51)	1 (0-1)
TpF	76 (73-79)	84 (80-88)	13 (11-15)		62 (59-65)	87 (83-89)	13 (12-14)
BF	2 (1-2)		1 (1-2)	14 (12-16)		9 (8-10)	13 (12-14)
TBG	5 (4-5)	34 (32-36)	104 (99-107)	98 (95-101)	34 (33-36)		9 (8-10)
ApT		1 (0-1)	2 (1-2)	3 (2-4)	7 (5-8)	5 (4-6)	

80

81 **Table S8. Basic information of the lineages for which phylogenies were compiled.** Total
82 number species was referred to Plants of the World Online (POWO) database.

83

Clade	Taxonomic level	Species in Phylogeny	Total Species	Crown Age	Sampling Fraction	References
<i>Abies</i>	Genus	46	47	30.49	0.98	70
<i>Acacia</i>	Genus	691	1085	21.41	0.64	71
<i>Acer</i>	Genus	103	154	70.15	0.67	72
<i>Adenanthos</i>	Genus	26	34	24.02	0.76	73
<i>Aglaia</i>	Genus	92	121	24.46	0.76	74
<i>Albizia</i>	Genus	71	99	21.19	0.72	71
<i>Allium</i>	Genus	442	1078	33.54	0.41	63
<i>Alnus</i>	Genus	30	41	22.26	0.73	75
<i>Alocasia</i>	Genus	36	89	13.49	0.40	76
<i>Anemopaegma</i>	Genus	42	48	27.57	0.88	77
<i>Angelica</i>	Genus	32	105	13.60	0.30	78
Arbutoideae	Subfamily	72	98	28.62	0.73	79
<i>Areca</i>	Genus	43	45	15.38	0.96	80
<i>Artemisia</i>	Genus	88	498	32.65	0.18	37
<i>Astelia</i>	Genus	30	31	29.90	0.97	81
<i>Atriplex</i>	Genus	185	249	19.08	0.74	82
<i>Azorella</i>	Genus	49	58	21.14	0.84	83
<i>Bactris</i>	Genus	77	79	22.32	0.97	80
<i>Banisteriopsis</i>	Genus	33	62	9.90	0.53	41
<i>Banksia</i>	Genus	159	183	42.17	0.87	84
<i>Betula</i>	Genus	33	63	12.43	0.52	75
<i>Bossiaea</i>	Genus	41	82	12.31	0.50	85
<i>Bunchosia</i>	Genus	34	89	17.44	0.38	41
<i>Calamus</i>	Genus	322	416	27.39	0.77	80
<i>Calliandra</i>	Genus	83	150	13.74	0.55	71
<i>Calochortus</i>	Genus	71	77	10.28	0.92	86
<i>Calytrix</i>	Genus	63	92	36.89	0.68	87
<i>Camellia</i>	Genus	77	237	20.52	0.32	79
<i>Canavalia</i>	Genus	41	62	8.73	0.66	88
<i>Carex</i>	Genus	1263	2082	37.17	0.61	43
<i>Carpinus</i>	Genus	19	43	17.52	0.44	75
Casuarinaceae	Family	74	91	54.79	0.81	89

Clade	Taxonomic level	Species in Phylogeny	Total Species	Crown Age	Sampling Fraction	References
Cedreloideae	Subfamily	46	87	46.45	0.53	90
<i>Ceratozamia</i>	Genus	32	39	22.24	0.82	91
<i>Chamaedorea</i>	Genus	104	106	20.52	0.98	80
<i>Chionochoa</i>	Genus	23	25	6.96	0.92	92
<i>Coccinia</i>	Genus	22	28	6.92	0.79	93
<i>Coccothrinax</i>	Genus	51	61	8.53	0.84	80
<i>Coffea</i>	Genus	67	131	8.36	0.51	94
<i>Colchicum</i>	Genus	121	162	31.72	0.75	83
<i>Costus</i>	Genus	40	115	3.00	0.35	95
Cryptocaryeae	Tribe	153	831	102.13	0.18	96
<i>Cycas</i>	Genus	99	117	24.37	0.85	91
<i>Cymbidium</i>	Genus	39	87	45.00	0.45	97
Delphineae	Tribe	287	884	72.22	0.32	63
<i>Deutzia</i>	Genus	48	68	21.42	0.71	79
<i>Diplacus</i>	Genus	33	49	33.11	0.67	98
<i>Dipterocarpus</i>	Genus	37	65	45.93	0.57	99
<i>Disa</i>	Genus	124	185	19.29	0.67	100
<i>Draba</i>	Genus	213	432	12.20	0.49	63
<i>Dypsis</i>	Genus	102	107	13.48	0.95	80
<i>Elaeagnus</i>	Genus	52	93	14.72	0.56	101
<i>Encephalartos</i>	Genus	64	65	21.08	0.98	91
<i>Ephedra</i>	Genus	51	73	13.82	0.70	83
<i>Erica</i>	Genus	460	839	17.85	0.55	102
<i>Eriogonum</i>	Genus	100	254	30.44	0.39	103
<i>Erodium</i>	Genus	49	121	15.27	0.40	104
<i>Eryngium</i>	Genus	140	245	15.42	0.57	83
<i>Erysimum</i>	Genus	69	270	6.77	0.26	105
<i>Erythranthe</i>	Genus	53	128	37.32	0.41	98
<i>Eucalyptus</i>	Genus	544	713	34.78	0.76	106
<i>Euphorbia</i>	Genus	842	2054	61.45	0.41	107
<i>Festuca</i>	Genus	174	659	20.24	0.26	108
<i>Ficus</i>	Genus	228	880	42.69	0.26	109
<i>Fosterella</i>	Genus	24	34	9.61	0.71	110
<i>Fraxinus</i>	Genus	32	58	45.42	0.55	111
<i>Gentiana</i>	Genus	179	341	29.76	0.52	63
<i>Geonoma</i>	Genus	68	68	12.44	1.00	80

Clade	Taxonomic level	Species in Phylogeny	Total Species	Crown Age	Sampling Fraction	References
<i>Goniothalamus</i>	Genus	62	138	21.94	0.45	112
<i>Gonocarpus</i>	Genus	24	43	22.08	0.56	113
<i>Graffenrieda</i>	Genus	31	66	16.83	0.47	114
<i>Guarea</i>	Genus	40	70	19.72	0.57	90
<i>Hakea</i>	Genus	133	154	34.57	0.86	24
<i>Haplophyllum</i>	Genus	32	71	31.21	0.45	115
<i>Hedyosmum</i>	Genus	29	45	30.21	0.64	116
<i>Heliconia</i>	Genus	154	198	38.70	0.78	117
<i>Hopea</i>	Genus	42	114	49.59	0.37	99
<i>Hydrangea</i>	Genus	54	96	23.02	0.56	118
<i>Hypericum</i>	Genus	236	512	38.75	0.46	107
<i>Ilex</i>	Genus	152	564	50.75	0.27	119
<i>Inga</i>	Genus	125	281	14.28	0.44	71
<i>Iris</i>	Genus	164	312	22.87	0.53	83
<i>Jamesbrittenia</i>	Genus	68	84	45.13	0.81	120
<i>Juglans</i>	Genus	19	21	21.44	0.90	75
<i>Juniperus</i>	Genus	48	69	35.17	0.70	70
<i>Lagotis</i>	Genus	20	30	12.86	0.67	121
<i>Leucadendron</i>	Genus	81	85	31.76	0.95	83
<i>Licuala</i>	Genus	134	149	13.67	0.90	80
<i>Linaria</i>	Genus	122	193	21.31	0.63	122
<i>Lonicera</i>	Genus	86	158	19.48	0.54	83
<i>Lupinus</i>	Genus	118	580	12.29	0.20	123
<i>Lysimachia</i>	Genus	121	282	33.89	0.43	79
<i>Macrolobium</i>	Genus	27	78	19.16	0.35	124
<i>Macrozamia</i>	Genus	26	41	18.55	0.63	91
<i>Magnolia</i>	Genus	80	363	36.04	0.22	125
<i>Mammillaria</i>	Genus	117	145	31.70	0.81	103
<i>Meconopsis</i>	Genus	31	95	15.06	0.33	126
<i>Menonvillea</i>	Genus	23	24	14.63	0.96	127
<i>Meriania</i>	Genus	62	117	25.69	0.53	114
<i>Metalasia</i>	Genus	55	57	6.90	0.96	128
<i>Miconia</i>	Genus	998	1906	53.03	0.52	129
<i>Mimosa</i>	Genus	344	611	28.15	0.56	71
<i>Momordica</i>	Genus	45	52	35.45	0.87	130
<i>Moraea</i>	Genus	156	232	17.41	0.67	83

Clade	Taxonomic level	Species in Phylogeny	Total Species	Crown Age	Sampling Fraction	References
<i>Mussaenda</i>	Genus	71	185	8.99	0.38	131
<i>Myrceugenia</i>	Genus	32	46	27.42	0.70	132
<i>Myrica</i>	Genus	26	50	21.63	0.52	75
<i>Nepenthes</i>	Genus	81	197	40.82	0.41	103
<i>Nothofagus</i>	Genus	25	38	41.58	0.66	75
Oleinae	Subtribe	116	368	33.75	0.32	133
<i>Opuntia</i>	Genus	92	145	31.69	0.63	103
<i>Oxera</i>	Genus	24	24	5.39	1.00	134
<i>Pagamea</i>	Genus	21	26	10.33	0.81	135
<i>Panicum</i>	Genus	94	264	36.60	0.36	136
<i>Paphiopedilum</i>	Genus	70	109	20.46	0.64	137
<i>Passiflora</i>	Genus	211	593	40.75	0.36	107
<i>Pedicularis</i>	Genus	335	679	29.30	0.49	138
<i>Pentameris</i>	Genus	67	80	14.33	0.84	92
<i>Phlox</i>	Genus	50	68	27.37	0.74	139
<i>Picea</i>	Genus	33	37	26.21	0.89	140
<i>Pinanga</i>	Genus	137	145	13.34	0.94	80
<i>Pinus</i>	Genus	108	122	124.51	0.89	141
<i>Planchonella</i>	Genus	59	110	41.21	0.54	142
<i>Pleioluma</i>	Genus	22	40	17.54	0.55	142
<i>Poa</i>	Genus	279	578	17.39	0.48	108
<i>Podocarpus</i>	Genus	73	116	49.90	0.63	70
<i>Polygonum</i>	Genus	52	171	63.47	0.30	103
<i>Primulina</i>	Genus	136	232	14.45	0.59	122
Primuloideae	Subfamily	382	827	39.59	0.46	63
<i>Protium</i>	Genus	92	154	28.92	0.60	143
<i>Pseuduvaria</i>	Genus	54	60	15.52	0.90	83
<i>Pycnandra</i>	Genus	36	62	16.24	0.58	142
<i>Quercus</i>	Genus	233	469	56.00	0.50	144
Rhamnaceae	Family	573	1194	83.60	0.48	145
<i>Rheum</i>	Genus	31	56	44.56	0.55	103
<i>Rhodiola</i>	Genus	44	73	21.87	0.60	146
<i>Rhododendron</i>	Genus	419	1091	59.36	0.38	63
<i>Ribes</i>	Genus	82	193	20.69	0.42	146
<i>Rytidosperma</i>	Genus	50	74	5.22	0.68	92
<i>Salix</i>	Genus	166	471	46.08	0.35	63

Clade	Taxonomic level	Species in Phylogeny	Total Species	Crown Age	Sampling Fraction	References
<i>Salvia</i>	Genus	490	1024	31.35	0.48	25
<i>Saxifraga</i>	Genus	254	475	50.49	0.53	146
<i>Shorea</i>	Genus	34	50	65.16	0.68	99
<i>Sinningia</i>	Genus	53	81	37.38	0.65	147
Solanaceae	Family	975	2839	30.33	0.34	148
<i>Stachys</i>	Genus	114	372	17.73	0.31	122
<i>Stemonoporus</i>	Genus	23	26	55.83	0.88	99
<i>Stipa</i>	Genus	39	146	12.89	0.27	108
<i>Streptocarpus</i>	Genus	102	184	27.56	0.55	122
<i>Suaeda</i>	Genus	65	93	74.62	0.70	103
<i>Syagrus</i>	Genus	57	70	15.70	0.81	80
<i>Syncarpha</i>	Genus	20	21	5.56	0.95	149
Ulmaceae	Family	40	58	85.39	0.69	150
<i>Veronica</i>	Genus	195	464	34.08	0.42	122
<i>Viburnum</i>	Genus	115	203	69.39	0.57	50
<i>Viscum</i>	Genus	48	112	45.61	0.43	151
Vitaceae	Family	397	1031	92.78	0.39	152
<i>Zamia</i>	Genus	69	85	26.28	0.81	153
<i>Zygia</i>	Genus	34	60	17.39	0.57	71
Zygophyllaceae	Family	112	287	54.80	0.39	154
Total		20909	43026		0.49	

Clade	TrF	TDF	Sav	SF	MS	TpF	BF	TBG	ArT	Des	LF	CF	SbF	MSG	ApT	Pa	Af	Na	Nt	Au	IM
<i>Banksia</i>	2		1		143	12				1										159	
<i>Betula</i>				3		23	5	1				2	4			20		12			1
<i>Bossiaea</i>			5		24	12		1		1										41	
<i>Bunchosia</i>	22	13	1	3						1									34		
<i>Calamus</i>	303	14	1	9		1					6						1			8	313
<i>Calliandra</i>	27	50	3	7	1	1				3	1							5	78		
<i>Calochortus</i>		14			23	16		11		14			2	1	1			71			
<i>Calytrix</i>			4		58	1				1										63	
<i>Camellia</i>	22			60							1	2									77
<i>Canavalia</i>	25	14	3	6												1	5	1	28		7
<i>Carex</i>	35	32	30	167	62	603	125	182	59	23	14	56	75	139	118	479	72	479	93	106	34
<i>Carpinus</i>				13	1	9						1				16		1			2
Casuarinaceae	17	1	6		29	28		1		1										59	15
Cedreloideae	28	6	3	4						1	6	1					21		22		4
<i>Ceratozamia</i>	18	5								2	8							4	28		
<i>Chamaedorea</i>	85	4		1							26	1							104		
<i>Chionochloa</i>						4		18	1						8					23	
<i>Coccinia</i>	8		13		1					2							22				
<i>Coccothrinax</i>	19	30								2									51		
<i>Coffea</i>	42	17	9							2							64			1	2
<i>Colchicum</i>			3		70	14		6		39			1	7		89	32				
<i>Costus</i>	40										2								40		
Cryptocaryaceae	94		2	37	3	24					2	1					19		20	45	69
<i>Cycas</i>	41	21	25	13		1					1					3	1			27	68
<i>Cymbidium</i>	18			25		2					1	8				8				1	30
Delphineae		2	3	7	49	76	13	45	3	30		12	47	76	36	220	4	64			

Clade	TrF	TDF	Sav	SF	MS	TpF	BF	TBG	ArT	Des	LF	CF	SbF	MSG	ApT	Pa	Af	Na	Nt	Au	IM
<i>Guarea</i>	39	1		1							1								40		
<i>Hakea</i>			7		92	27		4		10										133	
<i>Haplophyllum</i>					6	4		12		15						31					1
<i>Hedyosmum</i>	10	2		1							11	16							28		1
<i>Heliconia</i>	129	1		5							36								148		7
<i>Hopea</i>	41	4																			42
<i>Hydrangea</i>	3			49		13						4	1			40		3			11
<i>Hypericum</i>	4	6	16	44	39	73	2	13		7	3	30	6	49	1	114	18	44	55	1	6
<i>Ilex</i>	25	6	1	97	1	21	1	1			7	17	3			80	1	14	24	1	32
<i>Inga</i>	111	2		15							7								125		
<i>Iris</i>				12	37	42	6	64		14		3	1	11	4	140		21			3
<i>Jamesbrittenia</i>	1		20		12					35				9			68				
<i>Juglans</i>	2	2		1	3	6		1		2	7	1				4		7	10		
<i>Juniperus</i>		9	1	4	5	12	1	5		9	3	7	12	1	6	24	2	18	5		
<i>Lagotis</i>								2	1	1				6	14	19		1			
<i>Leucadendron</i>					80					4							81				
<i>Licuala</i>	132	5																		1	133
<i>Linaria</i>					72	19	1	26		14				6	2	122					
<i>Lonicera</i>	1	1		20	6	47	1	9				16	10	6	4	68		17			1
<i>Lupinus</i>		6	11	15	28	20	2	6	2	16		1	5	29		11	2	50	56		
<i>Lysimachia</i>	19	6	14	56	9	27	2	2			3	1				63	16	10	4		28
<i>Macrolobium</i>	27										1								27		
<i>Macrozamia</i>			9		3	14				1										26	
<i>Magnolia</i>	26	3		41		10					5	2				12		6	10		53
<i>Mammillaria</i>		51						1		86								117			
<i>Meconopsis</i>														29	21	31					

Clade	TrF	TDF	Sav	SF	MS	TpF	BF	TBG	ArT	Des	LF	CF	SbF	MSG	ApT	Pa	Af	Na	Nt	Au	IM
<i>Pleioluma</i>	17	9	1			1														7	15
<i>Poa</i>		1	2	4	29	95	16	78	21	11		1	5	50	32	77	4	51	76	64	9
<i>Podocarpus</i>	35	4	3	8	5	9					21	4	1			2	7		22	11	32
<i>Polygonum</i>					8	17	4	20	1	17				1		44	1	7			
<i>Primulina</i>	38				100											23					113
Primuloideae	2		1	32	5	52	15	37	16	15	2	42	35	155	110	331	2	45	1		4
<i>Protium</i>	91	1	1	3							1						3		87		3
<i>Pseuduvaria</i>	52	1									3									5	49
<i>Pycnandra</i>	32	2		1							3										36
<i>Quercus</i>	21	53		59	33	59		12		15	16	7				63		118	28		24
Rhamnaceae	115	78	37	90	149	72		19		61	6	18	8	10	2	110	127	85	125	74	52
<i>Rheum</i>				1		5	1	9		4		2	4	10	10	31					
<i>Rhodiola</i>				1		4	1	8	2	3		5	8	21	22	42		2			
<i>Rhododendron</i>	31			121		46	8	1	4		35	94	106	135	44	313		25		2	79
<i>Ribes</i>		2		6	8	56	7	5		3		11	21	5	6	34		44	4		
<i>Rytidosperma</i>	2				5	28		16			1	1		8	3				5	44	3
<i>Salix</i>		3	1	12	5	67	58	14	27	9		2	12	16	12	88	2	77			
<i>Salvia</i>	24	133	11	60	69	54		42		86	30	23	13	37	5	198	25	68	199		
<i>Saxifraga</i>				5	14	36	16	3	19			15	53	137	124	233		19	2		
<i>Shorea</i>	32	4		1																	34
<i>Sinningia</i>	16	2	2	33				1			1								53		
Solanaceae	183	119	88	70	111	69		105		198	153	46	1	32	14	47	62	84	637	133	12
<i>Stachys</i>	2	13	9	2	35	31	1	13		21	5	3	4	5		59	17	23	16		
<i>Stemonoporus</i>	19										6										23
<i>Stipa</i>					4	9	1	23		5				6	8	39					
<i>Streptocarpus</i>	39	1	36		1						25			12			102				

Clade	TrF	TDF	Sav	SF	MS	TpF	BF	TBG	ArT	Des	LF	CF	SbF	MSG	ApT	Pa	Af	Na	Nt	Au	IM
<i>Suaeda</i>			6	3	12	8		18	1	32						44	4	12	4	1	
<i>Syagrus</i>	22	13	20	9							2								57		
<i>Syncarpha</i>					20					1							20				
Ulmaceae	5	3		14	1	20		3		1		3		1		26		7	5		2
<i>Veronica</i>	1		2	8	23	70	6	48	7	7		5	13	32	17	109	4	13	1	67	4
<i>Viburnum</i>	14	13		47	2	30	1	2		1	14	20	5	1		58		14	26		17
<i>Viscum</i>	17	4	15	2	6	2				4		1	1			4	34			4	6
Vitaceae	174	46	81	82	8	31		11		15	7	4				49	121	27	42	24	134
<i>Zamia</i>	58	9		1							5								69		
<i>Zygia</i>	31		2								2								34		
Zygophyllaceae		1	2		24	1		10		88						35	57	8	1	9	2
Total	4651	1457	1380	2134	3249	3148	406	1599	266	1907	972	739	618	1567	913	5497	2699	2641	4960	2625	2523

Table S10. Co-occurrence matrix of biomes. 1 indicates possible co-occurrence of the two biomes while null cell indicates impossible co-occurrence (TrF: Tropical Forest, TDF: Tropical Dry Forest, Sav: Savanna, SF: Subtropical Forest, MS: Mediterranean Sclerophyllous, TpF: Temperate Forest, BF: Boreal Forest, TBG: Temperate and Boreal Grassland, ArT: Arctic Tundra, Des: Dessert, LF: Laurel Forest, CF: Cloud Forest, SbF: Subalpine Forest, MSG: Montane and Subalpine Grassland, ApT: Alpine Tundra).

	TrF	TDF	Sav	SF	MS	TpF	BF	TBG	ArT	Des	LF	CF	SbF	MSG	ApT
TrF	-	1	1	1		1					1				
TDF	1	-	1	1	1	1				1	1	1			
Sav	1	1	-	1	1	1		1		1				1	
SF	1	1	1	-		1					1	1			
MS		1	1		-	1		1	1	1		1		1	
TpF	1	1	1	1	1	-	1	1				1	1	1	
BF						1	-	1	1				1	1	1
TBG			1		1	1	1	-	1	1				1	1
ArT					1		1	1	-	1					1
Des		1	1		1			1	1	-				1	1
LF	1	1		1							-	1			
CF		1		1	1	1					1	-	1	1	
SbF						1	1					1	-	1	1
MSG			1		1	1	1	1		1		1	1	-	1
ApT							1	1	1	1			1	1	-

100 Table S11. **Co-occurrence matrix of biogeographic realms.** 1 indicates possible co-occurrence
101 of the two realms while null cell indicates impossible co-occurrence (Pa: Palearctic, Af: African,
102 Na: Nearctic, Nt: Neotropical, Au: Australian, IM: Indo-Malesian; C: continent, I: island).

103

	Pa-C	Pa-I	Af-C	Af-I	Na-C	Na-I	Nt-C	Nt-I	Au-C	Au-I	IM-C	IM-I
Pa-C	-	1	1		1				1		1	1
Pa-I	1	-										
Af-C	1		-	1			1		1		1	
Af-I			1	-								
Na-C	1				-	1	1					
Na-I					1	-						
Nt-C			1		1		-	1	1		1	
Nt-I							1	-				
Au-C	1		1				1		-	1	1	1
Au-I									1	-		
IM-C	1		1				1		1		-	1
IM-I	1								1		1	-

104

Table S12. Summary of the interpretation and prior distribution of parameters used in the model.

Parameter	Interpretation	Prior
n	Number of sampled species	/
L	Total branch lengths (Myr)	/
T_r	Root age (Ma)	/
e	Global extinction rate (Myr ⁻¹) Biome contraction rate (Myr ⁻¹)	$LogNormal(\ln\left(\frac{\ln \frac{n}{2}}{T_r}\right), 1)$
λ_{sym}	Sympatric speciation rate (Myr ⁻¹)	<i>Exponential</i> (L)
λ_{subsym}	Subset sympatric speciation rate (Myr ⁻¹)	<i>Exponential</i> (L)
λ_{allo}	Allopatric speciation rate (Myr ⁻¹)	<i>Exponential</i> (L)
d_r	Range expansion rates (Myr ⁻¹)	<i>Exponential</i> (L)
d_b	Biome expansion rate (Myr ⁻¹)	<i>Exponential</i> (L)

109 **Table S13. Summary of variables hypothesized to mediate biome shift dynamics.**

110

Category	Name	Definition	Unit	Range	Transformed before model implementation	Expected affect and reference
Single Biome – Biogeographic	Area	Amount of landmass occupied by a biome	km ²	(0, ∞)	Log-transformed	Larger biomes are expected to associate with more biome shifts ^{13, 26, 27} .
	Connectivity	Opposite of mean of minimum distance to other biomes within the same realm	km	(0, ∞)	Log(x+1)-transformed	Better connected biomes are expected to associate with more biome shifts ^{13, 26, 27} .
Single Biome – Historical	Evolutionary Time	Time when the biome was first colonized	Myr	(0, ∞)	/	Biomes with longer evolutionary history are expected to associate with more biome shifts and function as source of biome shifts ¹³ .
Single Biome – Biotic	Branch Length	Amount of time lineages inhabiting a biome in phylogenies	Myr	(0, ∞)	Log-transformed	Biomes with more biodiversity are expected to associate with more biome shifts and function as source of biome shifts ^{13, 26, 27} .
Biome Pairs – Geographic	Geographic Proximity	Degree to which two biomes are adjacent or isolated in geographic space	km	(-∞, ∞)	Log(x +1)-transformed with the original sign kept	More biome shifts are expected between geographically closer biomes ^{13, 26, 27} .
Biome Pairs – Environmental	Thermal Similarity	Degree to which two biomes are similar in thermal conditions	/	(0, 1)	/	More biome shifts are expected between environmentally more similar biomes ¹³ .
	Moisture Similarity	Degree to which two biomes are similar in moisture conditions	/	(0, 1)	/	

111

112 **Table S14. Summary of single-biome variables hypothesized to mediate biome shift**
113 **dynamics.** Abbreviations follow Table S1.

114

Realm	Biome	Area (km ²)	Mean distance to other biomes (km)	Evolutionary time (Myr)	Branch length (Myr)
Palearctic	SF	1873200	1031.44	72	4687
	TpF	8768722	0	70	8270.5
	BF	10437822	956.79	35	669.5
	TBG	4596778	318.68	74	4859
	ArT	6182052	209.39	20	165.5
	MS	1130289	1761.59	72	5236
	Des	5063678	290.42	63	2396
Nearctic	TDF	1034678	532.9	44	2360
	SF	594604	708.8	34	540
	TpF	4718217	43.89	71	5030
	BF	5408460	957.58	18	136
	TBG	3036681	82.46	37	1039.5
	ArT	3906415	1291.77	10	63
	MS	173655	832.24	36	2418
African	Des	2365867	220.94	32	5370
	TrF	2872929	123.86	66	2037.5
	Sav	9714155	0	45	4043.5
	MS	121716	342.58	36	4697
	Des	1435159	57.64	61	1597
	TrF	8380964	348.41	60	10973
	TDF	2587518	632.35	60	4170
Neotropical	SF	822553	762.39	28	2018.5
	TpF	401991	487.6	29	662
	Sav	4060471	221.27	41	853.5
	TBG	1612170	216.79	26	962.5
	MS	163132	328.97	27	412
	Des	1264357	521.11	29	519.5
	TrF	33328	314.45	87	781.5
Australian	TpF	495081	68.02	41	2842
	Sav	2199321	35.28	28.5	1758.5
	TBG	602553	62.9	14	94
	MS	845596	200.68	42	8202
	Des	3504846	144.21	32	696.5
	TrF	3186996	205.08	92	3435.5
	TDF	1491369	370.7	14	156
Indo-Malesian	SF	1873200	317.54	70.5	1778

115 **Table S15. Summary of biome-pair variables hypothesized to mediate biome shift dynamics.**
116 In each biome pair, the biome listed before the dash represents the source of biome shifts, while
117 the biome listed after the dash represents the sink (i.e., more biome shifts from the former to the
118 latter than in the reverse direction). Abbreviations follow Table S1.

Realm	Biome pair	Geographic Proximity (km)	Thermal Similarity	Moisture Similarity
Australian	TpF-TrF	-29.88	0.03	0.02
	Sav-TrF	3642.92	0.02	0.03
	TrF-TBG	-377.38	0	0
	MS-TrF	-992.45	0.03	0.02
	Des-TrF	-487	0.01	0
	TpF-Sav	2842.89	0.05	0.07
	TpF-TBG	3852.53	0.09	0.08
	MS-TpF	1386.48	0.55	0.17
	TpF-Des	-378.27	0.07	0.01
	Sav-TBG	6058.54	0.13	0.08
	MS-Sav	-211.65	0.11	0.16
	Sav-Des	6148.15	0.2	0.24
	MS-TBG	1535.16	0.2	0.67
	Des-TBG	3117.08	0.26	0.26
	MS-Des	7057.83	0.14	0.24
Palearctic	TpF-SF	4214.3	0.12	0.1
	SF-BF	-1639.45	0	0.01
	SF-TBG	-566.2	0.04	0.01
	SF-ArT	-361.97	0	0
	SF-MS	-5409.98	0.55	0.21
	SF-Des	-400.34	0.01	0
	TpF-BF	14067.17	0.16	0.21
	TpF-TBG	21331.65	0.34	0.11
	TpF-ArT	1087.12	0.02	0.2
	TpF-MS	10882.11	0.29	0.25
	TpF-Des	4053.07	0.13	0.02
	TBG-BF	5114.71	0.07	0.21
	BF-ArT	33191.17	0.11	0.21
	MS-BF	-1412.62	0	0.14
	Des-BF	-205.23	0.01	0.02
	TBG-ArT	247.06	0	0.02
	TBG-MS	387.01	0.08	0.27
	TBG-Des	14161.48	0.21	0.2
	MS-ArT	-1405.34	0	0.01
	Des-ArT	-46.9	0	0

Realm	Biome pair	Geographic Proximity (km)	Thermal Similarity	Moisture Similarity
Palearctic	MS-Des	-449.62	0.04	0.05
Nearctic	TDF-SF	-760.84	0.08	0.05
	TpF-TDF	-25.37	0.02	0.03
	TDF-BF	-1904.46	0	0
	TBG-TDF	12.55	0.04	0.02
	TDF-ArT	-2227.49	0	0
	MS-TDF	-379.81	0.09	0.18
	Des-TDF	11456.15	0.26	0.11
	TpF-SF	4821.27	0.14	0.1
	BF-SF	-851.75	0	0.01
	TBG-SF	139.22	0.05	0.06
	ArT-SF	-1748.87	0	0.03
	MS-SF	-2248.36	0.3	0
	Des-SF	-681.46	0.12	0
	TpF-BF	6779.19	0.2	0.15
	TpF-TBG	13259.76	0.18	0.06
	TpF-ArT	3375.03	0.09	0.3
	TpF-MS	2700.62	0.12	0.01
	TpF-Des	12993.51	0.1	0.01
	TBG-BF	3148.97	0.04	0.02
	BF-ArT	20917.88	0.23	0.17
	MS-BF	-1339.01	0	0
	Des-BF	-762.98	0	0
	TBG-ArT	-329.62	0	0.02
	TBG-MS	162.9	0.1	0.15
	Des-TBG	2016.11	0.39	0.14
	MS-ArT	-1096.05	0	0
	Des-ArT	-764.92	0	0
	Des-MS	1135.86	0.18	0.49
African	Sav-TrF	37042.86	0.23	0.21
	MS-TrF	628.02	0.05	0.02
	Des-TrF	-11.68	0.05	0.01
	MS-Sav	1558.91	0.1	0.04
	Sav-Des	7857.71	0.23	0.09
	MS-Des	5430.44	0.22	0.15
Neotropical	TrF-TDF	26316.34	0.3	0.09
	TrF-SF	825.04	0.07	0.06
	TrF-TpF	-608.37	0	0.18
	TrF-Sav	23834.48	0.18	0.13
	TrF-TBG	-203.78	0.01	0
	TrF-MS	-285.54	0.03	0.04

Realm	Biome pair	Geographic Proximity (km)	Thermal Similarity	Moisture Similarity
Neotropical	TrF-Des	2482.72	0.15	0.02
	TDF-SF	-330.04	0.14	0.08
	TDF-TpF	-1294.67	0	0
	TDF-Sav	10031.12	0.43	0.56
	TDF-TBG	-899.17	0.02	0.05
	TDF-MS	-379.81	0.03	0.05
	TDF-Des	13029.96	0.24	0.29
	SF-TpF	-1493.96	0.01	0.01
	SF-Sav	11932.26	0.32	0.19
	SF-TBG	-206.44	0.03	0.01
	SF-MS	-1225.84	0.14	0.02
	SF-Des	-1147.73	0.14	0.04
	Sav-TpF	-270.14	0.01	0.01
	TBG-TpF	3171.77	0.26	0.01
	TpF-MS	1786.06	0.07	0.01
	Des-TpF	-721.31	0.02	0
	TBG-Sav	2465.56	0.12	0.07
	Sav-MS	-231.5	0.17	0.05
	Sav-Des	1290.09	0.17	0.19
	TBG-MS	-66.15	0.22	0.05
	TBG-Des	-575.56	0.06	0.11
	Des-MS	1063.94	0.4	0.09
Indo-Malesian	TrF-TDF	16694.97	0.39	0.12
	TrF-SF	3493.32	0.1	0.02
	SF-TDF	-306.79	0	0

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