Online Supplementary Material

Determinism and stochasticity in seed dispersal-successional feedbacks

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Appendix S1: Supplemental Methods Section

Statistical Analysis: Constructing seed rain community matrices

All analyses were performed in R statistical software (R Core Development Team, 2019). We constructed community matrices of the seed rain data in which each cell is the total number of all seeds of each species recorded in each trap in a plot, summed over the 24 monitoring months in a time period, separately for time periods 1997-1999 and 2015-2017 for a total of nine abundance community matrices. Based on the abundance matrices, we created incidence matrices (presence/absence of species within a trap). We used these matrices for all analyses. Although the seed rain in the mature forest was only quantified for time period 2015-2017, we assumed that the composition of the seed rain of the mature forest would be similar in 1997-1999 since no major disturbances or changes in forest structure have occurred to the mature forest plot. We therefore compared data from the successional plots in both time periods with the mature forest data collected in 2015-2017.

Using only successional plots at each time period (1997-1999 and 2015-2017), we determined species present during the 12 consecutive months at each time period. Also, using a generalized negative binomial model, where number of seeds was the response variable, trap and time periods were fixed factors and plot, month and species as random factors, we calculated which time period had higher species seed abundance by m^2. A similar model where plot and time period were fixed factors and, trap, month and species were random effects, calculated the species with highest and lowest abundance across all the successional plot.

Table S1. List of codes, scientific names, and family for all species in this study.

N	Code	Genus	Species	Family
1	Abemos	*Abelmoschus*	*moschatus*	Malvaceae
2	Abupan	*Abuta*	*panamensis*	Menispermaceae
3	Acahay	*Acacia*	*hayesii*	Leguminosae
4	Acaten	*Acacia*	*tenuifolia*	Leguminosae
5	Aegela	*Aegiphila*	*elata*	Lamiaceae
6	Albsp	*Albizia*	*sp*	Leguminosae
7	Alcflo	*Alchorneopsis*	*floribunda*	Euphorbiaceae
8	Allplu	*Allomarkgrafia*	*plumeriiflora*	Apocynaceae
9	Anacra	*Anaxagorea*	*crassipetala*	Annonaceae
10	Annpap	*Annona*	*papilionella*	Annonaceae
11	Annsp	*Annona*	*sp*	Annonaceae
12	Anoret	*Anomospermum*	*reticulatum*	Menispermaceae
13	Apemem	*Apeiba*	*membranacea*	Malvaceae
14	Ardfim	*Ardisia*	*fimbrillifera*	Primulaceae
15	Ardnig	*Ardisia*	*nigropunctata*	Primulaceae
16	Arispr	*Aristolochia*	*sprucei*	Aristolochiaceae
17	Arrflo	*Arrabidea*	*florida*	Bignoniaceae
18	Astcon	*Astrocaryum*	*confertum*	Arecaceae
19	Bachon	*Bactris*	*hondurensis*	Arecaceae
20	Balele	*Balizia*	*elegans*	Leguminosae
21	Bighya	*Bignonia*	*hyacinthina*	Bignoniaceae
22	Brolac	*Brosimum*	*lactescens*	Moraceae
23	Bunoce	*Bunchonsia*	*ocellata*	Malpighiaceae
24	Byrart	*Byrsonima*	*arthropoda*	Malpighiaceae
25	Byrcra	*Byrsonima*	*crassifolia*	Malpighiaceae
26	Calbra	*Calophyllum*	*brasiliense*	Clusiaceae
27	Casarb	*Casearia*	*arborea*	Salicaceae
28	Cedodo	*Cedrela*	*odorata*	Meliaceae
29	Cesspa	*Cespedesia*	*spathulata*	Ochnaceae
30	Chrnic	*Chrysochlamys*	*nicaraguensis*	Clusiaceae
31	Cismic	*Cissus*	*microcarpa*	Vitaceae
32	Cispse	*Cissus*	*pseudocyoides*	Vitaceae
33	Cissp	*Cissus*	*sp*	Vitaceae
34	Cistro	*Cissampelos*	*tropaeolifolia*	Menispermaceae
35	Cisver	*Cissus*	*verticillata*	Vitaceae
36	Commex	*Compsoneura*	*mexicana*	Myristicaceae
37	Conple	*Conceveiba*	*pleiostemona*	Euphorbiaceae
38	Corbic	*Cordia*	*bicolor*	Boraginaceae
39	Crywar	*Cryosophila*	*warscewiczii*	Arecaceae
40	Cucsp	*Cucurbitaceae*	*sp*	Cucurbitaceae
41	Cupgla	*Cupania*	*glabra*	Sapindaceae
42	Cupliv	*Cupania*	*livida*	Sapindaceae
43	Davkun	*Davila*	*kunthii*	Dilleniaceae
44	Davnit	*Davila*	*nitida*	Dilleniaceae
45	Denarb	*Dendropanax*	*arboreus*	Araliaceae
46	Dicamp	*Dicranostyles*	*ampla*	Convolvulaceae
47	Dilsp	*Dillacarapacea*	*sp*	Dillacarapaceae

48	Dolmul	*Doliocarpus*	*multiflorus*	Dilleniaceae
49	Dugsp	*Duguetia*	*sp*	Annonaceae
50	Eugsar	*Eugenia*	*sarapiquensis*	Myrtaceae
51	Eugsp	*Eugenia*	*sp*	Myrtaceae
52	Eutole	*Euterpe*	*oleracea*	Arecaceae
53	Eutpre	*Euterpe*	*precatoria*	Arecaceae
54	Fargla	*Faramea*	*glandulosa*	Rubiaceae
55	Farsp	*Faramea*	*sp*	Rubiaceae
56	Frisch	*Fridericia*	*schumanniana*	Bignoniaceae
57	Galsp	*Gallesia*	*sp*	Lauraceae
58	Geocon	*Geonoma*	*congesta*	Arecaceae
59	Goemei	*Goethalsia*	*meiantha*	Malvaceae
60	Goulup	*Gouania*	*lupuloides*	Rhamnaceae
61	Goupol	*Gouania*	*polygama*	Rhamnaceae
62	Guaaer	*Guatteria*	*aeruginosa*	Annonaceae
63	Guaamp	*Guatteria*	*amplifolia*	Annonaceae
64	Guadio	*Guatteria*	*diospyroides*	Annonaceae
65	Guagui	*Guarea*	*guidonia*	Meliaceae
66	Guarec	*Guatteria*	*recurvisepala*	Annonaceae
67	Hamapp	*Hampea*	*appendiculata*	Malvaceae
68	Heisca	*Heisteria*	*scandens*	Olacaceae
69	Helapp	*Heliocarpus*	*appendiculatus*	Malvaceae
70	Herdid	*Hernandia*	*didymantha*	Hernandiaceae
71	Hetsp	*Heteropteris*	*sp*	Malpighiaceae
72	Ilesku	*Ilex*	*skutchii*	Aquifoliaceae
73	Ingalb	*Inga*	*alba*	Leguminosae
74	Ingexa	*Inga*	*exalata*	Leguminosae
75	Ingoer	*Inga*	*oerstediana*	Leguminosae
76	Ingpun	*Inga*	*punctata*	Leguminosae
77	Ingsp	*Inga*	*sp*	Leguminosae
78	Ingthi	*Inga*	*thibaudiana*	Leguminosae
79	Ingumb	*Inga*	*umbellifera*	Leguminosae
80	Iridel	*Iriartea*	*deltoidea*	Arecaceae
81	Jaccop	*Jacaranda*	*copaia*	Bignoniaceae
82	Jubwil	*Jubelina*	*wilburii*	Malpighiaceae
83	Laepro	*Laetia*	*procera*	Salicaceae
84	Licmis	*Licaria*	*misantlae*	Lauraceae
85	Lozpit	*Lozania*	*pittieri*	Lacistemataceae
86	Mabocc	*Mabea*	*occidentalis*	Euphorbiaceae
87	Macsen	*Machaerium*	*senmani*	Leguminosae
88	Manhir	*Mandevilla*	*hirsuta*	Apocynaceae
89	Marnic	*Maripa*	*nicaraguensis*	Convolvulaceae
90	Mensp	*Mendoncia*	*sp*	Acanthaceae
91	Necmem	*Nectandra*	*membranacea*	Lauraceae
92	Ococer	*Ocotea*	*cernua*	Lauraceae
93	Ormsub	*Ormosia*	*subsimplex*	Leguminosae
94	Paslob	*Passiflora*	*lobata*	Passifloraceae
95	Paugra	*Paullinia*	*granatensis*	Sapindaceae
96	Paugrn	*Paullinia*	*grandifolia*	Sapindaceae
97	Pauing	*Paullinia*	*ingifolia*	Sapindaceae
98	Pauobo	*Paullinia*	*obovata*	Sapindaceae

99	Pausp	*Paullinia*	*sp*	Sapindaceae
100	Penmac	*Pentaclethra*	*macroloba*	Leguminosae
101	Phagui	*Phanera*	*guianensis*	Leguminosae
102	Phopul	*Pholidostachys*	*pulchra*	Arecaceae
103	Pincor	*Pinzona*	*coriacea*	Dilleniaceae
104	Pippoe	*Piptocarpha*	*poeppigiana*	Compositae
105	Plusti	*Plukenetia*	*stipellata*	Euphorbiaceae
106	Posgra	*Posoqueria*	*grandiflora*	Rubiaceae
107	Poubic	*Pourouma*	*bicolor*	Urticaceae
108	Poudur	*Pouteria*	*durlandii*	Sapotaceae
109	Poumin	*Pourouma*	*minor*	Urticaceae
110	Procos	*Protium*	*costaricense*	Burseraceae
111	Propan	*Protium*	*panamense*	Burseraceae
112	Propit	*Protium*	*pittieri*	Burseraceae
113	Prorav	*Protium*	*ravenii*	Burseraceae
114	Psybra	*Psychotria*	*brachiata*	Rubiaceae
115	Psyela	*Psychotria*	*elata*	Rubiaceae
116	Psymar	*Psychotria*	*marginata*	Rubiaceae
117	Psyoff	*Psychotria*	*officinalis*	Rubiaceae
118	Psypan	*Psychotria*	*panamensis*	Rubiaceae
119	Psyrac	*Psychotria*	*racemosa*	Rubiaceae
120	Psysue	*Psychotria*	*suerrensis*	Rubiaceae
121	Pteroh	*Pterocarpus*	*rohrii*	Leguminosae
122	Quaoch	*Quararibea*	*ochrocalyx*	Malvaceae
123	Ransp	*Randia*	*sp*	Rubiaceae
124	Reisp	*Reinhardtia*	*sp*	Arecaceae
125	Rhokun	*Rhodostemonodaphne*	*kunthiana*	Lauraceae
126	Rhyery	*Rhynchosia*	*erythrinoides*	Leguminosae
127	Ricdre	*Richeria*	*dressleri*	Phyllanthaceae
128	Rindef	*Rinorea*	*deflexiflora*	Violaceae
129	Rolpit	*Rollinia*	*pittieri*	Annonaceae
130	Rolsp	*Rollinia*	*sp*	Annonaceae
131	Ryaspe	*Ryania*	*speciosa*	Salicaceae
132	Sensp	*Senegalia*	*sp*	Leguminosae
133	Sergon	*Serjania*	*goniocarpa*	Sapindaceae
134	Serpyr	*Serjania*	*pyramidata*	Sapindaceae
135	Sersp	*Serjania*	*sp*	Sapindaceae
136	Simama	*Simarouba*	*amara*	Simaroubaceae
137	Sipthe	*Siparuna*	*thecaphora*	Siparunaceae
138	Smidom	*Smilax*	*domingensis*	Smilacaceae
139	Smimol	*Smilax*	*mollis*	Smilacaceae
140	Smipur	*Smilax*	*purhampuy*	Smilacaceae
141	Smisp	*Smilax*	*sp*	Smilacaceae
142	Socexo	*Socratea*	*exorrhiza*	Arecaceae
143	Solsp	*Solanum*	*sp*	Solanaceae
144	Spasp	*Spachea*	*sp*	Malpighiaceae
145	Stesp	*Stemmadenia*	*sp*	Apocynaceae
146	Strmic	*Stryphodendron*	*microstachyum*	Leguminosae
147	Stylin	*Stygmaphyllum*	*lindenianum*	Malpighiaceae
148	Swacos	*Swartzia*	*costaricensis*	Leguminosae
149	Taccos	*Tachigali*	*costaricensis*	Leguminosae

150	Tanpyr	*Tanaecium*	*pyramidatum*	Bignoniaceae
151	Tapgui	*Tapirira*	*guianensis*	Anacardiaceae
152	Terama	*Terminalia*	*amazonia*	Combretaceae
153	Tethyd	*Tetracera*	*hydrophila*	Dilleniaceae
154	Tetpan	*Tetragastris*	*panamensis*	Burseraceae
155	Thitom	*Thinouia*	*tomocarpa*	Sapindaceae
156	Triles	*Trichospermum*	*lessertianum*	Malvaceae
157	Trimex	*Trichospermum*	*mexicanum*	Malvaceae
158	Trisep	*Trichilia*	*septentrionalis*	Meliaceae
159	Troinv	*Trophis*	*involucrata*	Moraceae
160	Trorac	*Trophis*	*racemosa*	Moraceae
161	Unopit	*Unonopsis*	*pittieri*	Annonaceae
162	Unosp	*Unonopsis*	*sp*	Annonaceae
163	Virkos	*Virola*	*koschnyi*	Myristicaceae
164	Virseb	*Virola*	*sebifera*	Myristicaceae
165	Virsp	*Virola*	*sp*	Myristicaceae
166	Visbac	*Vismia*	*baccifera*	Hypericaceae
167	Visbil	*Vismia*	*billbergiana*	Hypericaceae
168	Vitcoo	*Vitex*	*cooperi*	Lamiaceae
169	Vocfer	*Vochysia*	*ferruginea*	Vochysiaceae
170	Vocgua	*Vochysia*	*guatemalensis*	Vochysiaceae
171	Vouano	*Vouarana*	*anomala*	Sapindaceae
172	Welreg	*Welfia*	*regia*	Arecaceae
173	Xylboc	*Xylopia*	*bocatorena*	Annonaceae
174	Xylser	*Xylopia*	*sericea*	Annonaceae
175	Xylsei	*Xylopia*	*sericophylla*	Annonaceae
176	Xylsp	*Xylosma*	*sp*	Salicaceae
177	Zanekm	*Zanthoxylum*	*ekmanii*	Rutaceae
178	Zansp	*Zanthoxylum*	*sp*	Rutaceae

Table S2. Comparisons of species composition of the seed rain across four successional and mature forest plots over two time periods in Sarapiquí, Costa Rica. Summary statistics are for post-hoc tests after a significant pMANOVA test between successional and mature forests at each time period (1997-1999 and 2015-2017), between successional forests at each of the two time periods, and within successional forests across the two time periods, based on Holm-Bonferroni pairwise comparisons. Successional forests plots were sampled over two time periods; time period 1, in 1997-1999 (A1-D1 forest plots) and time period 2 in 2015-2017 (A2-D2 forest plots), and the mature forest (M) was sampled only in 2015-2017. All the pairs of forest plots statistically different from each other, after adjustment for multiple comparisons, are in bold under the *p adj* column.

Successional vs. Mature Forest in 1997-1999			
Plots	***F***	***p***	***p adj***
A1 and M	10.27	0.001	**0.036**
B1 and M	11.68	0.001	**0.036**
C1 and M	10.98	0.001	**0.036**
D1 and M	10.55	0.001	**0.036**
Successional vs. Mature Forest in 2015-2017			
Plots	***F***	***p***	***p adj***
B2 and M	3.08	0.002	**0.036**
C2 and M	2.75	0.009	**0.039**
D2 and M	2.57	0.019	**0.041**
A2 and M	9.64	0.001	**0.036**
Across successional forests in 1997-1999			
Plots	***F***	***p***	***p adj***
A1 and B1	5.56	0.002	**0.039**
B1 and C1	5.28	0.001	**0.036**
B1 and D1	3.96	0.002	**0.038**
C1 and D1	4.12	0.001	**0.036**
Across successional forests in 2015-2017			
Plots	***F***	***p***	***p adj***
A2 and B2	7.54	0.001	**0.036**

B2 and C2	2.86	0.004	**0.037**
B2 and D2	2.18	0.003	**0.036**
C2 and D2	2.18	0.052	0.067
Within successional forests between 1997-1999 vs. 2015-2017			
Plot	***F***	***p***	***p adj***
A1 and A2	9.88	0.001	**0.036**
B1 and B2	9.05	0.001	**0.036**
C1 and C2	3.24	0.024	**0.044**
D1 and D2	6.86	0.001	**0.036**

Table S3. Percentage and number of observed and shared species present in the seed rain in forests of different successional ages compared with mature forest in Sarapiquí, Costa Rica. For forest successional age, A1, B1, C1, D1 and A2, B2, C2, D2 represent the 1997-1999 and 2015-2017 time periods, respectively. Values inside parenthesis reflect the age of the successional forest at 1997 and 2017. *Total no. species* is the number of species present in the seed rain. *Unique species No. (%)* is the number and percentage of species respectively that are unique in the seed rain. *All species No. (%)* is the total number and percentage of species respectively which are present in the seed rain. *Shared species No. (%)* is the total number and percentage of species respectively which are present in both the successional and the mature forest. All percentages are calculated based on the total number of species.

Forest successional age	Total no. species	Successional forests	Mature Forest		Shared species No. (%)
		Unique species No. (%)	All species No. (%)	Unique species No. (%)	
A1 (12)	86	35 (41%)	51 (59%)	35 (41%)	16 (18%)
B1 (15)	90	39 (43%)	51 (57%)	42 (47%)	9 (10%)
C1 (20)	88	37 (42%)	51 (58%)	36 (41%)	15 (17%)
D1 (25)	87	36 (41%)	51 (59%)	38 (44%)	13 (15%)
A2 (32)	70	19 (27%)	51 (73%)	23 (33%)	28 (40%)
B2 (35)	71	20 (28%)	51 (72%)	39 (55%)	12 (17%)
C2 (40)	69	18 (26%)	51 (74%)	31 (45%)	20 (29%)
D2 (45)	67	16 (24%)	51 (76%)	34 (51%)	17 (25%)

Figure S1. Map of the study region in Sarapiquí, Costa Rica, showing the locations of the five forest plots of different successional ages (A-D; red dots) and the mature forest (M; blue dot). Successional plots were sampled in two time periods, 1997-1999 with plot ages varying from 12 to 25 in 1997 and 2015-2017 with plots ages varying from 32 to 45 years old in 2017. The mature forest was sampled only in 2015-2017. See Table 1 in the main text for the details for each forest plot. The map was constructed using the *get_map* function in the ggmap package (Kahle and Wickham 2013).

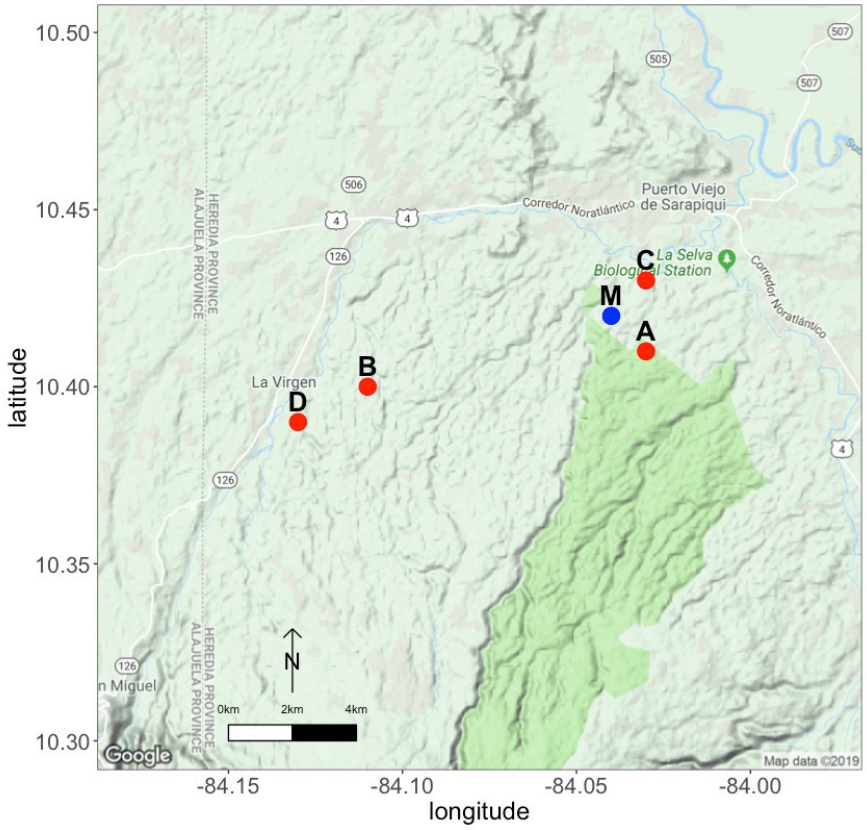
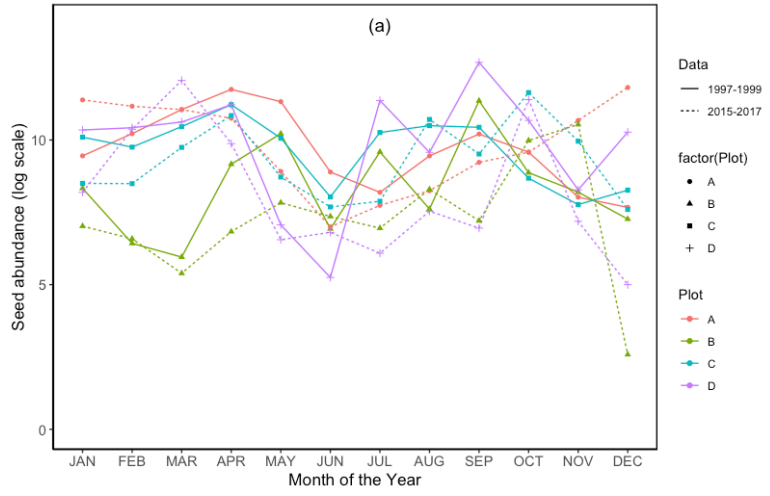


Figure S2. (a) Variation in the seed rain across four successional forest plots by months over two time periods in Sarapiquí, Costa Rica. Successional plots were sampled in two time periods, 1997-1999 (A-D) with plot ages varying from 12 to 25 in 1997 and 2015-2017 (A-D) with plots ages varying from 32 to 45 years old in 2017 (Table 1). Different colors represent the different forest plots; the 1997-1999 and 2015-2017 data are represented by a continuous and a dotted line, respectively. (b) Differences in average abundance of seeds rain across four successional forest plots and at two time periods (1997 – 1999 in red and 2015 – 2017 in blue) in Sarapiquí, Costa Rica, after controlling for variation in seed abundance by species. See Table 1 in the main text for details about each forest plot.



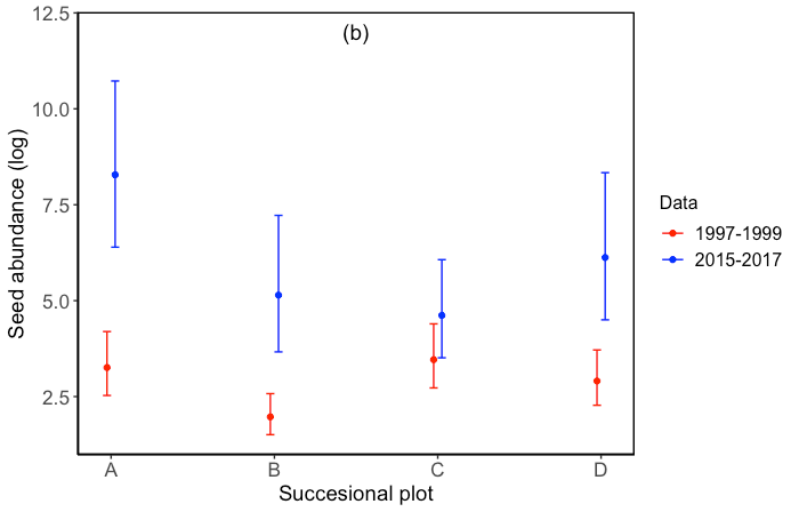


Figure S3. Abundance of woody species in the seed rain summed across four secondary forest plots in Sarapiquí, Costa Rica. The figure shows the 32 species that are higher or lower than the average seed abundance across all species. Nine species were significantly lower in abundance, and 23 species were higher in abundance, than the mean abundance across all species. Species abbreviations correspond to the first three letters of the genus and species (Table S1).

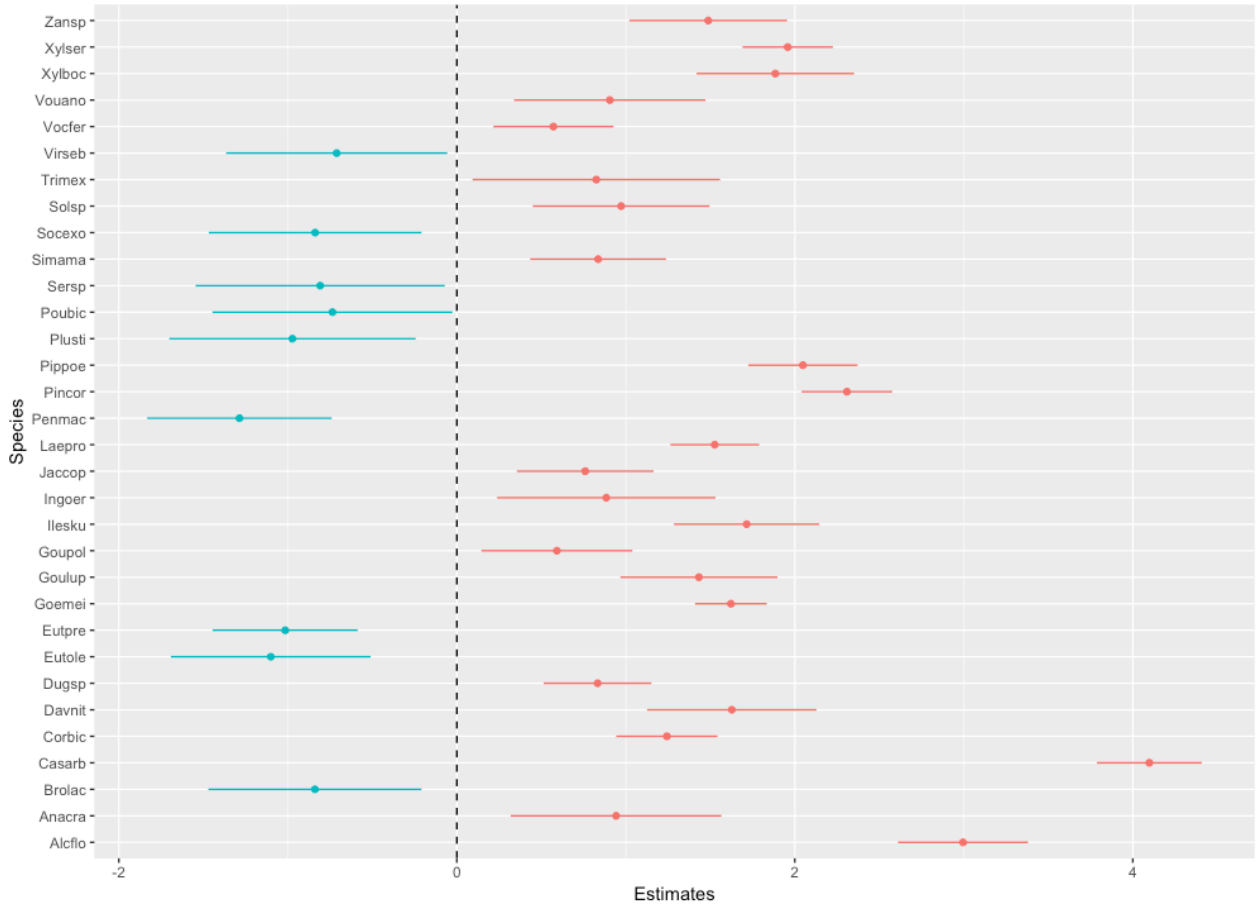


Figure S4. Abundance of seed rain across all secondary forests plots for species represented in seed traps continuously during all twelve months during 1997-1999 (top panel) and 2015-2017 (bottom panel) in Sarapiquí, Costa Rica. Species in 1997-1999 are light-demanding lianas (*Aristolochia sprucei* and *Pinzona coriacea*) or light-demanding tree species (*Cordia bicolor* and *Zanthoxylum sp*). Species in 2015-2017 are two shade tolerant palms (*Euterpe precatoria* and *Welfia regia*) and two light-demanding trees (*Goethalsia meiantha* and *Laetia procera*). Species abbreviations correspond to the first three letters of the genus and species (Table S1). See Table 1 in the main text for details about the successional forest plots.

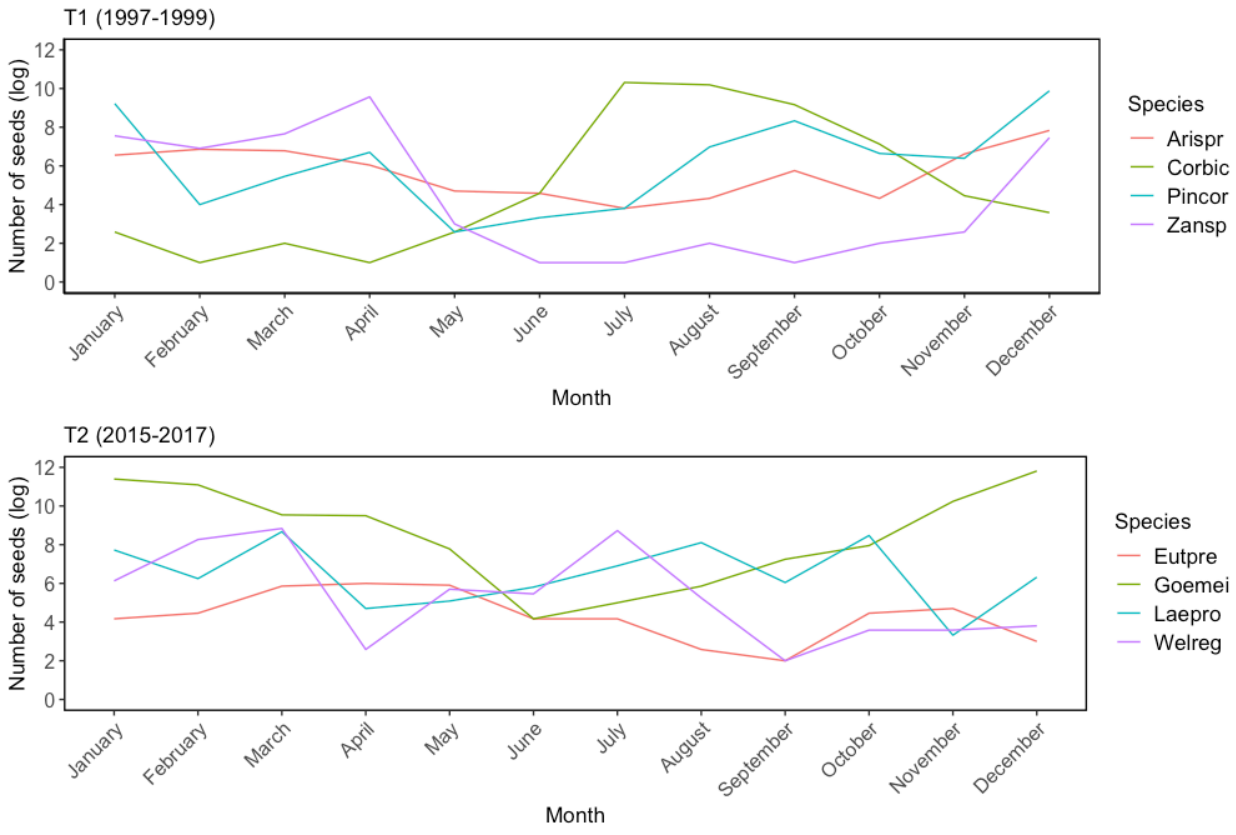


Figure S5. Null distributions of expected random Schoener's (*Cij*) co-occurrence indexes for species in successional vs mature forest plots, compared to the observed value, for each plot of different successional age. A1, B1, C1, D1 and A2, B2, C2, D2 represent successional plots in the 1997-1999 and 2015-2017 time periods, respectively. The red line represents the observed value, and the blue line is the mean, and the dotted blue lines are the 2.5th and 97.5th quantiles, of the null distribution. The standardized effect size of the co-occurrence index was calculated as the deviation of the observed value from the mean of the null distribution divided by the standard deviation of the null distribution.

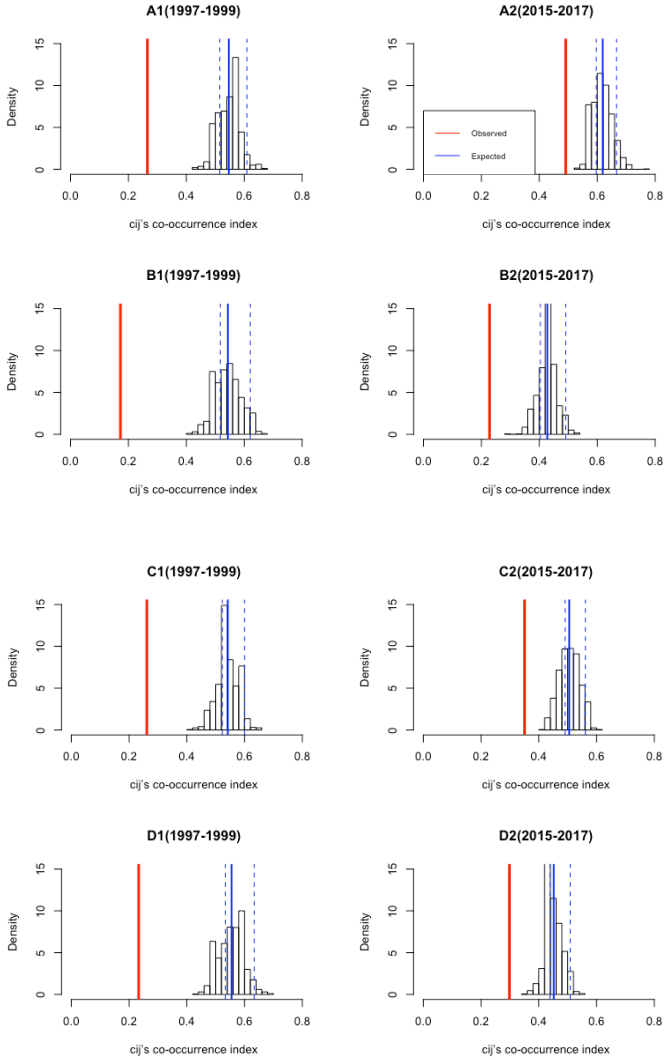


Figure S6. Species accumulation curves based on rarefaction of the seed rain in four successional (A-D) and mature (M) forest plots in Sarapiquí, Costa Rica. Successional plots were sampled in 1997-1999 (A1-D1 in red) and 2015-2017 (A2-D2 in blue), and the mature forest (M in black) was sampled only in 2015-2017. Plot successional ages: A1 = 12 B1 = 15, C1 = 20, D1 = 25, A2 = 32, B2 = 35, C2 = 40, and D2 = 45 years old. (a) small seeds (≤ 6 mm) and (b) large seeds (> 6 mm); (c) seeds of light demanding and (d) species shade tolerant species; (e) seeds of non-animal dispersed and (f) animal-dispersed species.

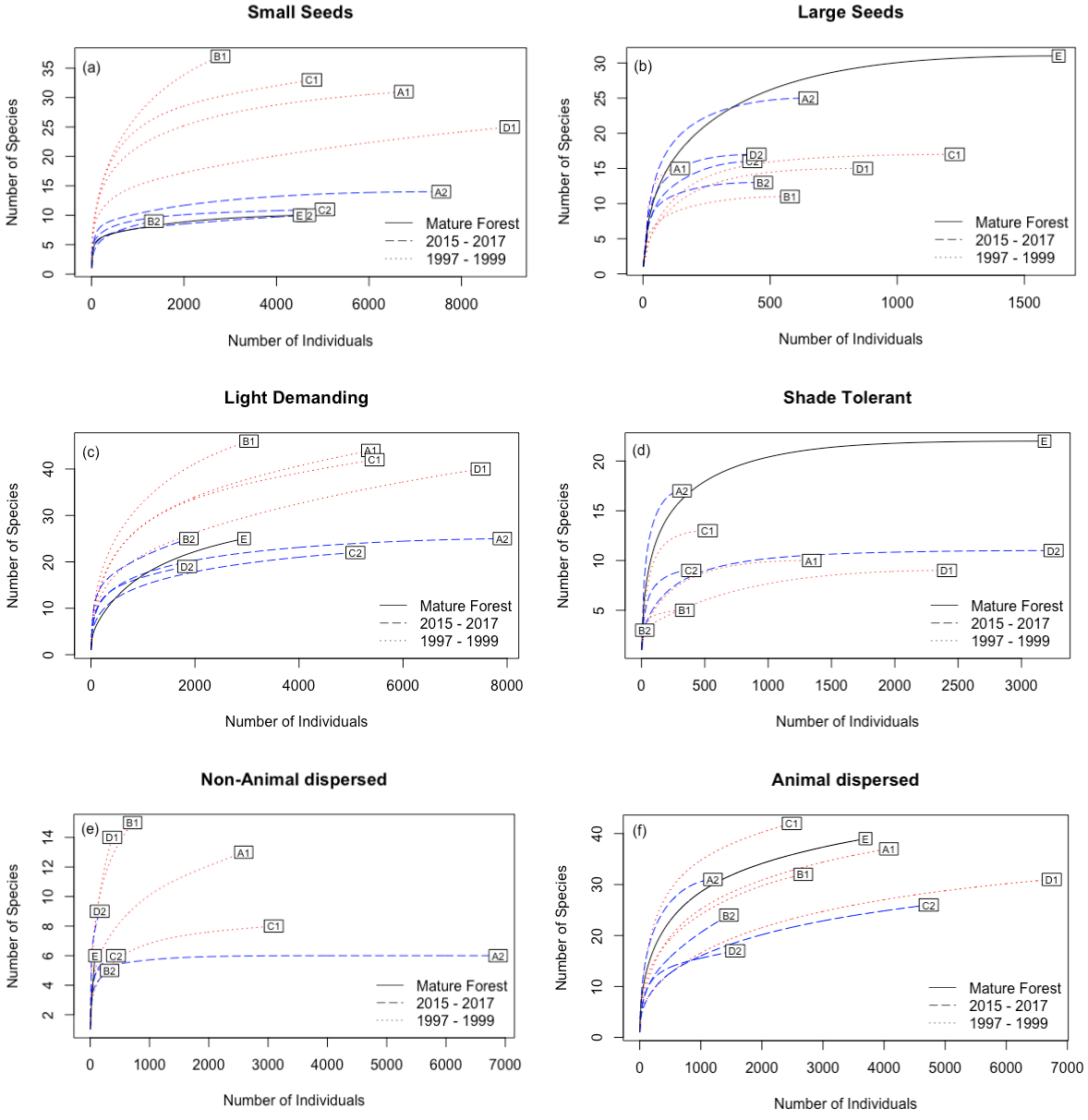
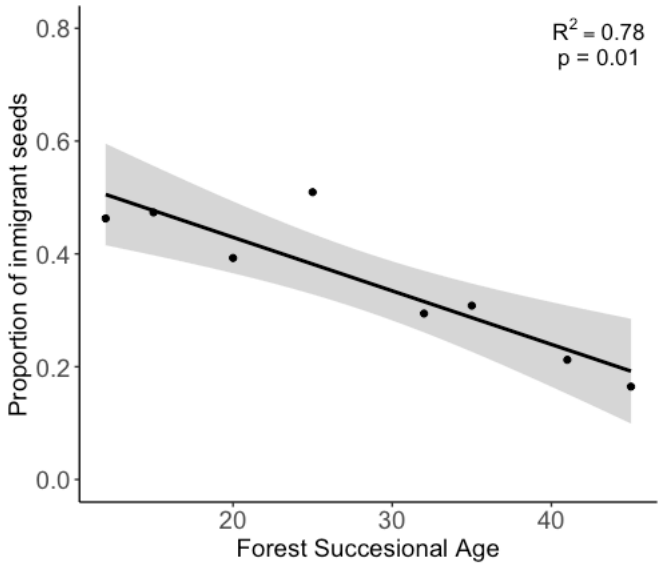


Figure S7. Decreasing proportion of immigrant seeds in secondary forests of increasing successional age in Sarapiquí, Costa Rica. The black line is the best fit line from ordinary least squares regression, and the gray shading indicates the confidence interval on the fit.



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