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 Spatial patterns of sapling mortality in a moist tropical
 forest: consistency with total density-dependent effects.
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Appendix 1

Estimation of conspecific density-dependent mortality at community and light-guild levels

The analysis of conspecific DDM uses the following data structure: each sapling present at the beginning of the study period is characterized by its coordinates, its status at the end of the study interval (i.e. type = surviving or dead) and its species identity $s = 1, 2, \dots, S$. Thus, in comparison with the data structure used for assessment of total DDM we used additionally the species identity s . This information is needed for two purposes. First, the estimators of the test statistic $DDM(r)$ consider only pairs of points composed of conspecifics whereas the estimators for the analogous analyses of total DDM used con- and heterospecific pairs. Second, the mortality rate of each species is conserved whereas the analysis of total DDM does not differentiate between con- and heterospecifics and therefore randomizes mortality among all individuals based on the total mortality rate.

To estimate the neighbourhood density $O_{ij}(r) = \lambda_i g_{ij}(r)$ of type j points around type i points needed in Eq. 1 we use an estimator recommended in Illian et al. (2008). This estimator counts basically the average number of type j points that are located within the observation window W and are at distance $r \pm dr / 2$ of type i points (i.e. within a ring with radius r and width dr centred in type i points), and divides this by the average area of the rings taken over all type i points. More formally this yields (Wiegand and Moloney 2014: their equation 3.118):

$$\hat{O}_{ij}(r) = \frac{\frac{1}{n_i} \sum_{o=1}^{n_i} \left(\sum_{p=1}^{n_j, \neq} k^{dr} (\|\mathbf{x}_o^i - \mathbf{x}_p^j\| - r) \right)}{\frac{1}{n_i} \sum_{o=1}^n \nu_{d-1}(W \cap \partial b(\mathbf{x}_o^i, r)) dr} = \frac{\sum_{o=1}^{n_i} \left(\sum_{p=1}^{n_j, \neq} k^{dr} (\|\mathbf{x}_o^i - \mathbf{x}_p^j\| - r) \right)}{\sum_{o=1}^n \nu_{d-1}(W \cap \partial b(\mathbf{x}_o^i, r)) dr} \quad (\text{A1})$$

where the denominator contains the quantity $\nu_{d-1}(W \cap \partial b(\mathbf{x}_o^i, r))$ which is the part of the length of the circumference of a circle with radius r around point \mathbf{x}_o^i that is located in W and the numerator contains the kernel function $k^{dr}(\|\mathbf{x}_o^i - \mathbf{x}_p^j\| - r)$ which yields a value of one if points \mathbf{x}_p^j is located at distance $r \pm dr / 2$ of points \mathbf{x}_o^i . The focal type i points are indexed with index $o = 1, \dots, n_i$ and the

counted type j points are indexed with index $p = 1, \dots, n_j$. The second part of Eq. A1 shows that this estimator basically adds up the number of type j points around each focal point i (enumerator) and adds up the area of the corresponding circles around the type i points (denominator).

If we name the number of type j points located in the ring $R_o^i(r)$ around type i point \mathbf{x}_o^i

Points $_j[R_o^i(r)]$ and the corresponding area **Area** $[R_o^i(r)]$:

$$\mathbf{Points}_j[R_o^i(r)] = \sum_{p=1}^{n_j, \neq} k^{dr} (\|\mathbf{x}_o^i - \mathbf{x}_p^j\| - r) \quad (\text{A2})$$

$$\mathbf{Area}[R_o^i(r)] = \nu_{d-1}(W \cap \partial b(\mathbf{x}_o^i, r)) dr \quad (\text{A3})$$

we can rewrite Eq. A1 to:

$$\hat{O}_{ij}(r) = \frac{\sum_{o=1}^{n_i} \mathbf{Points}_j[R_o^i(r)]}{\sum_{o=1}^{n_i} \mathbf{Area}[R_o^i(r)]} \quad (\text{A4})$$

The operator **Points** $_j[X]$ counts the number of points of type j inside an area X , and the operator **Area** $[X]$ determines the area of X . Now we order the o - p point pairs into con- and heterospecific pairs:

$$\hat{O}_{ij}(r) = \frac{\left(\sum_{o=1}^{n_i} C_{11}(\mathbf{x}_o^i, \mathbf{x}_p^j) \mathbf{Points}_j[R_o^i(r)] + \mathbf{mix} \right) + \dots + \left(\sum_{o=1}^{n_i} C_S(\mathbf{x}_o^i, \mathbf{x}_p^j) \mathbf{Points}_j[R_o^i(r)] + \mathbf{mix} \right)}{\sum_{o=1}^{n_i} C_1(\mathbf{x}_o^i) \mathbf{Area}[R_o^i(r)] + \dots + \sum_{o=1}^{n_i} C_S(\mathbf{x}_o^i) \mathbf{Area}[R_o^i(r)]} \quad (\text{A5})$$

where the enumerator terms $C_{ss}(\mathbf{x}_o^i, \mathbf{x}_p^j) \mathbf{Points}_j[R_o^i(r)]$ contains all conspecific o - p pairs of species s and **mix** contains all other heterospecific o - p pairs. The function $C_{ss}(\mathbf{x}_o^i, \mathbf{x}_p^j)$ thus yields a value of one if both points \mathbf{x}_o^i and \mathbf{x}_p^j are of species s and zero otherwise. Similarly, the function $C_s(\mathbf{x}_o^i)$ yields a value of 1 if the focal point \mathbf{x}_o^i is of species s . The estimator of the neighbourhood used for analysis of conspecific density dependence omits the heterospecific pairs **mix** and uses only conspecific pairs:

$$\hat{O}_{ij}^{con}(r) = \frac{\overbrace{\left(\sum_{o=1}^{n_i} C_{11}(\mathbf{x}_o^i, \mathbf{x}_p^j) \mathbf{Points}_j[R_o^i(r)] \right)}^{\text{species 1}} + \dots + \overbrace{\left(\sum_{o=1}^{n_i} C_S(\mathbf{x}_o^i, \mathbf{x}_p^j) \mathbf{Points}_j[R_o^i(r)] \right)}^{\text{species S}}}{\underbrace{\sum_{o=1}^{n_i} C_1(\mathbf{x}_o^i) \mathbf{Area}[R_o^i(r)]}_{\text{species 1}} + \dots + \underbrace{\sum_{o=1}^{n_i} C_S(\mathbf{x}_o^i) \mathbf{Area}[R_o^i(r)]}_{\text{species S}}} \quad (\text{A6})$$

The estimator of Eq. A6 is equivalent to the case where we first estimate the neighbourhood density for all species s :

$$\hat{O}_{ij}(r) = \frac{\sum_{o=1}^{n_i} C_{ss}(\mathbf{x}_o^i, \mathbf{x}_p^j) \mathbf{Points}_j[R_o^i(r)]}{\sum_{o=1}^{n_i} C_s(\mathbf{x}_o^i) \mathbf{Area}[R_o^i(r)]}, \quad (\text{A7})$$

and treat them formally as ‘replicates’. We then can apply the estimator for replicate patterns shown in Wiegand and Moloney (2014: their equations 3.107 and 3.114). Thus, to estimate the conspecific neighbourhood density $\hat{O}_{ij}^{con}(r)$ of Eq. A6 we can first conduct random labelling for each species s and then use the techniques of replicate patterns presented in Wiegand and Moloney (2014) to estimate the $\hat{O}_{ij}^{con}(r)$ (i.e. conspecific density-dependent mortality) at the community or light-guild level.

References

Illian, J. et al. 2008. Statistical analysis and modelling of spatial point patterns. – Wiley.

Table A1. Species showing significant density dependent mortality among saplings (i.e. individuals with 1–4 diameter at breast height) in the forest dynamic plot of Barro Colorado Island (Panama), during inter-census periods 1982–1985 to 2005–2010, and during the entire 27-year period considered (1982–2010). Data presented are; number of dead (n_1), surviving (n_2) and total saplings (n_{1+2}), range of spatial neighbourhoods of radius r at which spatial patterns indicative of density dependence mortality (i.e. significant positive deviations of the values of the test statistic $g_{1,1+2}(r) - g_{2,1+2}(r)$ from the random null model of random mortality), were observed. Goodness-of-fit test (Gof) of the analyses are shown together with their significance level (* $p < 0.005$), according to Rice’s correction. Abundance class ($<10^2$, 10^2-10^3 , 10^3-10^4 , $>10^4$) and light-guild (i.e. light-demanding, intermediate, shade-tolerant and unclassified) of the species, are also indicated.

Species	Inter-census period	n_1	n_2	n_{1+2}	Spatial neighbourhoods of radius r (m)	Gof	Abundance class	Shade-tolerance guild
<i>Alibertia edulis</i>	1985–1990	16	269	285	0–1, 11, 16, 22–23, 28–29, 36, 49 m	200*	10^2-10^3	shade-tolerant
<i>Anaxagorea panamensis</i>	1982–1985	58	401	459	0–18 m	200*	10^2-10^3	unclassified
	2000–2005	29	285	314	2–14 m	200*	10^2-10^3	unclassified
	2005–2010	74	669	743	4–14, 22–24 m	200*	10^2-10^3	unclassified
<i>Aspidosperma spruceanum</i>	1985–1990	13	332	345	0–1, 5–9, 17, 16–28, 33, 39–40, 44–47 m	200*	10^2-10^3	shade-tolerant
	1995–2000	17	320	337	1–4, 10–15, 21–22 m	200*	10^2-10^3	shade-tolerant
<i>Beilschmiedia pendula</i>	1990–1995	212	1862	2074	0–1.5 m	200*	10^3-10^4	intermediate
<i>Capparis frondosa</i>	1982–1985	91	3111	3202	0–50 m	200*	10^3-10^4	unclassified
<i>Cecropia insignis</i>	2005–2010	441	76	517	0–5, 8–10, 15–17, 15–19, 14–16, 48–50 m	200*	10^2-10^3	gap
<i>Chamguava schippii</i>	1985–1990	11	184	195	0–16 m	200*	10^2-10^3	shade-tolerant
	2000–2005	20	290	310	0–1, 3–6, 9–11, 18, 22–30, 32–34, 38–40 m	200*	10^2-10^3	shade-tolerant
<i>Coussarea curvigemma</i>	1982–1985	26	1066	1092	0–50 m	200*	10^3-10^4	shade-tolerant
	1990–1995	66	1354	1420	10–50 m	200*	10^3-10^4	shade-tolerant

	1995–2000	111	1350	1461	0–10, 13–50 m	200*	10^3 – 10^4	shade-tolerant
	2000–2005	126	1344	1470	6–9, 14–32, 35–40, 42–43, 46–50 m	200*	10^3 – 10^4	shade-tolerant
	2005–2010	147	1302	1449	4–6, 10–50 m	200*	10^3 – 10^4	shade-tolerant
<i>Croton billbergianus</i> subsp. <i>Billbergianus</i>	1990–1995	482	222	704	0–14, 16–23 m	200*	10^2 – 10^3	gap
<i>Drypetes standleyi</i>	1990–1995	107	1295	1402	0–9 m	199*	10^3 – 10^4	shade-tolerant
<i>Faramea occidentalis</i>	1985–1990	619	15062	15681	11–13, 17–36, 39–40, 43–50 m	200*	$>10^4$	shade-tolerant
	1995–2000	903	15138	16041	0–50 m	200*	$>10^4$	shade-tolerant
<i>Hampea appendiculata</i>	2005–2010	56	51	107	0–2, 7–8, 12, 27–19, 49–50 m	200*	10^2 – 10^3	intermediate
<i>Mouriri myrtilloides</i> subsp. <i>Parvifolia</i>	1985–1990	1040	6457	7497	0–50 m	200*	10^3 – 10^4	unclassified
	2000–2005	777	5496	6273	0–1, 6–10, 14–18, 20–37, 39–50 m	200*	10^3 – 10^4	unclassified
<i>Piper cordulatum</i>	1985–1990	1277	2428	3705	0–9, 12–15, 25–50 m	200*	10^3 – 10^4	unclassified
<i>Prioria copaiifera</i>	2005–2010	35	555	590	1–3, 9–12 m	200*	10^2 – 10^3	shade-tolerant
<i>Protium costaricense</i>	1985–1990	64	470	534	0–1 m	200*	10^2 – 10^3	shade-tolerant
<i>Psychotria deflexa</i>	1982–1985	27	61	88	0–4, 9, 31 m	200*	$<10^2$	unclassified
<i>Psychotria marginata</i>	1990–1995	172	516	688	0–4, 8–26 m	200*	10^2 – 10^3	unclassified
<i>Simarouba amara</i>	2000–2005	208	483	691	0–18 m	200*	10^2 – 10^3	intermediate
<i>Siparuna pauciflora</i>	1985–1990	27	171	198	0–1 m	192*	10^2 – 10^3	shade-tolerant
<i>Tachigali versicolor</i>	1985–1990	400	2174	2574	0–3, 8–13, 24–25, 29–39, 48–50 m	200*	10^3 – 10^4	shade-tolerant
	1995–2000	641	1824	2465	0–3, 7–8, 12, 29–31, 38–42, 47 m	200*	10^3 – 10^4	shade-tolerant
<i>Tetragastris panamensis</i>	2005–2010	324	3083	3407	0–25, 27–34, 37–45 m	200*	10^3 – 10^4	shade-tolerant
<i>Trophis racemosa</i>	1995–2000	24	190	214	0–6 m	200*	10^2 – 10^3	shade-tolerant
<i>Xylopia macrantha</i>	1995–2000	41	625	666	0–1, 3–6, 10–21, 23–40, 42–44, 46–50 m	200*	10^2 – 10^3	shade-tolerant

Table A2. Results of the linear regressions to study the relationship between the number of saplings and the effect sizes in those species showing significant negative density dependence. Adjusted R^2 in the different inter-census periods and in the entire 27-year period (1982–2010), at spatial neighbourhoods of radius $r = 5, 15$ and 30-m are shown. Asterisks indicate the statistical significance of each variable in the test; ** $p < 0.001$; * $p < 0.05$; ns, non-significant

Period	1982–1985	1985–1990	1990–1995	1995–2000	2000–2005	2005–2010	1982–2010
Effect size							
5-m	-0.33	0.22	0.01	-0.01	-0.24	0.61*	0.03
15-m	-0.06	0.08	-0.01	0.17	0.20	0.33	0.02
30-m	0.19	0.13	0.32	0.54*	0.08	0.24	0.08

Table A3. Mean, and minimum and maximum absolute values of the effect sizes $DDM^{ses}(r)$ at the entire range of spatial neighbourhoods considered ($r = 0-50$ m) for total and conspecific density-dependent mortality (DDM) at community and light-guild levels, over the six inter-census periods and the entire period (1982–2010) considered. Maximum absolute values are used as a measure of the strength of density-dependent mortality, whereas minimum absolute values are used as a measure of the strength of density-dependent survival.

		Community-level			Light-guild level					
		All			Light-demanding			Shade-tolerant		
		Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
Total DDM	1982–1985	-1.19	-4.21	2.56	4.59	-0.43	13.03	1.99	-1.17	4.44
	1985–1990	6.86	4.26	12.21	3.69	-2.05	15.62	3.70	-0.32	5.39
	1990–1995	5.57	3.78	6.78	8.09	0.52	20.25	2.12	-0.20	4.69
	1995–2000	1.58	-3.05	5.77	2.75	-1.72	10.69	3.71	1.92	6.14
	2000–2005	1.58	-2.93	9.74	3.23	-3.26	15.35	0.49	-2.74	3.45
	2005–2010	0.55	-4.80	8.97	6.88	-1.22	22.55	1.15	-0.80	2.82
	1982–2010	9.73	3.15	12.67	4.01	1.17	9.50	6.84	4.97	9.13
Conspecific DDM	1982–1985	-0.26	5.96	6.67	-0.01	-3.42	3.68	-0.28	-5.96	4.23
	1985–1990	0.13	-3.97	9.60	0.12	-2.86	4.03	0.07	-3.97	6.03
	1990–1995	1.10	-13.1	6.25	-0.09	-2.80	5.00	0.15	-3.60	5.32
	1995–2000	0.05	-6.44	6.48	0.14	-2.29	3.01	0.09	-3.26	6.08
	2000–2005	0.04	-5.45	6.60	0.15	-3.63	4.06	0.09	-3.99	6.60
	2005–2010	0.13	-5.45	5.44	0.38	-2.54	5.44	0.10	-3.74	4.93
	1982–2010	0.29	-7.85	6.17	0.31	-3.19	5.70	0.35	-4.34	6.17

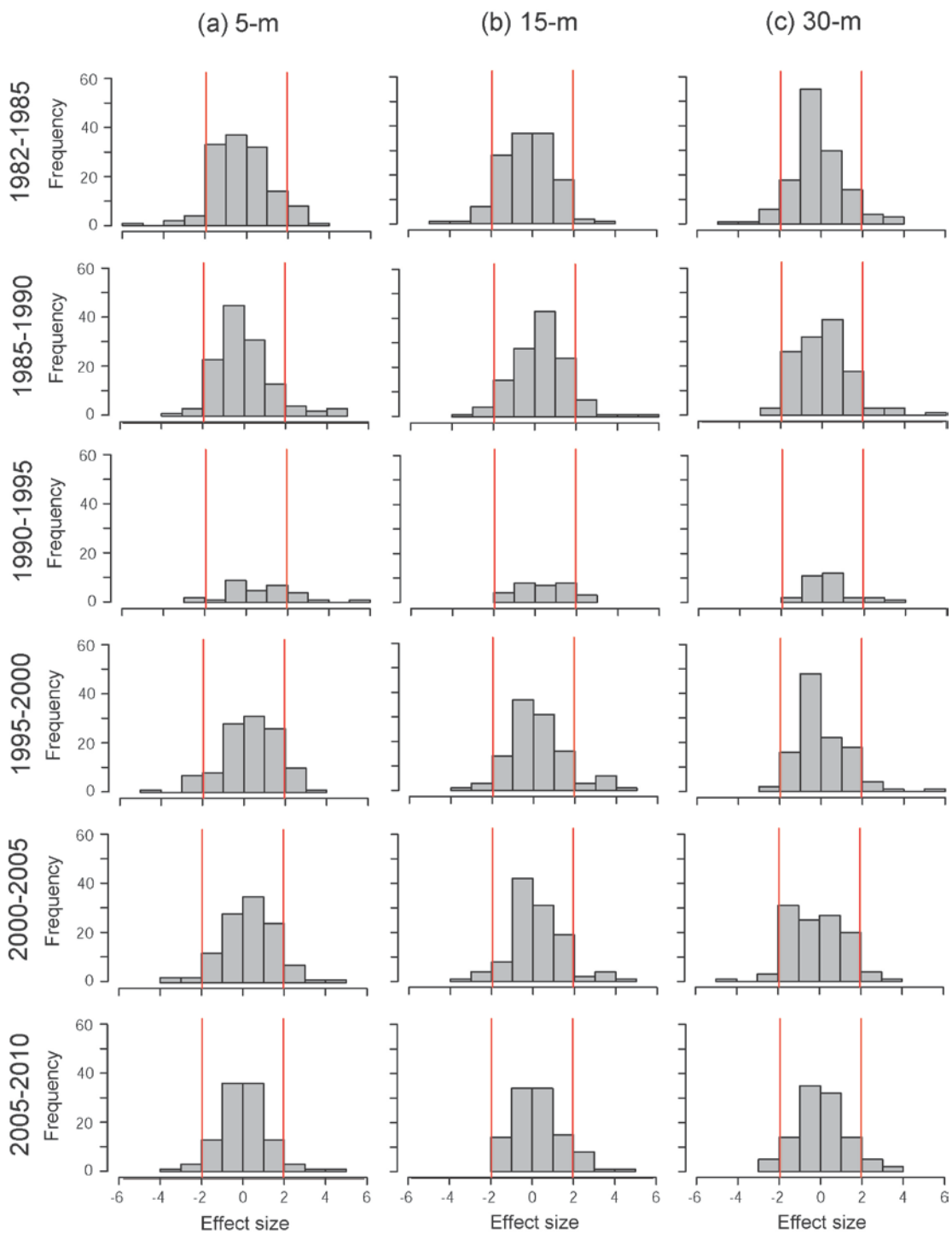


Figure A1. Frequency histograms indicating the distribution of the values of the effect sizes $DDM^{ses}(r)$ of the analysis of conspecific density dependent mortality in the different inter-census periods, at spatial neighbourhoods of radius $r = 5$ (a), 15 (b) and 30 (b) m. Columns indicate the frequencies (%) of species showing effect sizes of different magnitude (-6 to 6). Vertical redlines indicate the range $(-1.96, 1.96)$ where the effect size is not significant at a 5% confidence level. Effect sizes < -1.96 (black columns) indicate significant ($p < 0.05$) density dependent mortality effects. Effect sizes > -1.96 (white columns) indicate significant ($p < 0.05$) density dependent survival effects.

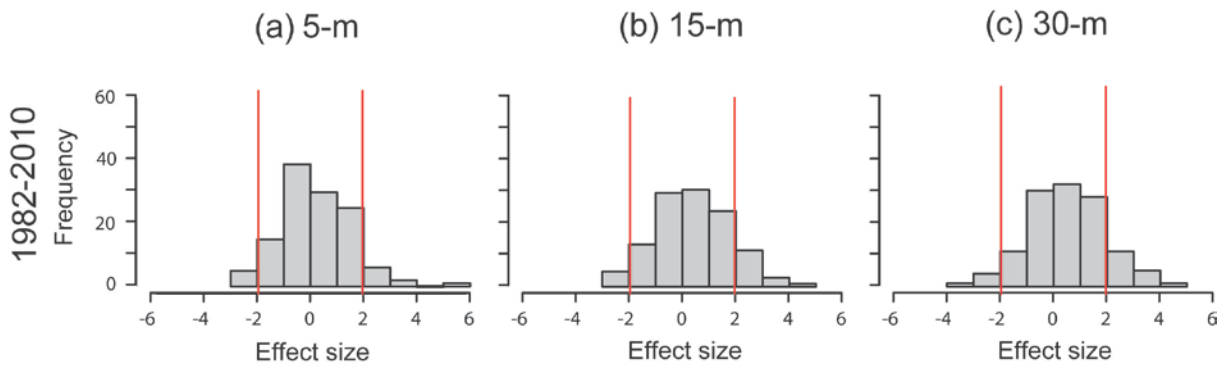


Figure A2. Frequency histograms indicating the distribution of the values of the effect sizes $DDM^{ses}(r)$ of the analysis of conspecific density dependent mortality in the 1982–2010 period, at spatial neighbourhoods of radius $r = 5$ (a), 15 (b) and 30 (b) m. Columns indicate the frequencies (%) of species showing effect sizes of different magnitude (–6 to 6). Vertical redlines indicate the range (–1.96, 1.96) where the effect size is not significant at a 5% confidence level. Effect sizes < -1.96 (black columns) indicate significant ($p < 0.05$) density dependent mortality effects. Effect sizes > 1.96 (white columns) indicate significant ($p < 0.05$) density dependent survival effects.

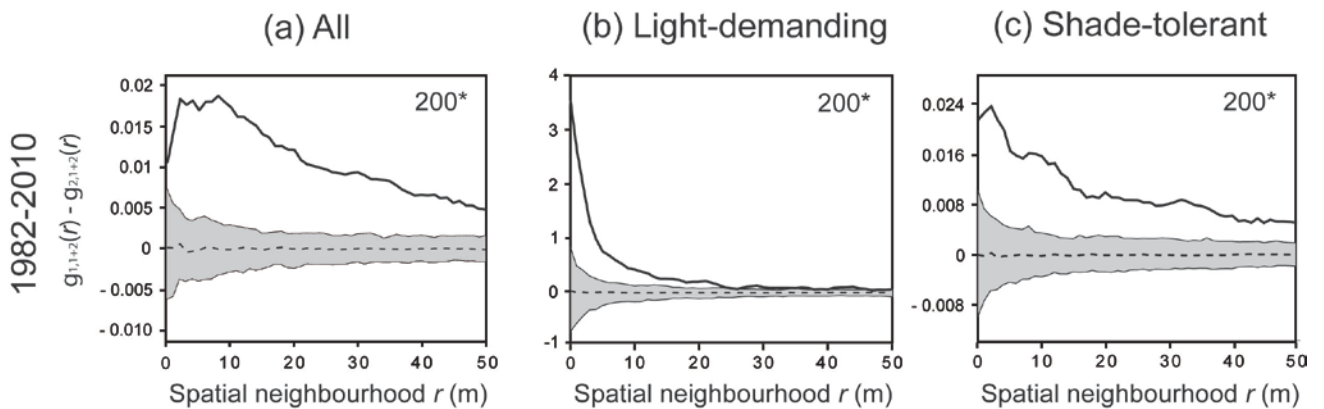


Figure A3. Analysis of total density-dependent mortality among (a) all saplings, and (b) saplings of light-demanding and (c) shade-tolerant species, in the Barro Colorado Island Forest Dynamics Plot, Panama, over the 1982–2010 period. To detect density-dependent mortality we used the summary statistic $DDM(r) = g_{1,1+2}(r) - g_{2,1+2}(r)$ that compares the mean density of saplings at distance r of dead saplings (subscript 1) with that around surviving saplings (subscript 2). The observed $DDM(r)$ (bold lines) was contrasted with simulation envelopes (grey area) of the random mortality null model, being the 5th highest and lowest values of $DDM(r)$ taken from 199 simulations of the null model. If the observed $DDM(r)$ wanders above the simulation envelopes we have DDM and if it wanders below we have DDS. On each panel, the ranks of the goodness-of-fit tests (GoF) are also shown together with their significance levels over the entire range of spatial neighbourhoods considered; ** $p < 0.001$, * $p < 0.05$.

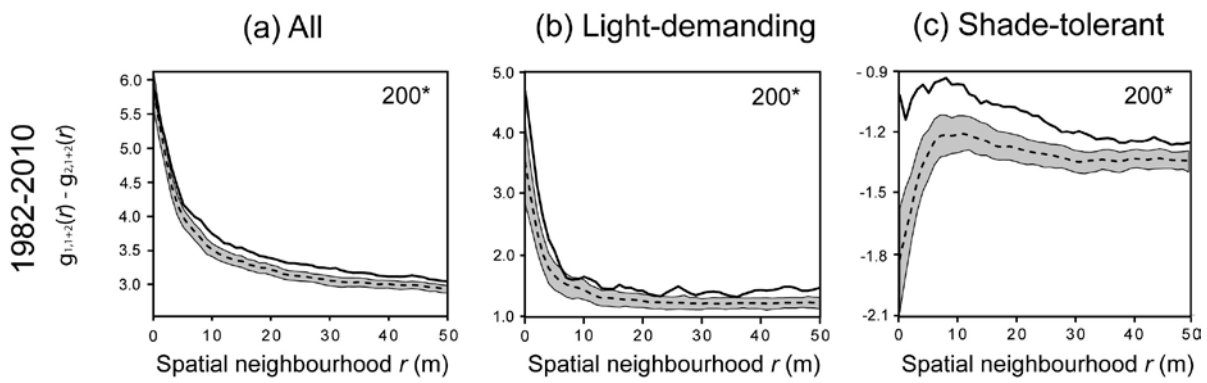


Figure A4. Analysis of conspecific density-dependent mortality among saplings for (a) all species (i.e. community level), (b) light-demanding and (c) shade-tolerant species (i.e. light-guild level), in the Barro Colorado Island Forest dynamics plot, Panama, over the six inter-census periods. Other conventions as in Fig. A2.