

Supplementary information

Title: Global chocolate supply is limited by low pollination and high temperatures

Authors:

Tonya A. Lander¹, Acheampong Atta-Boateng², Manuel Toledo-Hernández^{3,4,5}, Andrew Wood¹,
Yadvinder Malhi^{2,6}, Mirco Solé⁷, Teja Tschardt⁸, Thomas Cherico Wanger^{3,4,5,9*}

Affiliations:

¹ Department of Biology, University of Oxford; Oxford UK.

² Environmental Change Institute, School of Geography and Environment, University of Oxford; Oxford, U.K.

³ Sustainable Agricultural Systems and Engineering Laboratory, School of Engineering, Westlake University; Hangzhou, China.

⁴ Key Laboratory of Coastal Environment and Resources of Zhejiang Province, Westlake University; Hangzhou, China.

⁵ GlobalAgroforestryNetwork.com; Hangzhou, China.

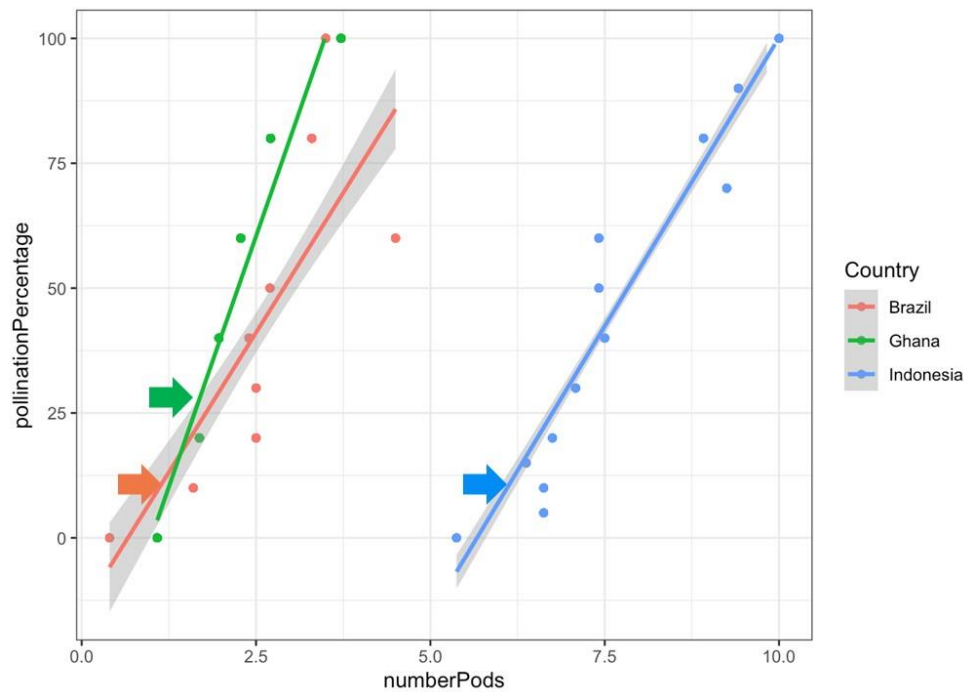
⁶ Leverhulme Centre for Nature Recovery, University of Oxford; Oxford, U.K.

⁷ Department of Biological Sciences, Universidade Estadual de Santa Cruz; Ilhéus, Brazil.

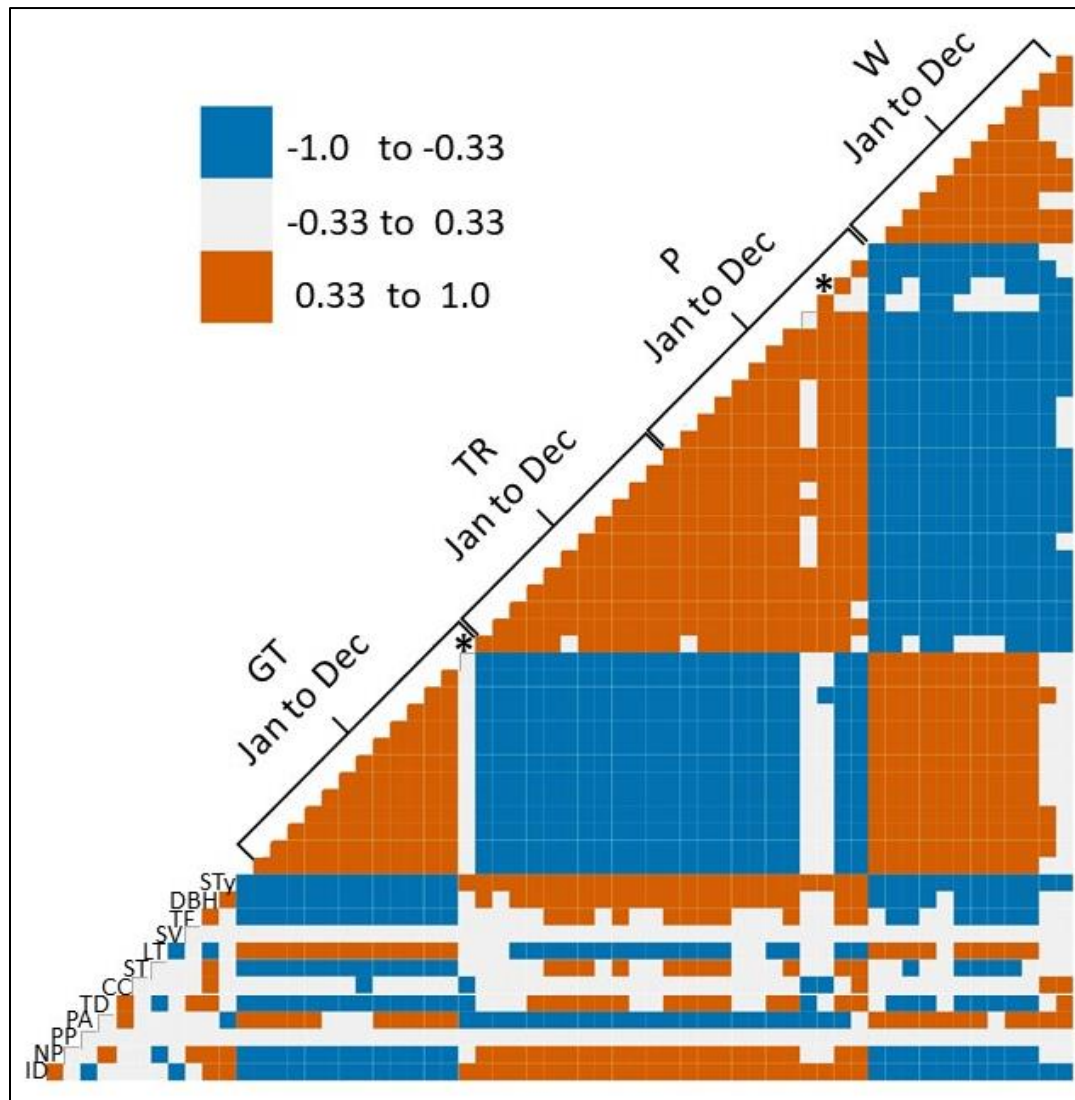
⁸ Functional Agrobiodiversity and Agroecology, Department of Crop Sciences, University of Göttingen; Göttingen, Germany.

⁹ Production Technology & Cropping Systems Group, Department of Plant Production, AgroScope, Nyon, Switzerland

*Corresponding author. Email: tomcwanger@gmail.com



Supplementary Figure 1: The standard curves of number of pods harvested against hand pollination percentage was generated using generalised linear models (GLM) with zero-inflated log-linked Poisson error structure ($R^2 = 0.74$). The model was then used to estimate number of pods as a function of pollination percentage. Country was included as a fixed effect (pollinationPercentage ~ numberPods+Country). The amount of natural pollination that occurred at the study sites is the point along the fitted line at which the observed number of pods from the zero-percent hand pollination treatment is located, indicated by the arrows.



Supplementary Figure 2: Pearson correlation between the variables used in Models 1-3.

Orange represents positive correlation ≥ 0.33 , blue represents negative correlation ≤ -0.33 , white represents low correlation: between 0.33 and -0.33. W = wind, P = precipitation, TR = temperature range, GT = ground temperature, Sty = soil type, DBH = diameter at breast height, TF = total flowers, SV = surrounding vegetation, LT = litter thickness, ST = shade trees, CC = canopy cover, TD = tree density, PA = plantation age, PP = pollination percentage, NP = number of pods, ID = tree identity. ‘*’ indicates ground temperature in December, and precipitation in September, which were included in Models 1-3.

Supplementary Table 1: Estimates of achieved cocoa yield, Y_a , potential yield, Y_p , and theoretical yield, Y_t , in major cocoa-producing countries, from a literature review Sources: 1, 2, 3, 4, 5, 6, 7, 8. Yield gap was calculated as the difference between the averages of reported Y_a and Y_p values for each country. A negative yield gap indicates reported ‘potential yields’ are lower than reported achieved yields. Yield gap/ Y_a shows the size of the yield gap relative to Y_a ; a value of 1.0 indicates that the yield gap, the gap between Y_a and Y_p expressed as kg/ha pods, is the same value as the currently achieved yield (Y_a). ‡<http://data.un.org/>.

Country	% global cocoa production, 2020‡	Y_a (kg/ha)	Y_p (kg/ha)	Y_t (kg/ha)	Yield gap (yield gap/ Y_a)
Brazil	4.9	400; 458	350-390; 800	3000	84 (0.20)
Cameroon	5.2	418	410-550	--	62 (0.15)
Columbia	1.1	337	460-790	--	288 (0.85)
Côte d’Ivoire	39.8	460	840-1000	--	460 (1.00)
Dominican Republic	1.4	449	360	--	-89 (n/a)
Ecuador	5.9	621	260-360	--	-311 (n/a)
Ghana	14.5	300-400; 551; 2331	380-510; 800-3000	970; 5000; 1891-3500; 4178-6567	277 (0.31)
Indonesia	13.4	39-3586; 467	430-1000; 3600	--	313 (0.23)
Nigeria	6.1	270	320-620	--	200 (0.74)
Peru	2.9	937	580-860	--	-217 (n/a)
~48 other countries	4.8	--	--	--	--

Supplementary Table 2: Study sites. Private plantation owners/managers are anonymized as ‘A’-‘J’, with owner ‘A’ managing multiple sites in Ghana. In Indonesia the farms were each owned by separate small-scale producers, but from one month before data collection started until the end of the experiments, the farmers agreed not to apply agrichemicals to the study sites to improve comparability across sites (see ⁹). ‘Mean dbh’ is the average diameter at breast height (dbh) of all trees within 2m either side of a diagonal transect of the study plot. Canopy cover is percent canopy cover measured below the cocoa canopy: L (low = 0-39%) or H (high = 40-100%). ‘Shade trees’ is a binary indication of the presence or absence of non-cocoa shade trees within the cocoa plantation. ‘Veg’ is a binary classification of neighbouring land-use: S (simple: farm, single species plantation, or grass field), or C (complex: high floral diversity, primary or secondary forest or wetland). ‘Mean pods/tree, open poll’ is the average number of pods per tree in the natural pollination treatment. ‘Mean pods/tree, all poll’ is the average number of pods per tree in all of the pollination treatments combined, including natural pollination.

ID	Site	Latitude	Longitude	Study years	Plantation owner/ manager	Cocoa variety	Mean dbh (cm)	Mean annual temp. (°C)	Mean tree age	Tree density (trees/ha)	Canopy cover (L/H)	Shade trees (Y/N)	Veg (C/S)	Litter depth (cm)	Mean pods/ tree, open poll	Mean pods/ tree, all poll
1	Brazil, Ilhéus	-14.6711	-39.1886	2018-19	Fazenda Almada	<i>parazinho</i>	40.11	24.00	90	800	L	Y	C	3.80	1.00	4.89
2	Brazil, Ilhéus	-14.6722	-39.1902	2018-19	Fazenda Almada	<i>parazinho</i>	30.88	24.00	90	800	L	Y	C	3.40	1.00	3.56
3	Brazil, Ilhéus	-14.6717	39.1902	2018-19	Fazenda Almada	<i>parazinho</i>	38.71	24.00	90	800	L	Y	C	3.80	0.00	3.44
4	Brazil, Ilhéus	-14.6717	-39.1925	2018-19	Fazenda Almada	<i>parazinho</i>	37.74	24.00	90	800	L	Y	C	3.40	1.00	4.67
5	Brazil, Ilhéus	-14.6736	-39.1939	2018-19	Fazenda Almada	<i>parazinho</i>	35.37	24.00	90	800	L	Y	C	2.80	1.00	3.33
6	Brazil, Ilhéus	-14.6721	-39.1897	2018-19	Fazenda Almada	<i>parazinho</i>	34.90	24.00	90	800	H	Y	C	3.80	0.00	2.11
7	Brazil, Ilhéus	-14.6725	-39.1914	2018-19	Fazenda Almada	<i>parazinho</i>	32.73	24.00	90	800	H	Y	C	4.20	0.00	0.67
8	Brazil, Ilhéus	-14.6725	-39.1925	2018-19	Fazenda Almada	<i>parazinho</i>	32.82	24.00	90	800	H	Y	C	3.50	0.00	0.44
9	Brazil, Ilhéus	-14.6717	-39.1942	2018-19	Fazenda Almada	<i>parazinho</i>	47.02	24.00	90	800	H	Y	C	4.10	0.00	1.22
10	Brazil, Ilhéus	-14.6736	-39.1939	2018-19	Fazenda Almada	<i>parazinho</i>	27.07	24.00	90	800	H	Y	C	3.40	0.00	1.67
11	Ghana, Tarkwa-Breman	5.56173	-2.14415	2019-20	Private owner A	<i>Amelorado</i>	10.61	25.82	39	440	L	Y	C	5.32	0.75	1.40
12	Ghana, Tarkwa-Breman	5.56226	-2.14443	2019-20	Private owner A	<i>Amelorado</i>	11.01	25.82	39	329	L	N	C	5.99	0.58	1.49
13	Ghana, Tarkwa-Breman	5.56373	-2.14393	2019-20	Private owner A	<i>Amelorado</i>	13.05	25.82	39	206	L	Y	C	5.44	0.92	2.63
14	Ghana, Tarkwa-Breman	5.56466	-2.14400	2019-20	Private owner A	<i>Amelorado</i>	12.95	25.82	39	212	L	N	S	6.52	1.92	2.56

Ghana, Tarkwa- 15 Breman	5.56216	-2.14347	2019-20	Private owner A	Amelorado	10.98	25.82	39	308	L	Y	S	6.84	0.83	1.82
Ghana, Anti- 16 korkoh	5.54138	-2.14485	2019-20	cocoa360.org	Amelorado	12.76	25.67	39	178	L	N	S	6.40	2.25	3.39
Ghana, Anti- 17 korkoh	5.54263	-2.14585	2019-20	cocoa360.org	Amelorado	12.39	25.67	39	184	L	Y	S	6.08	0.33	1.75
Ghana, Amezugbe 18	5.54383	-2.15915	2019-20	Private owner B	Amelorado	13.17	25.67	39	386	H	N	C	6.69	1.08	2.90
Indonesia, Napu 19 Valley	-1.38453	-1.38453	2017	Private owner C	Trinitario x Forastero	59.00	18.97	10	493	L	Y	S	4.50	5.00	6.47
Indonesia, Napu 20 Valley	-1.38553	120.3177	2017	Private owner D	Trinitario x Forastero	51.80	18.97	15	577	L	Y	C	2.30	5.00	8.31
Indonesia, Napu 21 Valley	-1.44574	120.3076	2017	Private owner E	Trinitario x Forastero	44.60	18.97	15	882	L	N	S	2.96	10.00	9.33
Indonesia, Napu 22 Valley	-1.3875	120.3126	2017	Private owner F	Trinitario x Forastero	46.65	18.97	12	1065	H	N	S	2.60	3.00	6.41
Indonesia, Napu 23 Valley	-1.43885	120.3082	2017	Private owner G	Trinitario x Forastero	46.65	18.97	19	777	H	Y	S	2.20	5.00	9.18
Indonesia, Napu 24 Valley	-1.43224	120.3370	2017	Private owner H	Trinitario x Forastero	50.60	18.97	12	1000	L	Y	S	3.10	4.00	6.65
Indonesia, Napu 25 Valley	-1.42341	120.3369	2017	Private owner I	Trinitario x Forastero	46.65	18.97	13	900	L	N	C	1.10	5.00	9.12
Indonesia, Napu 26 Valley	-1.44625	120.3249	2017	Private owner J	Trinitario x Forastero	42.70	18.97	13	412	H	N	C	1.10	6.00	6.71

Supplementary Table 3: The breakpoint regression (SETAR) models outputs. These models are two coupled linear models which aim to find the plateau ('breakpoint') of a dataset where two lines provide a better fit for the data than one line. The presence of a break point would suggest physiological limitation on pod production. As these are linear models, nonlinearity is not captured. The total AIC value is the sum of the AIC values of the linear models either side of the break point. The breakpoint for each country is the % hand pollination value with the lowest total AIC, indicated by '*'. Brazil and Ghana have a 'breakpoint' of 0, which is equivalent to no breakpoint. The analyses also included a null model (no breakpoint), tested by comparing the AIC score between the break point models and the null model.

% hand pollination	AIC Segment 1	DF	AIC Segment 2	DF	Total AIC
Brazil					
* 0	18.10761	9	406.1588	88	424.2664
20	112.6471	28	327.8611	68	440.5082
40	205.1909	48	242.1714	48	447.3623
60	311.9705	68	146.8825	28	458.853
80	361.3126	78	95.45965	18	456.7722
100	406.1588	88	46.84796	9	453.0067
Ghana					
* 0	419.7849	95	2814.868	574	3234.653
20	855.8337	190	2385.46	478	3241.294
40	1301.74	286	1941.728	382	3243.468
60	1772.434	382	1487.859	286	3260.292
80	2275.299	478	1016.403	190	3291.702
100	2814.868	574	521.2303	95	3336.098
Indonesia					
0	37.24366	7	541.3121	134	578.5558
20	141.9568	38	427.4351	102	569.392
40	218.8621	62	357.3268	82	576.1889
* 60	298.8327	86	267.3704	58	566.2031
80	419.0291	110	168.7714	34	587.8005
100	541.3121	134	56.10345	11	597.4156

Supplementary Table 4: Results for Models 1-3. Model 1: natural pollination (0% hand pollination) data from all countries. This model tests whether tree, plantation, or climate factors explain patterns of natural pollination and pod production. **Model 2:** 100% hand pollination data from all countries. This model tests whether tree, plantation, or climate factors explain pod production when there is no pollination limitation. **Model 3:** Data from all countries and all hand-pollination treatments except the 0%, natural pollination, treatment, was used to understand the relative impact of cocoa tree, plantation, or climate factors compared to known levels of pollination on pod production. Model 1, 2 or 3 plus ‘:AIC’ indicates the AIC-selected model for Models 1, 2 or 3. Number of pods (‘pods’) was the dependent variable for all of the models. ‘dbh’ is diameter at breast height (1.3m above ground). ‘PlantationAge’ is the average age of the cocoa trees in the plantation. ‘shade’ is a binary variable indicating presence or absence of non-cocoa shade trees. ‘density’ is cocoa tree density within the plantation. ‘litter’ is litter depth on the plantation floor. ‘ground.temp.Dec’ is temperature at 2m above ground surface in the plantation in December during the study year. ‘precip.Sept’ is precipitation in the plantation in September. ‘pollination’ is percent hand pollination. Significance codes: <0.001 ‘***’, 0.001 ‘**’, 0.01 ‘*’.

Model	Null dev (DF)	Res dev (DF)	R ²	AIC	ΔAIC
1 pods ~ dbh + age + shade + density + litter + ground.temp.Dec + precip.Sept	385.35 (113)	296.14 (106)	0.2314	449.72	--
1:AIC pods ~ age + shade + density + ground.temp.Dec	--	297.39 (109)	0.2282	444.96	4.76
2 pods ~ dbh + age + shade + density + litter + ground.temp.Dec + precip.Sept	437.46 (117)	346.61 (110)	0.2076	680.14	--
2:AIC pods ~ shade + density + ground.temp.Dec	--	349.39 (114)	0.2013	674.92	5.22
3 pods ~ pollination + dbh + age + shade + density + litter + ground.temp.Dec + precip.Sept	612.8 (687)	1760.3 (679)	0.3263	3400	--
3:AIC pods ~ pollination + dbh + shade + density + litter + ground.temp.Dec	--	1761.9 (681)	0.3256	3397.7	2.30
Model results details					
Model 1: Open pollination, 0% hand pollination					
pods ~ dbh + age + shade + density + litter + ground.temp.Dec + precip.Sept					

	Min	1Q	Median	3Q	Max
Deviance residuals	-2.5891	-1.5798	-1.1346	0.4244	4.9874
Coefficients:	Estimate	Std. Error	t value	Pr(> t)	Sig.
(Intercept)	11.4523	4.5345	2.5260	0.0116	*
dbh	-0.0208	0.0230	-0.9060	0.3652	
PlantationAge	0.0132	0.0613	0.2150	0.8297	
Shadetrees	0.7772	0.2193	3.5440	0.0004	***
LitterThickness	-0.0214	0.1027	-0.2080	0.8350	
treedensity	-0.0014	0.0006	-2.2710	0.0232	*
groundtempDec	-0.4026	0.2450	-1.6430	0.1003	
precipSep	-0.1064	0.2386	-0.4460	0.6557	
Null deviance (DF): 385.35 (113)					
Residual deviance (DF): 296.14 (106)					
AIC: 449.72					
R ² : 0.2314					

Model 1 AIC selected (Model 1 in Figure 2): Open pollination, 0% hand pollination

pods ~ age + shade + density + ground.temp.Dec

	Min	1Q	Median	3Q	Max
Deviance residuals	-2.442	-1.6159	-1.136	0.4926	4.9071
Coefficients:	Estimate	Std. Error	t value	Pr(> t)	Sig.
(Intercept)	8.6122	1.6524	5.2120	0.0000	***
PlantationAge	0.0317	0.0106	2.9960	0.0027	**
shade	0.7548	0.1966	3.8390	0.0001	***
treedensity	-0.0013	0.0006	-2.2230	0.0262	*
groundtempDec	-0.3717	0.0701	-5.3060	0.0000	***
Null deviance (DF): 385.35 (113)					
Residual deviance (DF): 297.39 (109)					
AIC: 444.96					
R ² : 0.2282					

Model 2: Full pollination, 100% hand pollination

pods ~ dbh + age + shade + density + litter + ground.temp.Dec + precip.Sept

	Min	1Q	Median	3Q	Max
Deviance residuals	-3.0203	-1.4004	-0.2995	0.7762	4.9151
Coefficients:	Estimate	Std. Error	t value	Pr(> t)	Sig.
(Intercept)	2.7815	3.8031	0.7310	0.4645	
dbh	0.0215	0.0199	1.0770	0.2813	
PlantationAge	-0.0085	0.0362	-0.2360	0.8135	
Shadetrees	0.2047	0.1152	1.7770	0.0756	
LitterThickness	0.0546	0.0577	0.9470	0.3439	
treedensity	-0.0007	0.0006	-1.0870	0.2772	
groundtempDec	-0.0767	0.1564	-0.4910	0.6237	

precipSep	0.0449	0.1449	0.3100	0.7564
Null deviance (DF): 437.46 (117)				
Residual deviance (DF): 346.61 (110)				
AIC: 680.14				
R ² : 0.2076				

Model 2 AIC selected (Model 2 in Figure 2): Full pollination, 100% hand pollination

pods ~ shade + density + ground.temp.Dec					
	Min	1Q	Median	3Q	Max
Deviance residuals	-3.0911	-1.4963	-0.3541	0.8039	5.0469
Coefficients:	Estimate	Std. Error	t value	Pr(> t)	Sig.
(Intercept)	7.4873	1.1433	6.5490	0.0000	***
Shadetrees	0.2500	0.1036	2.4140	0.0158	*
density	-0.0013	0.0004	-2.8900	0.0039	**
ground.temp.Dec	-0.2253	0.0387	-5.8150	0.0000	***
Null deviance (DF): 437.46 (117)					
Residual deviance (DF): 349.39 (114)					
AIC: 674.92					
R ² of this model is: 0.2013					

Model 3: Pollination gradient, 20-100% hand pollination

pods ~ pollination + dbh + age + shade + density + litter + ground.temp.Dec + precip.Sept					
	Min	1Q	Median	3Q	Max
Deviance residuals	-2.8697	-1.7429	-0.3592	0.6001	5.6455
Coefficients:	Estimate	Std. Error	t value	Pr(> t)	Sig.
(Intercept)	2.9115	1.1032	2.6390	0.0083	**
pollinationPercentage	0.0082	0.0008	10.2820	0.0000	***
dbh	0.0171	0.0052	3.2690	0.0011	**
PlantationAge	0.0105	0.0132	0.7940	0.4270	
Shadetrees	0.1573	0.0584	2.6930	0.0071	**
LitterThickness	0.0480	0.0237	2.0220	0.0432	*
treedensity	-0.0002	0.0001	-1.6380	0.1014	
groundtempDec	-0.1494	0.0538	-2.7790	0.0055	**
precipSep	0.0596	0.0540	1.1020	0.2705	
Null deviance (DF): 2612.8 (687)					
Residual deviance (DF): 1760.3 (679)					
AIC: 3400					
R ² of this model is: 0.3263					

Model 3 AIC selected (Model 3 in Figure 2): Pollination gradient, 20-100% hand pollination

pods ~ pollination + dbh + shade + density + litter + ground.temp.Dec					
	Min	1Q	Median	3Q	Max

Deviance residuals	-2.9666	-1.7112	-0.3526	0.6091	5.6819
Coefficients:	Estimate	Std. Error	t value	Pr(> t)	Sig.
(Intercept)	3.7988	0.4862	7.8130	0.0000	***
pollinationPercentage	0.0084	0.0007	11.4290	0.0000	***
dbh	0.0123	0.0032	3.8580	0.0001	***
Shadetrees	0.1530	0.0572	2.6750	0.0075	**
LitterThickness	0.0592	0.0203	2.9170	0.0035	**
treedensity	-0.0003	0.0001	-2.0760	0.0379	*
groundtempDec	-0.1486	0.0175	-8.4740	0.0000	***
Null deviance (DF): 2612.8 (687)					
Residual deviance (DF): 1761.9 (681)					
AIC: 3397.7					
R ² of this model is: 0.3256					

Supplementary Table 5: Estimates of percent change in pod production driven by each of the variables found to be significant in the AIC selected models for Models 1-3. ‘HP’ is hand

pollination. †Average pods / tree is the average number of pods produced below 2m on the trees in this treatment. This value is estimated to represent 13% of pod production on the whole tree (see Methods). ‡Percent change in number of pods between the maximum and minimum value for the variable of interest in each model was calculated as: $(\text{model variable estimate} / |\text{model intercept}|) * (\text{variable maximum} - \text{variable minimum}) * 100$.

Model	% HP	Variable	Variable mean	Variable min.	Variable max.	Average pods / tree †	Model intercept	Model variable estimate	% change in number of pods ‡
3	20-100	dbh (cm)	20.28	7.00	65.40	3.53	3.7988	0.0123	18.8529
3	20-100	Litter	4.98	1.10	6.99	3.53	3.7988	0.0592	9.1777
1	0	Plantation age	39.06	10.00	60.00	1.32	8.6122	0.0317	18.4167
3	20-100	Pollination percentage	--	10	100	3.53	3.7988	0.0084	19.9761
1	0	Shadetrees (yes/no)	binary	0	1	1.32	8.6122	0.7548	8.7645
2	100	Shadetrees (yes/no)	binary	0	1	4.34	7.4873	0.2500	3.3389
3	20-100	Shadetrees (yes/no)	binary	0	1	3.53	3.7988	0.1530	4.0282
1	0	Temp. Dec. (°C)	25.67	19.36	26.57	1.32	8.6122	-0.3717	-31.1174
2	100	Temp. Dec. (°C)	25.67	19.36	26.57	4.34	7.4873	-0.2253	-21.6916
3	20-100	Temp. Dec. (°C)	25.67	19.36	26.57	3.53	3.7988	-0.1486	-28.2059
1	0	Tree density (trees/ha)	349.26	178.00	1065.00	1.32	8.6122	-0.0013	-13.7980
2	100	Tree density (trees/ha)	383.25	178.00	900.00	4.34	7.4873	-0.0013	-12.1376
3	20-100	Tree density (trees/ha)	431.52	178.00	1065.00	3.53	3.7988	-0.0003	-6.2950

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