Phylogenetic Biome Conservatism on a Global Scale

Supplementary information

Table of contents

Supplementary Results

Tests of biome conservatism

In transoceanic colonizations

To illustrate how we applied our null hypothesis, we observed 3.42 colonizations into Australia from forest elsewhere. As forest represents 2% of the Australian land mass, the expected number of colonizations of forest with no biome change equals 0.02 x 3.42 = 0.06. The observed number of such colonizations (forest to forest) was 2.42, exceeding the expectation, and was counted as a positive outcome for the sign test. Across all 226 observed colonizations, grouped by destination biomes (n = 28), there were 25 positive outcomes (Supplementary Table 3) and the result was significant ($P < 0.00001$), showing that biome stasis was more frequent than expected.

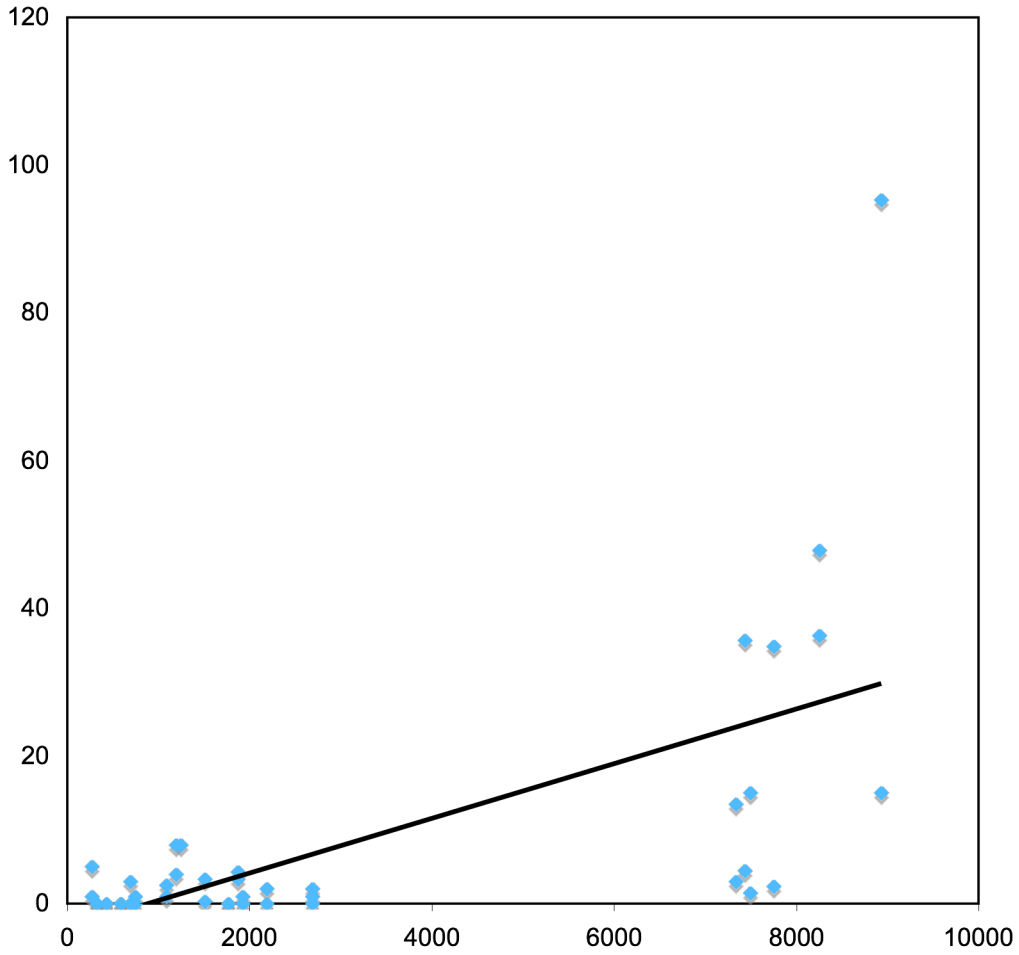
On individual taxa

The taxa tested were Araucariaceae, Asteraceae-*Craspedia*, Casuarinaceae, Droseraceae-*Drosera*, Fabaceae-Galegeae, Fabaceae-Mirbelieae, Fabaceae-*Senna*, Goodeniaceae-*Scaevola*, Myrtaceae-eucalypts (Supplementary Fig. 2), Orchidaceae-*Disa*, Pittosporaceae, Poaceae-Danthonioideae and Poaceae-*Ehrharta*. The null hypothesis was clearly rejected for all taxa ($P \leq 0.01$) except for *Craspedia*, which gave marginal significance ($P = 0.05$). *Nothofagus* was not tested because all species occur in a single biome (forest), and randomisation would have no effect. This case indicates a power limitation of this test because, clearly, *Nothofagus* represents an extreme example of biome conservatism, yet it is not amenable to the test.

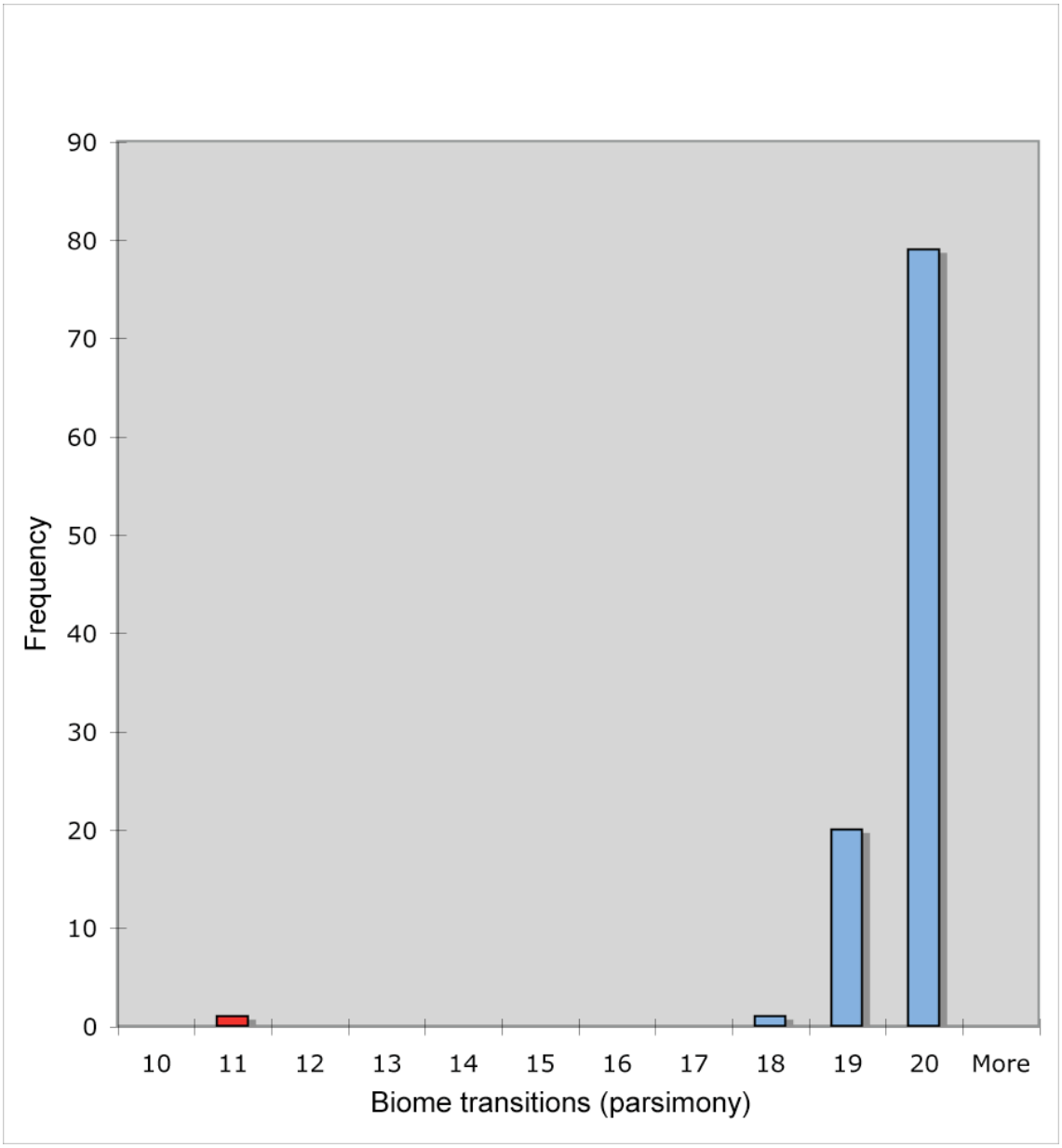
Tests of bias in biome shifts – effect of source richness

The initial test for bias indicated that sclerophyll was a net source, whilst all other biomes were net sinks, except forest, which showed no significant bias (Supplementary Table 1). However, there were large differences among biomes in the number of species we sampled (Fig. 1; Supplementary Table 2). It would be expected that these differences alone could account for bias in transitions: a richer source should contribute more colonists. As expected, there is a correlation between biome transitions and the richness of the source, which accounts for 41% of the variation (Supplementary Fig. 1). After correcting for the species richness effect (see Methods), values in Supplementary Table 1 were rescaled to yield those in Supplementary Table 2. When the tests for transition bias were repeated using the corrected scores, the principal change was that forest became a net source (Supplementary Table 2). Additionally, alpine, bog and grassland changed from net sinks to having no bias.

Supplementary Figures



Supplementary Figure 1 | Plot of number of biome shifts (*y*) against species richness of source (*x*) across all 36 pairwise combinations of biomes, in both directions (cf. Fig. 1). The linear relationship is $y = 0.0037x - 3.2401$ ($r^2 = 0.4112$).



Supplementary Figure 2 | Result of a test whether biome transitions in *Eucalyptus* were fewer than expected by chance. Red and blue bars show the biome transition frequencies respectively for the original phylogeny and 100 randomisations of its tips. Transitions were significantly fewer in the real data ($P \leq 0.01$). The tree topology and distribution of species in biomes were not perturbed by the randomisations.

Supplementary Tables

Supplementary Table 1 | Counts of within-continent biome transitions, with tests for directional bias between pairs.

Sink	Source									
	a[1]	b	f	g	h	m	s	Total	Prob[2]	Bias[3]
a		0	1	0	95.3[4]	4.3	1	101.6	< e-8	Sink
b	0		2.5	0	13.5	5	0	21	0.001	Sink
f	0	1		3.3	48.3	4	2	58.6	0.07 NS	None
g	2	0	0.3		34.8	0	0	37.1	0.00004	Sink
h	15	3	36.3	2.3		4.5	1.5	62.6	< e-8	Source
m	3	1	8	3	35.7		0	51	0.00003	Sink
s	0	0	8	1	15	0		24	0.0001	Sink
Total	20.3	5	56.1	9.6	242.6	17.8	4.5	355.9		

1. Biomes: a, arid; b, bog; f, wet forest; g, temperate grassland; h, sclerophyll; m, alpine; s, savannah. 2. Probability from binomial test; $P < 0.05$ indicates a significant bias. 3. Direction of bias, where significant. 4. Fractional values result from weighting to account for ambiguous reconstructions.

Supplementary Table 2 | Counts of within-continent biome transitions, corrected for biome richness by multiplying counts by (1-proportion of total richness) and rescaled to the original total.

	Source									
	a[1]	b	f	g	h	m	s	Total		
Richness[4]	1683	84	1005	504	7250	186	242	10955		
% of richness[5]	15.4	0.8	9.2	4.6	66.2	1.7	2.2	100		
Sink									Prob[2]	Bias[3]
a	-	0	2	0	62	8	2	73	0.002	Sink
b	0	-	4	0	9	9	0	22	0.052	None
f	0	2	-	6	31	8	4	50	0.0015	Source
g	3	0	1	-	23	0	0	26	0.138	None
h	24	6	63	4	-	8	3	109	0.007	Source
m	5	2	14	5	23	-	0	50	0.064	None
s	0	0	14	2	10	0	0	25	0.036	Sink
Total	33	9	98	18	157	33	8	356		

1. Biomes: a, arid; b, bog; f, wet forest; g, temperate grassland; h, sclerophyll; m, alpine; s, savannah. 2. Probability from binomial test; $P < 0.05$ indicates a significant bias. 3. Direction of bias, where significant. 4. Total species richness in biome. 5. Percentage proportion of total species richness.

Supplementary Table 3 | Test whether biome stasis associated with trans-oceanic colonization was more frequent than expected.

Destination biome	Colonizations from source biome (a)	Proportional area of destination biome (b)	Expected stases (a x b)	Observed stases	Sign test (*n* = 28, positives = 25, *P* = 0.0001)
AUSTRALIA					
Forest	3.42	0.02	0.06	2.42	+
Sclerophyll	5.67	0.28	1.61	2.33	+
Arid	1.00	0.65	0.65	1.00	+
Alpine	3.50	0.01	0.02	3.50	+
Grassland	2.67	0.00	0.00	2.00	+
Savannah	1.00	0.04	0.04	0.00	-
Bog	1.33	0.00	0.00	1.33	+
NEW ZEALAND					
Forest	17.33	0.84	14.56	16.33	+
Sclerophyll	75.67	0.05	3.78	60.00	+
Arid	1.00	0.00	0.00	0.00	NA
Alpine	8.50	0.09	0.76	7.50	+
Grassland	9.33	0.00	0.01	7.33	+
Savannah		0.00	0.00		NA
Bog	6.00	0.01	0.04	6.00	+

NEW CALEDONIA					
Forest	20.00	0.30	6.00	19.50	+
Sclerophyll	20.00	0.70	14.00	17.00	+
Arid		0.00	0.00		NA
Alpine		0.00	0.00		NA
Grassland		0.00	0.00		NA
Savannah		0.00	0.00		NA
Bog	1.00	0.00	0.00	1.00	+
AFRICA					
Forest	4.50	0.00	0.01	2.00	+
Sclerophyll	6.5	0.05	0.33	6.00	+
Arid		0.49	0.00		NA
Alpine		0.00	0.00		NA
Grassland	1.00	0.21	0.21	0.00	-
Savannah		0.25	0.00	0.00	NA
Bog	2.33	0.00	0.00	2.00	+
MADAGASCAR					
Forest	3.67	0.24	0.88	3.67	+
Sclerophyll	3.00	0.19	0.57	0.00	-
Arid		0.08	0.00		NA
Alpine		0.00	0.00		NA
Grassland	11.00	0.00	0.01	11.00	+

Savannah		0.48	0.00		NA
Bog		0.00	0.00		NA
SOUTH AMERICA					
Forest	6.92	0.43	2.98	6.92	+
Sclerophyll	2.67	0.03	0.08	1.00	+
Arid	1.00	0.21	0.21	1.00	+
Alpine	1.00	0.16	0.16	1.00	+
Grassland	2.33	0.15	0.35	2.33	+
Savannah		0.00	0.00		NA
Bog	3.00	0.01	0.04	3.00	+

Supplementary Table 4 | Taxa sampled (number of species) and references to data sources.

Taxon	References
Aizoaceae: Ruschioideae (1708)	39,40
Apiaceae: *Chaerophyllum* (12)	41,42
Araliaceae (109)	43,44,45
Araucariaceae: *Araucaria* (16)	46,47
Asteraceae: *Abrotanella* (18)	48,49
Asteraceae: Arctotidinae (62)	50
Asteraceae: *Chaetanthera* (48)	51
Asteraceae: *Craspedia* (23)	52
Atherospermataceae (15)	53,54
Boraginaceae: *Myosotis* (39)	55
Caryophyllaceae: *Scleranthus* (11)	56,57
Casuarinaceae (75)	24,58
Chenopodiaceae: Camphorosmeae (141)	59,60
Chenopodiaceae: Salicornioideae (55)	59,61
Colchicaceae: *Wurmbea* (41)	62,63,64
Coriariaceae + Corynocarpaceae (15)	65,66
Cunoniaceae + Elaeocarpaceae (360)	67,68,69,70
Cupressaceae: callitroids (35)	71,72,73,74
Cycadales: Zamiaceae (107)	73,75,76,77,78
Droseraceae: *Drosera* (140)	79,80

Ericaceae: Styphelioideae (558)	81,82,83,84
Fabaceae: astragaloids (164)	85,86,87,88,89
Fabaceae: mirbelioids (700)	64,90
Fabaceae: *Senna* (161)	89,91,92
Gnetales (14)	73
Goodeniaceae: *Scaevola* (77)	64,93
Haemodoraceae (74)	94,95
Iridaceae (1346)	96,97,98
Myrtaceae: *Eucalyptus* (865)	24,99,100
Nothofagaceae (36)	37,101,102
Onagraceae: *Fuchsia* (7)	103
Orchidaceae: *Disa* (147)	104
Orchidaceae: Diurideae (940)	105,106
Orchidaceae: Pterostylidinae (160)	107,108
Penaeaceae (31)	109
Pittosporaceae (141)	110,111
Plantaginaceae: *Ourisia* (31)	112
Poaceae: Danthonioideae (297)	113,114,115
Poaceae: *Ehrharta* (32)	116
Proteaceae (1684)	117,118,119,120
Ranunculaceae: *Caltha* (7)	121,122
Restionaceae, Centrolepidaceae, Anarthriaceae (510)	123

Solanaceae: *Schizanthus* (12)	124
Rhamnaceae: Colletieae (13)	125,126
Tropaeolaceae: *Tropaeolum* sect. *Chilensia* (22)	127

Supplementary Table 5 | Comparison of the numbers of biome transitions estimated by parsimony and maximum likelihood (MK1 model) for four data sets.

Taxon	Parsimony transitions	ML transitions
Casuarinaceae	15	12
Eucalyptus	11	11
Mirbelieae-Bossiaeeae	25	21
Scaevola	6	5

Supplementary Table 6 | Geological estimates of the times of separation of the land masses by continental drift.

	Australia	N. Zealand	S. Africa	S. America
N. Zealand	95/76	-	-	-
S. Africa	120/105	120/105	-	-
S. America	50/30	95/76	120/105	-
N. Caledonia	95/76 (35)	70/30	120/105	95/76

Numbers are in millions of years: the first number is the beginning of rifting and the second number is first separation by deep ocean.

Supplementary Notes

Supplementary References

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