Supplementary Material: Climate change alters impacts of extreme climate events on a tropical perennial tree crop

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Supplementary Results

Validation of the detrending approach

Supplementary Table 2 shows that for the vast majority of the individual time series within the district and regional datasets, the best fitting parameters for *p* (autoregression order), *d* (degree of differencing) and *q* (moving average) were equal to zero. While some individual time series do have non-zero values, this is to be expected by chance alone given the number of trials run, and the potential error generated by these data would only reduce the significance of downstream analyses.

For each dataset, a mixed effects model fitting production anomaly against the intercept with district or region as a random effect was determined to be singular with a tolerance of 0.0001, thus confirming that the detrending process removed sufficient variation between districts/regions.

ENSO-production relationships

We calculated cross-correlation between time series of detrended production and mamONI for the same purchase year and 12 delayed purchase years to identify potential instantaneous or delayed relationships between production and mamONI; these analyses show significant correlations at all years for the district dataset and several years including instantaneous for the regional dataset (Supplementary Figure 2).

ENSO-climate relationships

To examine climate impacts of ENSO with greater temporal resolution, we performed a cross-correlation on 3-monthly average ONI values against monthly temperature, precipitation and MWCD, including 36-month delays and leads. We observed that the climate of the purchase year prior to an El Niño is significantly cooler and wetter than average, with less drought, and vice-versa prior to a La Nina (Supplementary Figures 3 and 4).

Supplementary Figure 1 shows the results of multiple regressions fitting temperature, precipitation and (maximum) climatological water deficit (month: CWD, season: MCWD) against mamONI, with time period ("past" or "recent") as an interaction, for each month.

Supplementary Tables

Interaction	**logLik**	**AICc**	**delta**	**weight**
1986/87	-488.5993	999.9063	0	0.4074
1987/88	-488.8921	1000.4919	0.5856	0.3040
1985/86	-490.1034	1002.9145	3.0082	0.0905
1984/85	-490.2422	1003.1922	3.2859	0.0788
cont. year	-490.7982	1004.3041	4.3978	0.0452
1983/84	-491.0935	1004.8948	4.9886	0.0336
1989/90	-491.9460	1006.5994	6.6934	0.0143
1990/91	-492.4793	1007.6664	7.7602	0.0084
1994/95	-493.0507	1008.8092	8.9030	0.0048
1993/94	-493.1539	1009.0155	9.1092	0.0043

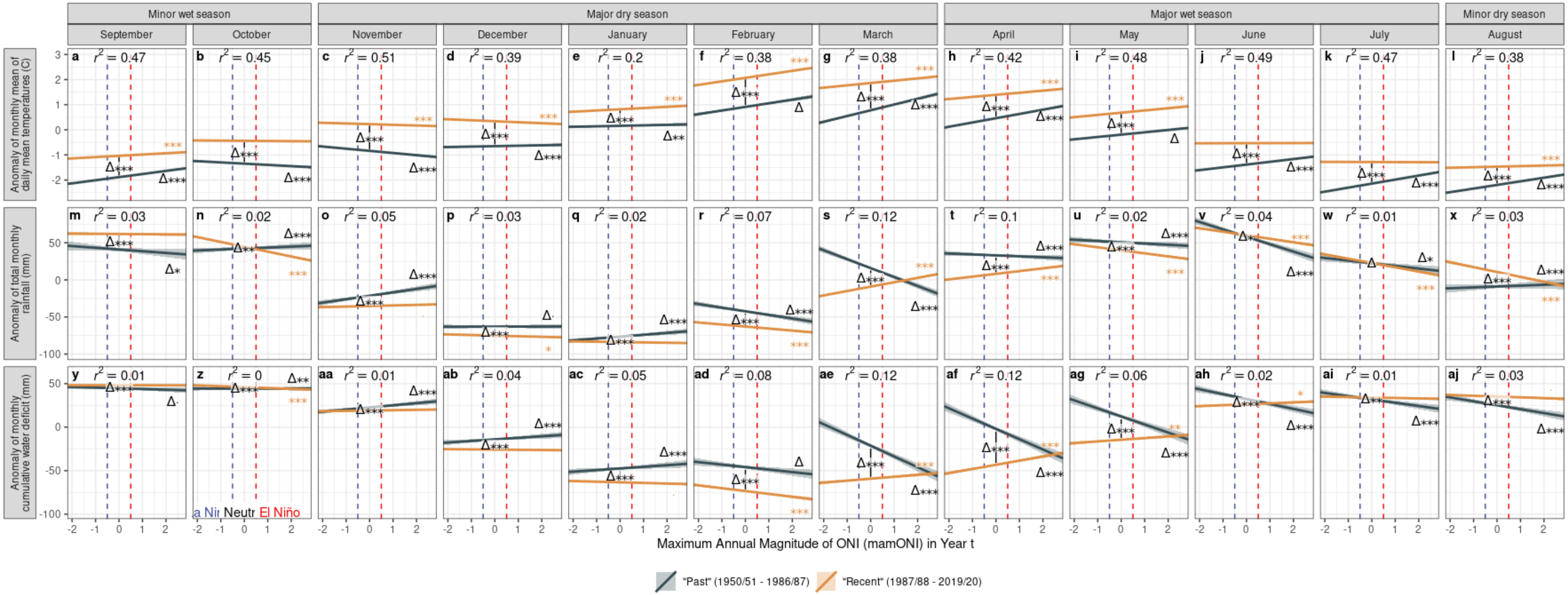
*Supplementary Table 1: Model selection to identify most parsimonious piecewise multiple regression for explaining change in production response to mamONI over time in the regional dataset. Showing top 10 models (out of 74) only. 73 models took the form pa ~ mamONI0 * pp[year] + mamONI0 * pp[year] + mamONI0 * pp[year] + mamONI0 * pp[year], where pa = production anomaly, $mamONI_t$ = mamONI at year t, and pp[year] = a categorical variable dividing the data piecewise into (i) years up to and including purchase year [year] and (ii) purchase years following [year]. 1 model instead fitted year as a continuous variable, i.e. pa ~ mamONI0 * year + mamONI0 *year + mamONI0 * year + mamONI0 * year. All models had d.f. = 11 in the model selection, total n = 412 in initial model fitting. The* **Interaction** *column gives the value of the piecewise categorical variable, i.e. [year] in pp[year], or notes the exceptional model with year fit as a continuous variable;* **logLik** *gives the log-likelihood and* **AICc** *the corrected Akaike Information Criterion of the corresponding model;* **delta** *the change in AICc from the top model and* **weight** *the relative Akaike weight of each model.*

Dataset	**Parameter**	**Count of time series by parameter value**					
		0	**1**	**2**	**3**	**4**	**5**

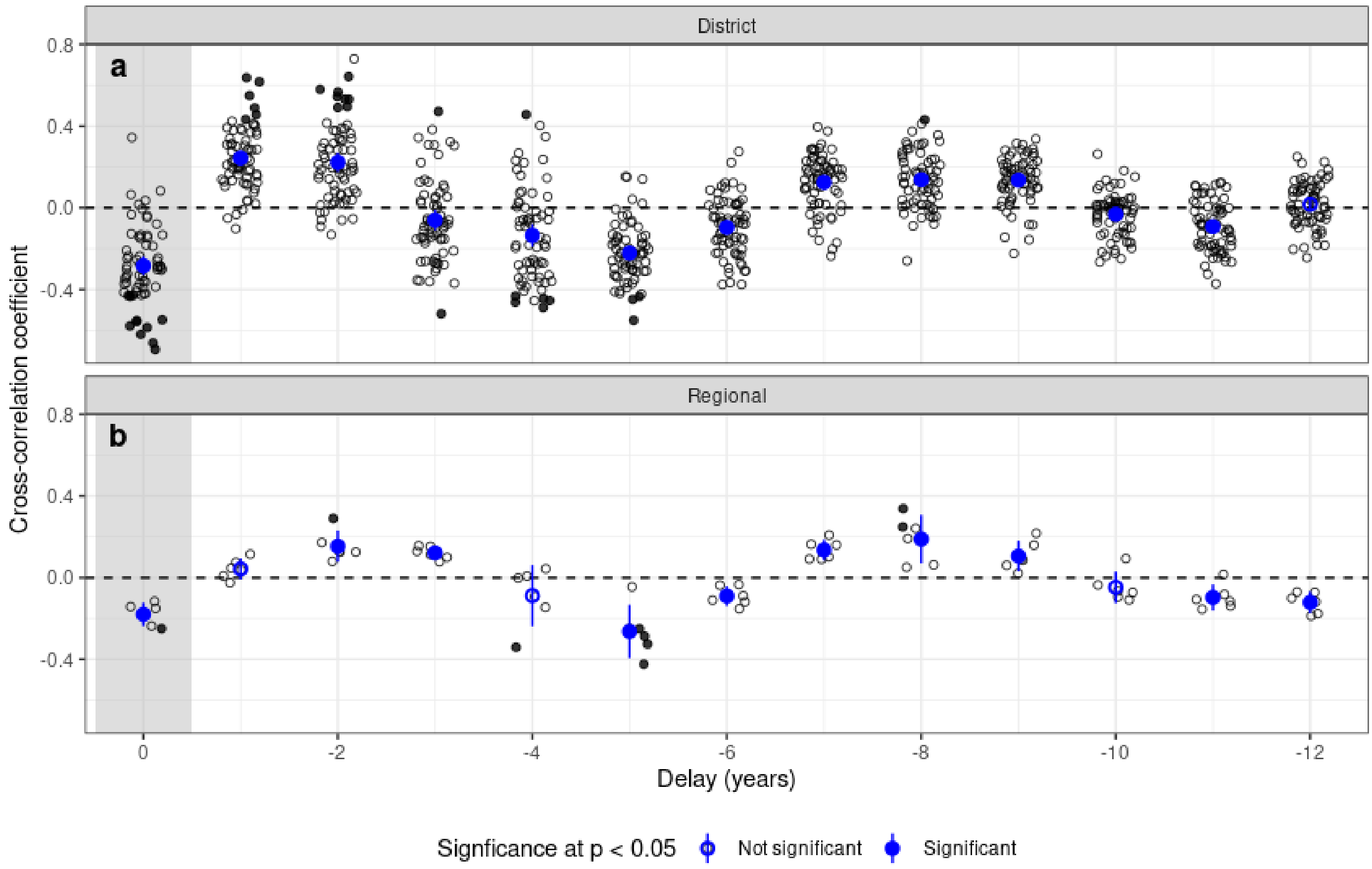
District n=68	*p*	46	14	3*	3	2	0
	d	68*	0	0			
	q	65	0	3*	0	0	0
Regional n=6	*p*	4	1	1*	0	0	0
	d	6*	0	0			
	q	3	1	1*	1	0	0

*Supplementary Table 2: Results of ARIMA parameter search conducted on the time series of individual district or region production z-scores with mamONI as an external regressor. Counts record the number of individual district or region time series for each parameter and parameter value where that value resulted in the best ARIMA model under AICc. Counts of 0 denote a parameter value that was included in value searching but was not selected for any time series; blank cells (i.e. d >= 3) denote parameter values that were not tested. Cells with * denote starting values (i.e. p = 2, d = 0, q = 2). For all parameters in both datasets, 0 was the most frequent parameter value.*

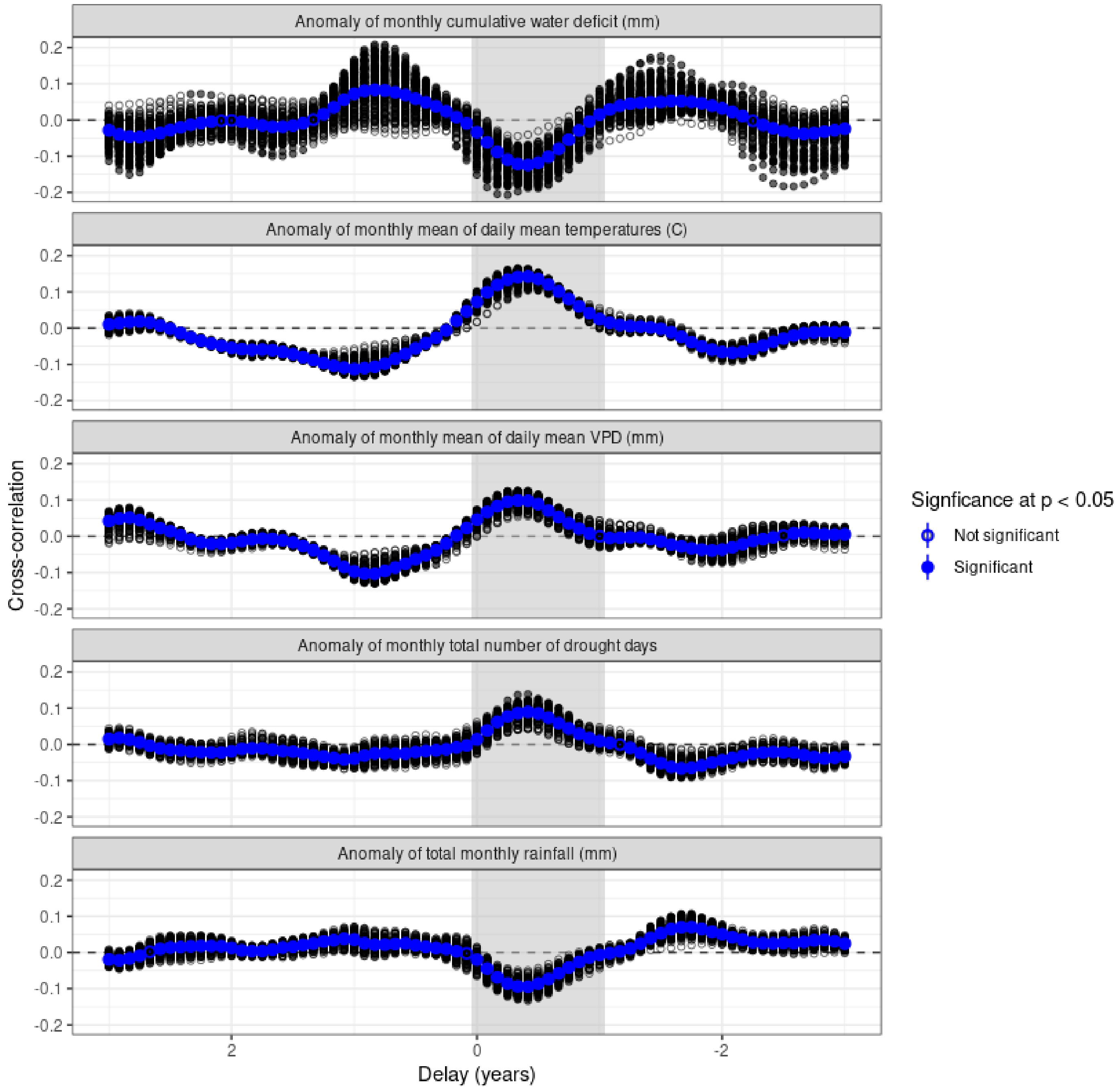
Supplementary Figures



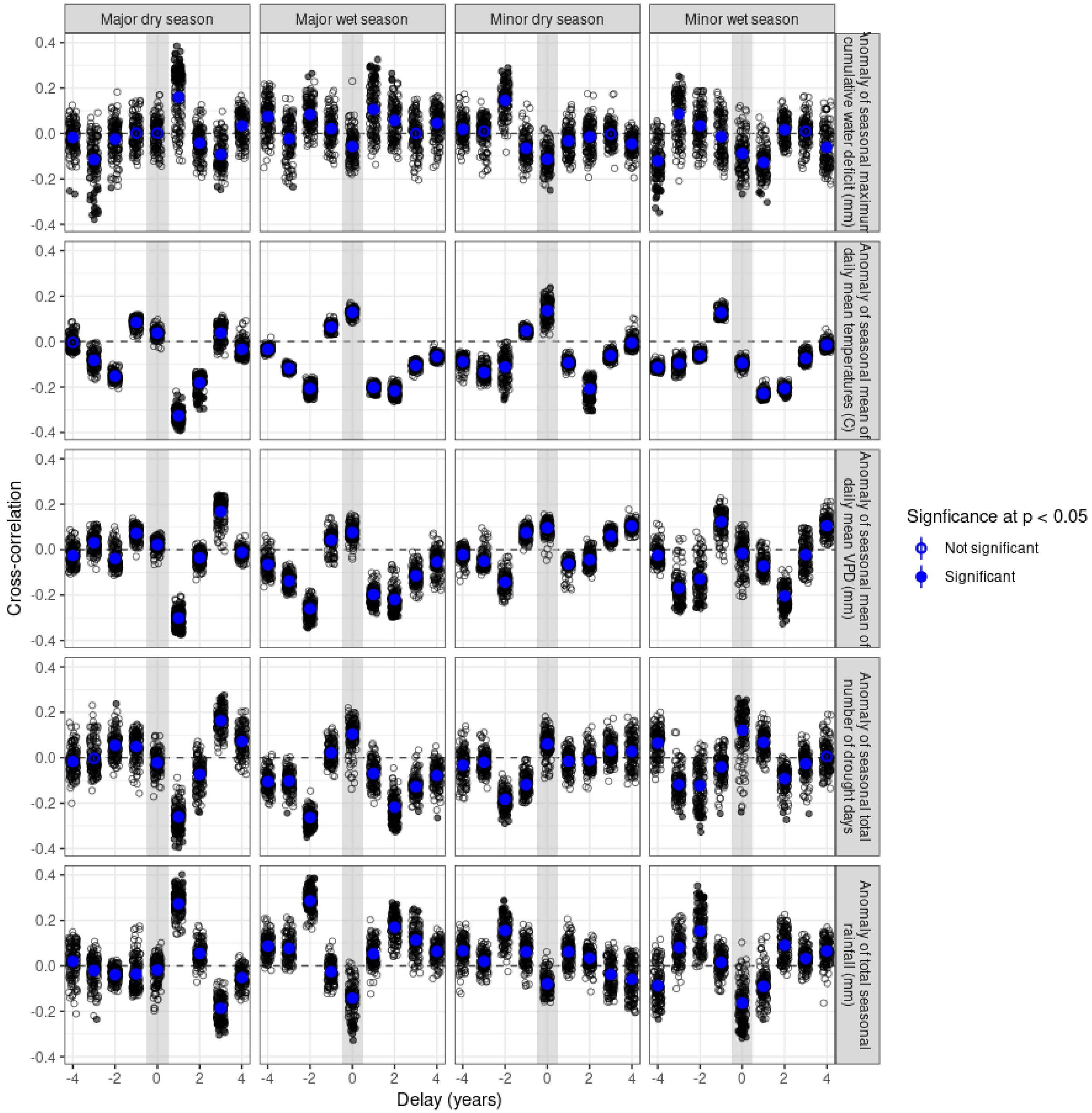
*Supplementary Figure 1: The response of climate to mamONI in different months during the purchase year, grouped into two sets of years corresponding to the best fitting break-point in the production data. Vertical dashed lines delineate La Nina (mamONI <= -0.5), Neutral (-0.5 < mamONI < 0.5) and El Nino (mamONI >= 0.5) conditions. Lines show the best linear fits and standard errors derived from 36 individual regressions of monthly climate against mamONI, with an interaction term fitting the year category. Significance stars denote p-values derived from these models (***: p<0.001, **: p < 0.01, *: p < 0.05, .: p < 0.1): (i) difference in means between year groups (delta in centre of plot), (ii) difference of the 1987/88-2018/19 slope from 0 (orange stars), (iii) difference between slopes (delta at right of plot). Adjusted R squared values are displayed.*



Supplementary Figure 2: Cross-correlation of production z-scores with instantaneous and delayed annual values of mamONI to illustrate potential delays in the response of cocoa production to El Nino from instantaneous (Delay = 0, shaded) to 12 (i.e. a response in production to ONI twelve years prior). Cross-correlations were performed on the time series of production z-scores for each district (a, top panel) or region (b, bottom panel) separately (black points, filled if correlation is significant at $p < 0.05$). Significant positive values indicate an increase in production with El Nino and decrease with La Nina, compared with the average trend of production. Blue points and error bars show the mean and 95% interval for each delay, filled blue points indicate that the mean is significantly different from zero (t test, $p < 0.05$). Horizontal jitter added to black points to avoid overfitting. Horizontal dashed line denotes cross-correlation coefficient of 0.



Supplementary Figure 3: Cross-correlation of monthly climate anomalies with leading/delayed monthly values of ONI to illustrate potential delays in the response of climate to ENSO from +36 to -36 months (i.e. respectively, leading responses of 36 months prior to ENSO, positive values on x axis, and delayed responses of 36 months after ENSO, negative values on x axis). Note that the x axis is reversed for consistency of treatment of time (left = leading, right = delayed) across all plots. Cross-correlations were performed on the time series of climate anomalies for each grid square separately (black points, filled if correlation is significant at $p < 0.05$). Significant positive values indicate an increase in that climate variable with El Nino and decrease with La Nina, compared with the average trend. Blue points and error bars show the mean and 95% interval for each lag, filled blue points indicate that the mean is significantly different from zero (t test, $p < 0.05$). Horizontal jitter added to black points to avoid overfitting. Horizontal dashed line denotes cross-correlation coefficient of 0. Shaded region denotes the 12 months of the buying year over which mamONI is calculated and cocoa production data is aggregated.



Supplementary Figure 4: Cross-correlation of annual climate anomalies with lagged and leading values of mamONI to illustrate potential lags in the response of climate to ENSO from +4 to -4 years (i.e. respectively, leading responses of 4 years prior to ENSO, positive values on x axis, and delayed responses of 4 years after ENSO, negative values on x axis). Note that the x axis is reversed for consistency of treatment of time (left = leading, right = delayed) across all plots. Cross-correlations were performed on the time series of climate anomalies for each grid square separately (black points, filled if correlation is significant at p < 0.05). Significant positive values indicate an increase in that climate variable with El Nino and decrease with La Nina, compared with the average trend. Blue points and error bars show the mean and 95% interval for each lag, filled blue points indicate that the mean is significantly different from zero (t test, p < 0.05). Horizontal jitter added to black points to avoid overfitting. Horizontal dashed line denotes cross-correlation coefficient of 0.