Supplementary Materials for

Ecosystem services at risk from declining taxonomic and interaction diversity in a tropical forest

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Materials and Methods

Study sites and sample methods

We collected plant-caterpillar-parasitoid interaction data within La Selva Biological Research Station located in Heredia Province, Costa Rica (10° 26′ N 83° 59′ W). La Selva is a 1600-ha patch of protected lowland tropical forest on the eastern Caribbean slope of the Cordillera Central connected via a corridor to the Braulio Carllio National Forest. Seasonality is marked by a wet season generally from May to December and a brief dry season beginning January to April. Peak rainfall occurs in June-July and March is the peak dry month. Samples were collected as a larger rearing program cataloguing plant-herbivore-parasitoid associations across the Americas *(14, 29)* from 1995 to present. We limited our results to records starting in 1997 up to 2018, and we excluded 2014 and 2016 because sampling days did not meet our minimum criteria of 20 sampling days/year. We sampled externally feeding immature Lepidoptera (caterpillars) from their host plant (including shelter builders) and reared them to adult moths or parasitoids *(33)*. Caterpillars were located opportunistically by visual inspection along trail transects (distance varies between 50-3000m and select transects are continuously sampled across years), or in 10m diameter plots (149 plots total) by staff scientists, graduate students, parataxonomists and teams of Earthwatch volunteers and students. We excluded *Eois* and *Quadrus* from all analyses because these focal genera present a bias in the rearing dataset due to focused collection for previous studies.

<u>Rearing Methods & Processing Data</u>

For our ongoing interaction diversity survey, collected larvae are given a unique voucher code that associate them with their host plant species. Caterpillars are reared individually in plastic containers or bags with a sample of hostplant. Species identifications are made initially by parataxonomists to lowest taxonomic level or morphospecies and verified by taxonomic experts or by referencing voucher specimens and image libraries. Some morphospecies are confirmed using mtDNA COI sequences, others by examining a mix of morphological characters, and others using genomic data. For the remaining species without morphospecies designations we assign morphotypes based on feeding relationships - consumers from the same family utilizing the same host family are designated a unique morphotype. This method is likely a conservative means to assigning species names, especially for tropical species *(34)*. Voucher specimens are sent to collaborating institutions including universities and museums (see www. caterpillars.org for a list of participating institutions).

Patterns in Diversity, Parasitism, Climate Variables

Abundance & Diversity

Taxonomic and interaction annual frequencies were obtained to understand patterns in diversity and abundance across time. Species-level and interaction frequencies were used for diversity analyses and genus-level frequencies of Lepidoptera were used to evaluate herbivore abundance patterns. Annual frequencies were calculated for each Lepidoptera genera. We limited genus-level abundance data analyses to genera with ≥5 years of data and sample points extending to 2010. Results are reported for the 64 Lepidoptera genera that met criteria. To obtain values of interaction diversity, we modified a community matrix such that rows were comprised of years and columns the unique interactions. Interactions were comprised of bi-trophic (plant-herbivore) and tri-trophic (plant-herbivore-enemy) interactions such that matrix cells represent annual frequencies of those interactions.

Diversity was calculated as Hill numbers, and values were interpreted as interaction or species equivalents *(35)*. Hill numbers vary as a function of the parameter q where q indicates the sensitivity of the index to rare species. We used functions provided in Chao et al. (2015) *(36)* to calculate Hill numbers for q=0, q=1, and q=2. Results for q=0 are reported in text and q=1 & q=2 in the supplemental information. Values for diversity were weighted by sampling effect per hectare, and observed diversity is presented and analyzed in models as species equivalents per hectare per year. To obtain estimated percent herbivore loss we differenced total diversity (an estimate based on averaged Chao estimates of the first 5 years of data) and the observed species decline extrapolated from beta coefficients of the models predicting diversity across years.

Climate Variables

Climate variables were calculated as annual means of daily precipitation and average, minimum and maximum temperatures. We used meteorological data acquired from weather stations within La Selva from 1983-2018 *(37)*. Temperature is reported as degrees Celsius (°C) and precipitation millimeters (mm). To examine effects of extreme weather events and climate variability on patterns of diversity, we calculated anomalies and the coefficients of variation (CV) for each precipitation and temperature variable. Precipitation anomalies were calculated as the sum of daily values exceeding 2.5 standard deviations (sd) of the annual mean. Similarly, for temperature anomalies we used 2sd. The coefficient of variation was calculated as the ratio of standard deviation to the annual mean. We used simple linear regression to evaluate patterns among each climate variable across time and with respect to each season in the supplemental figures.

Evaluating Patterns in Network Structural Properties

We pooled interaction data to the family level for the first (1997-2001) and last (2012-2018) five years of collection to illustrate changes in tri-trophic network structure. For each network illustration we calculated node degrees and relative edge weights and reported link and node richness for each trophic level (Table S2).

Parasitism Frequency

Percent parasitism was calculated as the ratio of parasitism events to the sum of successfully emerged Lepidopteran adults and parasitized individuals for each month from 1997-2018. Excluded from analyses were months with zero parasitism, zero eclosed caterpillars and those months without sufficient sample in the denominator (sum of adult eclosion and parasitism events). Sufficient sample was deemed as values exceeding the 1st quantile (Q_1) of the distribution of denominators (IQR=12-103).

Statistical Models

We used Bayesian linear models to estimate coefficients associated with change through time on Lepidoptera, parasitoid and interaction diversity and parasitism frequency. This model was applied to total parasitism and separately for specialized (Hymenoptera) and non-specialized (Diptera) orders. Models were fit in JAGS (version 3.2.0) run with R and the rjags package *(38)* using (for each analysis) two Markov chains and 1,000,000 steps each; performance was assessed through examination of chain histories (burnin was not required), effective sample sizes and the Gelman and Rubin convergence diagnostic *(39)*. Response variables were modeled as normal distributions with means dependent on an intercept plus predictor variables (either year alone, or year plus climatic variables), and vague or minimally-influential priors as follows: priors on beta coefficients (for year and climatic variables) were normal distributions with mean of zero and precision of 0.01 (variance = 100); priors on precisions were modeled as gamma distributions with rate = 0.1 and shape = 0.1. All data was z transformed prior to analysis.

An additional hierarchical model (with vague priors as already described) was used to estimate change across years in the frequency at which individual Lepidoptera genera were observed, with the year coefficients (and intercepts) estimated for each genus separately (as the lower level in the hierarchy) and simultaneously across all genera (the response variable for this analysis was log transformed prior to z transformation). For all models (simple and hierarchical) we retained point estimates from posterior distributions for beta coefficients, as well as 95% credible intervals for the diversity models and 80% intervals for the hierarchical model. We used the more liberal calculation of intervals for the latter in the interest of minimizing type II error in a situation involving the decline of entire genera (i.e., we would rather risk the possibility of erroneously inferring decline as opposed to mistakenly concluding that a declining taxon is stable). As a complementary measure of confidence not dependent on an arbitrary cutoff for importance, we calculated (for the beta coefficients estimated for each genus) the fraction of the posterior distribution less than zero, which can be interpreted as the probability that a genus has been observed with decreasing frequency over time.

We used Structural Equation Modeling (SEM) to test causal hypotheses that evaluated the effect of climate and time on taxonomic and interaction richness and parasitism. We used the global estimation method in the lavaan package v.0.6-3 *(40)* in R v 3.5.3 to generate 3 models. Models evaluated casual relationships among caterpillar, parasitoid, interaction richness or parasitism and climate variables. Climate variables included: Tmin and Tmax and their anomalies and precipitation anomalies. A priori predictions facilitated the test of causal hypotheses that parasitism was modeled by precipitation and its one year lag. Models were assessed using the $\chi2$ and model comparison using Akaike information criterion (AIC). We reported standardized path coefficients and illustrated the SEM results in a path diagram.

Figures S1-S11

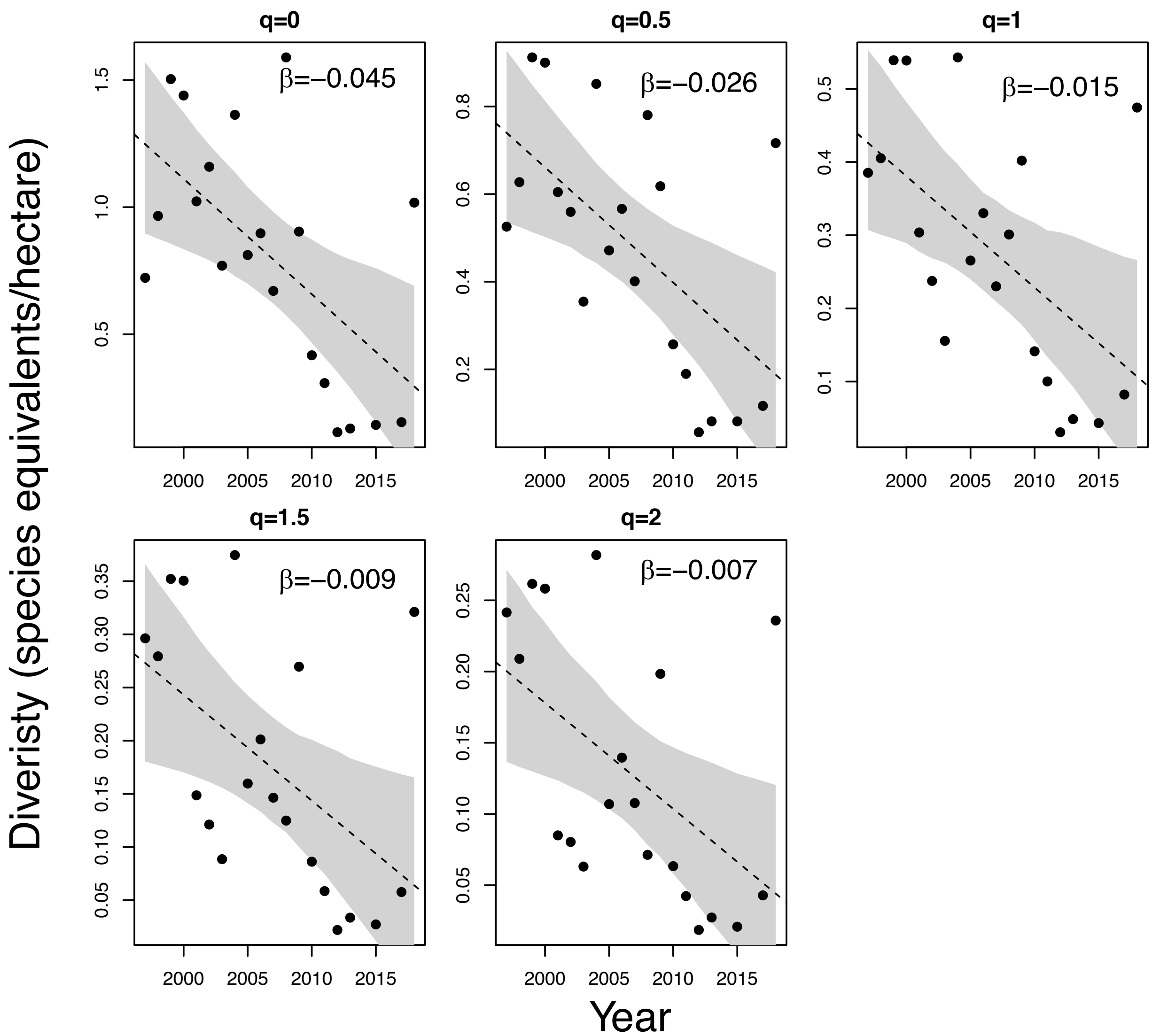

Fig. S1. Lepidoptera diversity measured as effective number of species/hectare across sampling years. Each panel represents Hill numbers between 0 and 2. Beta coefficients are estimated using Bayesian linear models and shaded areas represent 95% credible intervals.

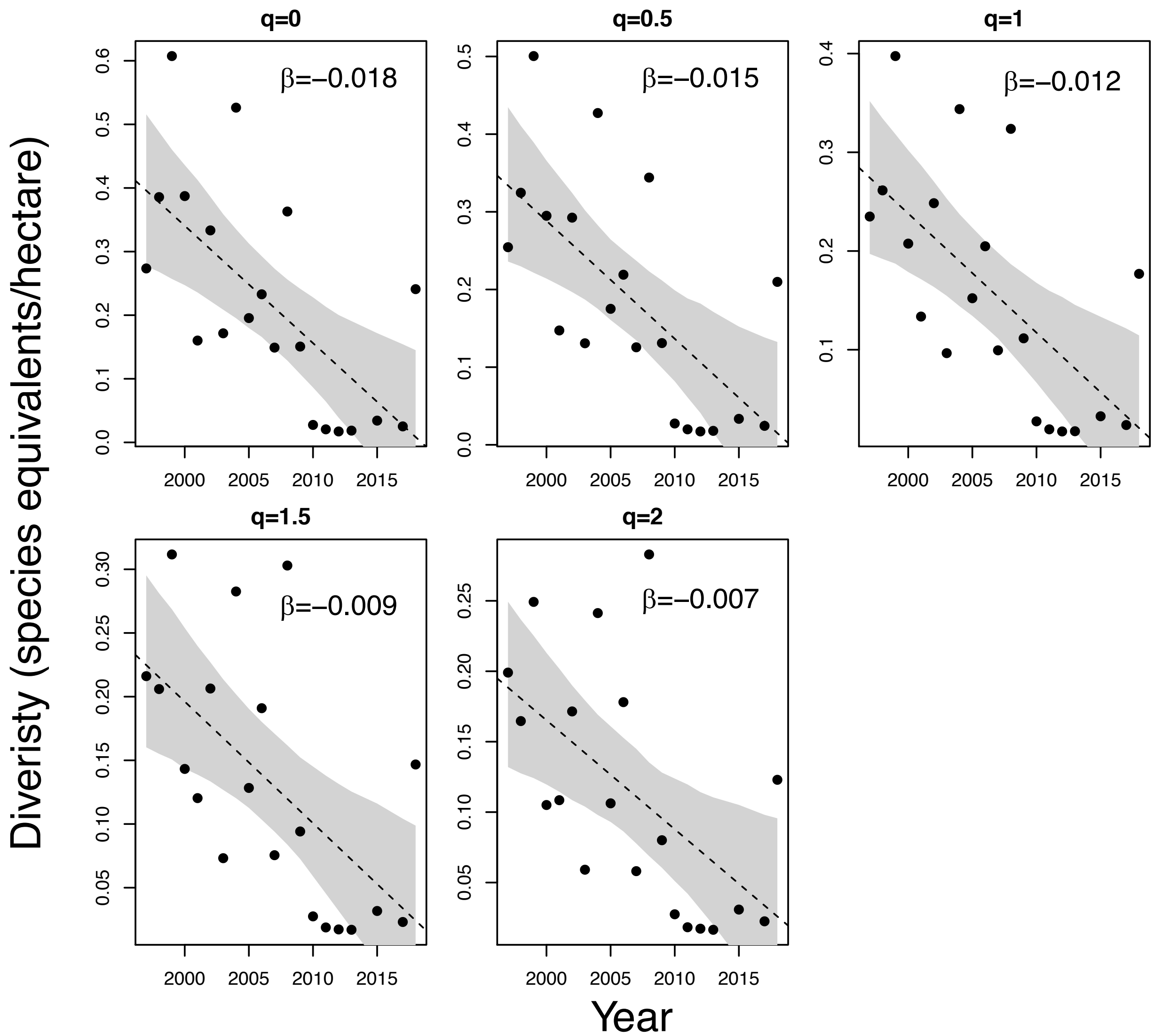

Fig. S2. Parasitoid diversity measured as effective number of species/hectare across sampling years. Each panel represents Hill numbers between 0 and 2. Beta coefficients are estimated using Bayesian linear models and shaded areas represent 95% credible intervals.

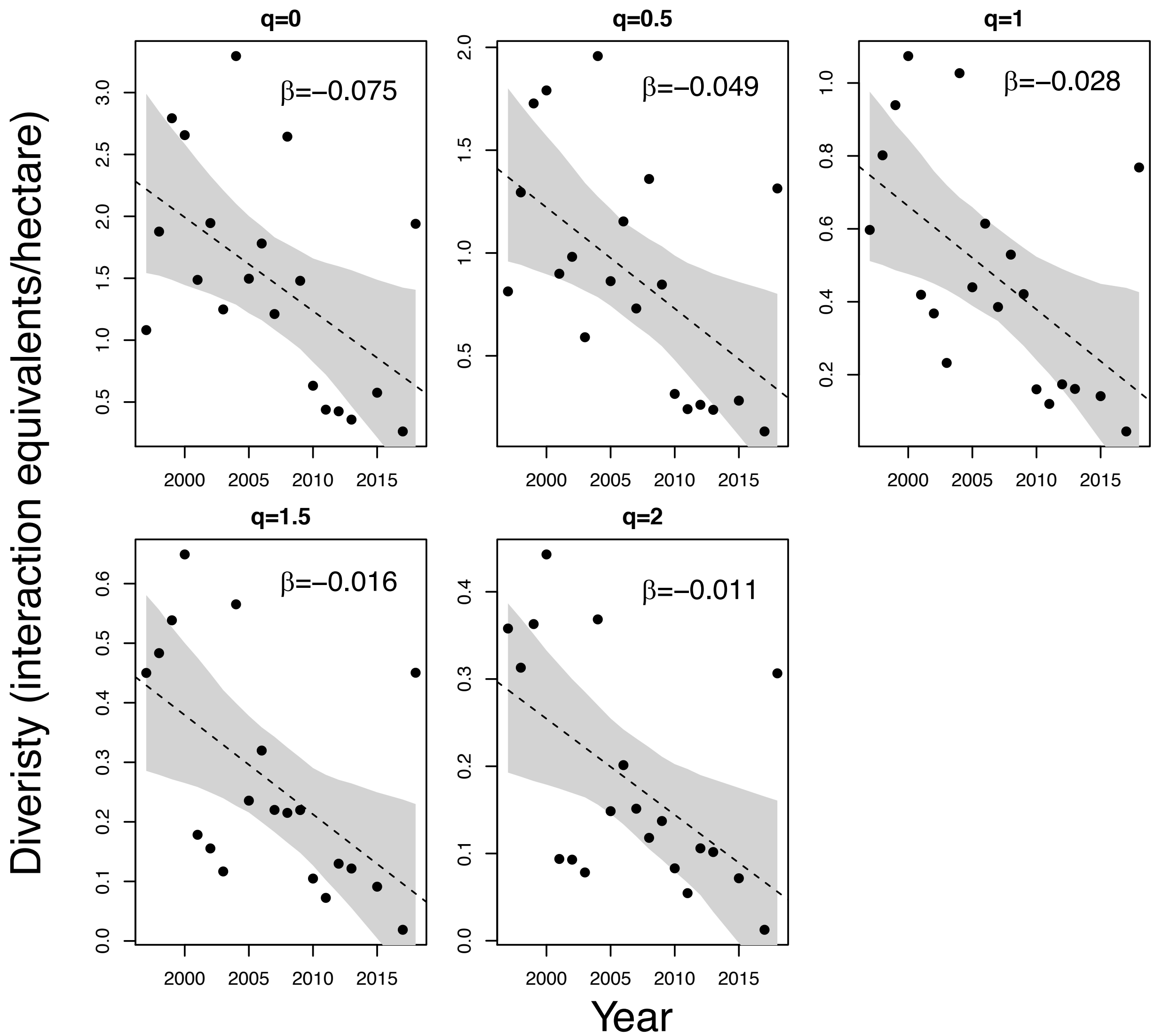

Fig. S3. Tri-trophic interaction diversity measured as effective number of interactions/hectare across sampling years. Each panel represents Hill numbers between 0 and 2. Beta coefficients are estimated using Bayesian linear models and shaded areas represent 95% credible intervals.

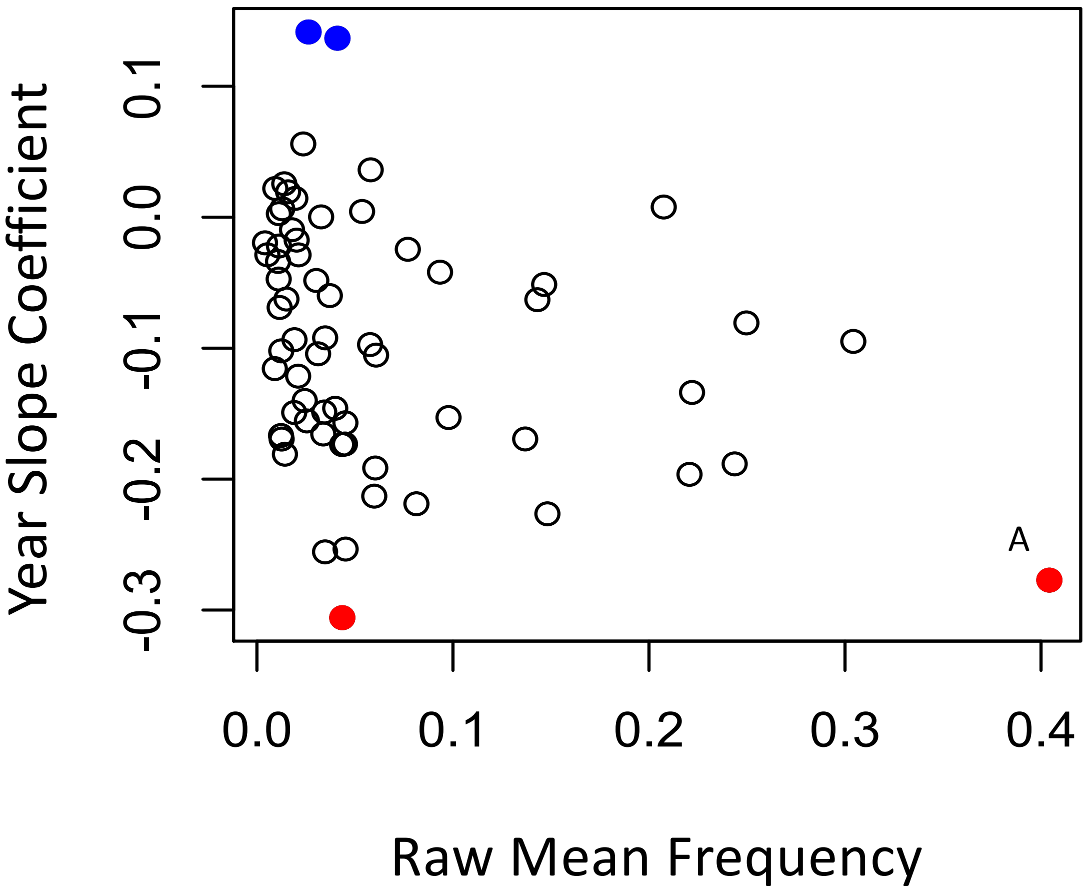

Fig. S4. Slope coefficients for years plotted against raw frequencies of observation for 64 Lepidoptera genera. The blue points the two biggest 'winners' (*Euceron* and *Saliana*) and the red points are our two biggest 'losers' (*Emesis* (A) and *Xylophanes*).

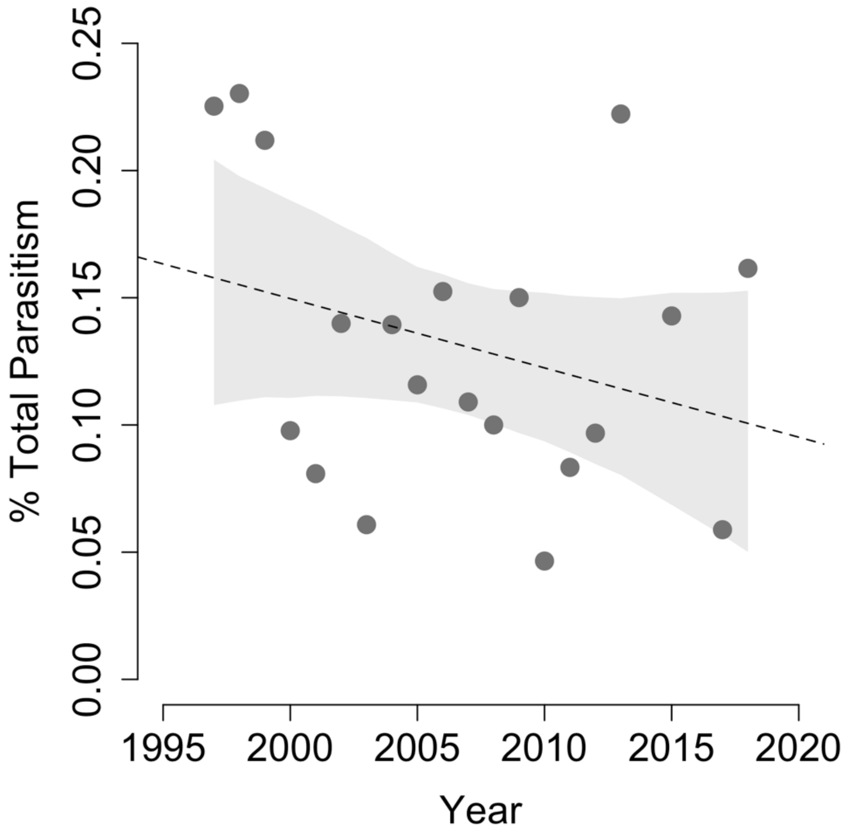

Fig. S5. Parasitism frequency at La Selva across years of study (1997-2018). Bayesian linear model was used to estimate beta coefficient (β =-0.003, [-0.007,0.001]) and shaded area displays 95% credible intervals.

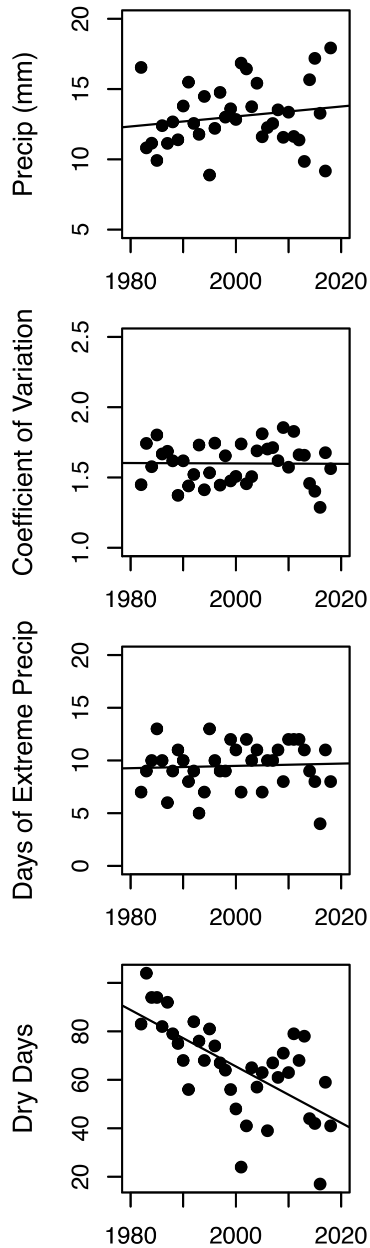

Fig. S6. Patterns in precipitation variables at LaSelva from 1982-2018. Each point represents a year of data. Precip (mm) is calculated as the annual mean of daily precipitation. The Coefficient of Variation (CV) in precipitation is calculated as intra-annual CV. Days of extreme precipitation are counts of daily precipitation exceeding 2.5 SD of annual mean precipitation. Dry days are calculated as total days within a year with zero rainfall.

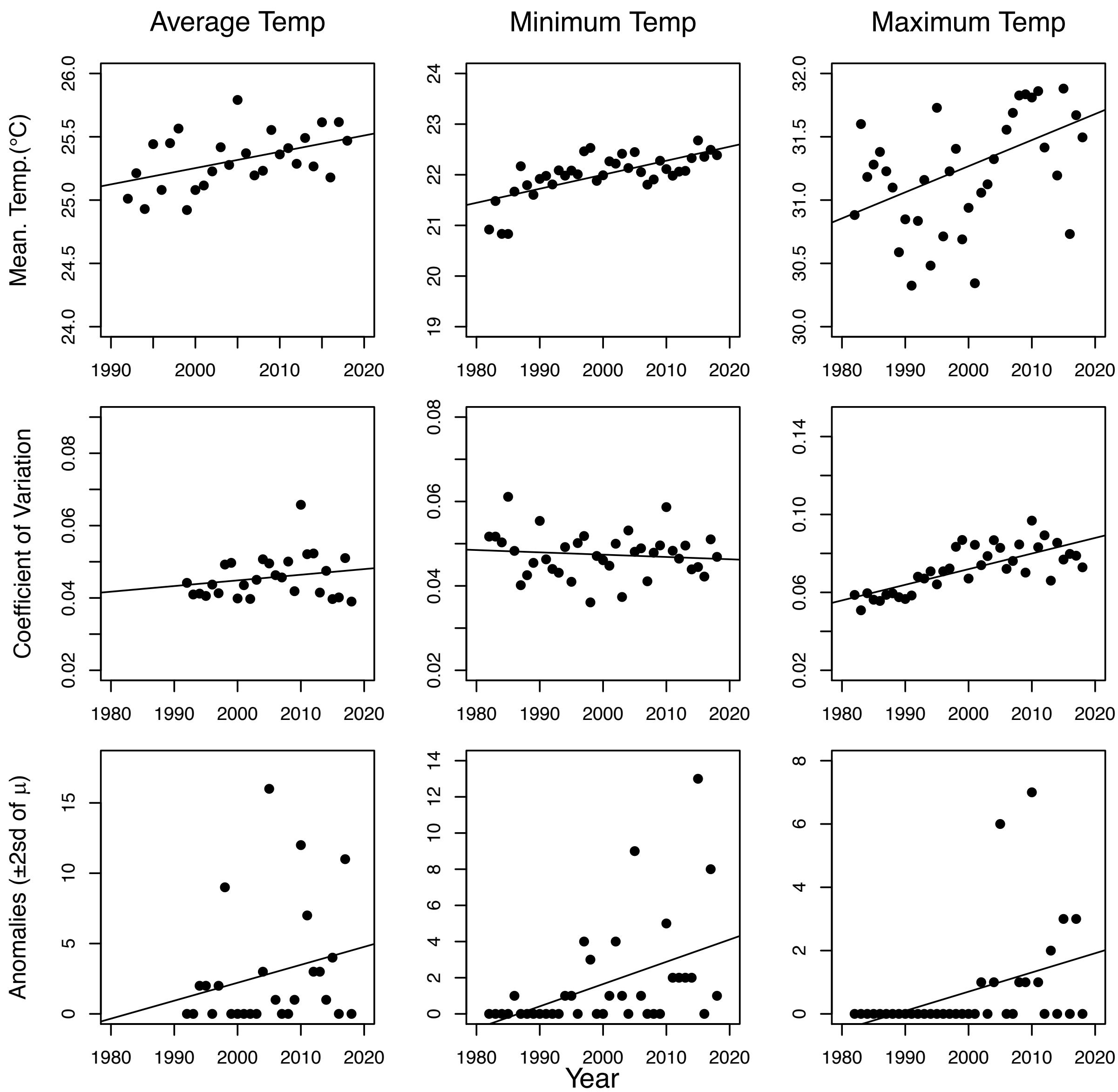

Fig. S7. Patterns in temperature variables (average, minimum and maximum daily temperature) at La Selva from 1982-2018. Each point represents a year of data. Graphs in the first row represent annual means of daily values for each temperature variable. The second row displays the intra-annual Coefficient of Variation. The third row displays temperature anomalies measured as the sum of daily values exceeding 2 SD of the annual mean.

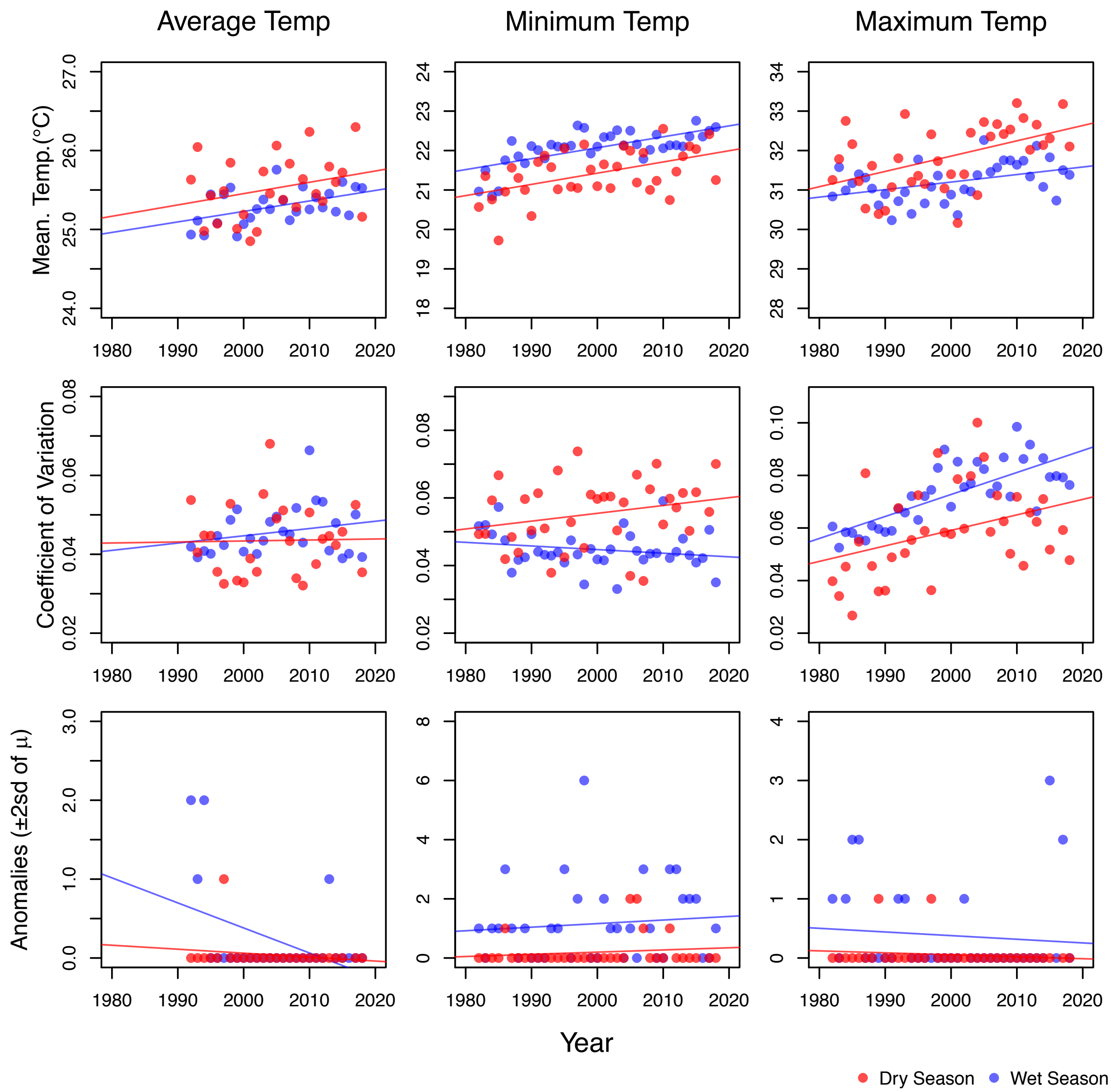

Fig. S8. Patterns in temperature variables at La Selva from 1982-2018 for the wet (blue) and dry (red) season. Wet season includes data from May-December and results for dry season include January-April. Each point represents a year of data. Graphs in the first row represent annual means of daily values for each temperature variable. The second row displays the intra-annual Coefficient of Variation. The third row displays temperature anomalies measured as the sum of daily values exceeding 2 SD of the annual mean.

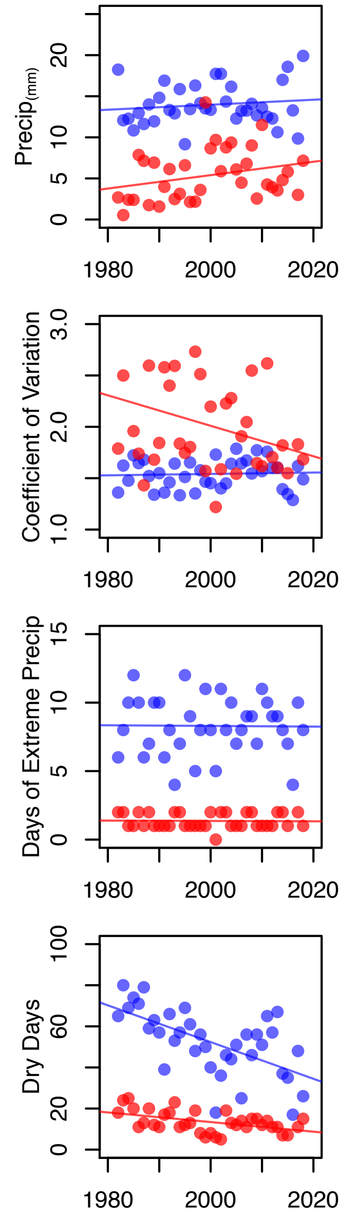

Fig. S9. Patterns in precipitation variables at La Selva from 1982-2018 for the wet (blue) and dry (red) season. Wet season includes data from May-December and results for dry season include January-April. Precip (mm) is calculated as the annual mean of daily precipitation. The Coefficient of Variation (CV) in precipitation is calculated as intra-annual CV. Days of extreme precipitation are counts of daily precipitation exceeding 2.5 SD of annual mean precipitation. Dry days are calculated as total days within a year with zero rainfall.

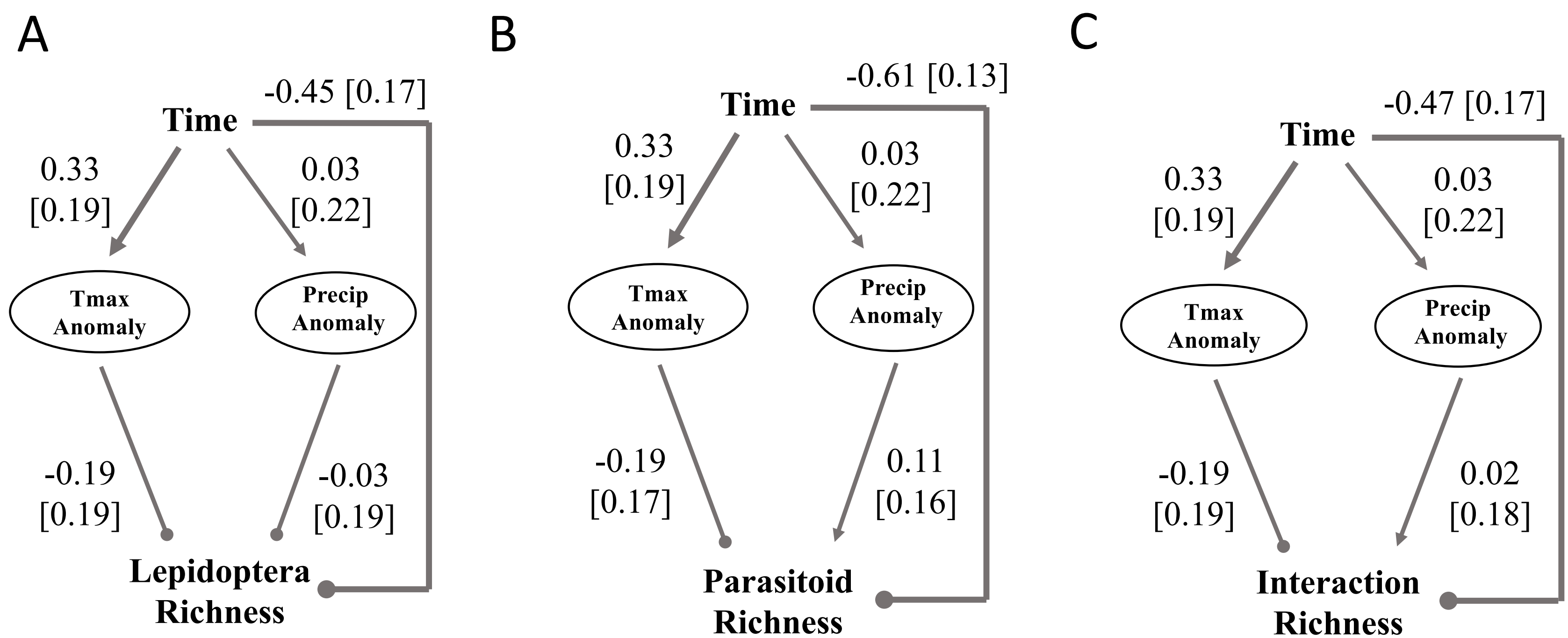

Fig. S10. Structural equation models (SEM) testing the effects of climate anomalies on caterpillar (A), parasitoid (B) and interaction (C) richness . Time is an exogenous variable representing year and the endogenous variables include richness, maximum temperature (Tmax) anomalies and precipitation (precip) anomalies. Path coefficients are standardized and width of arrows are scaled based on magnitude of path coefficients. Arrows represent positive associations and lines with circle represent negative associations. Model fit: (χ^2=9.67, p=0.02, df=3).

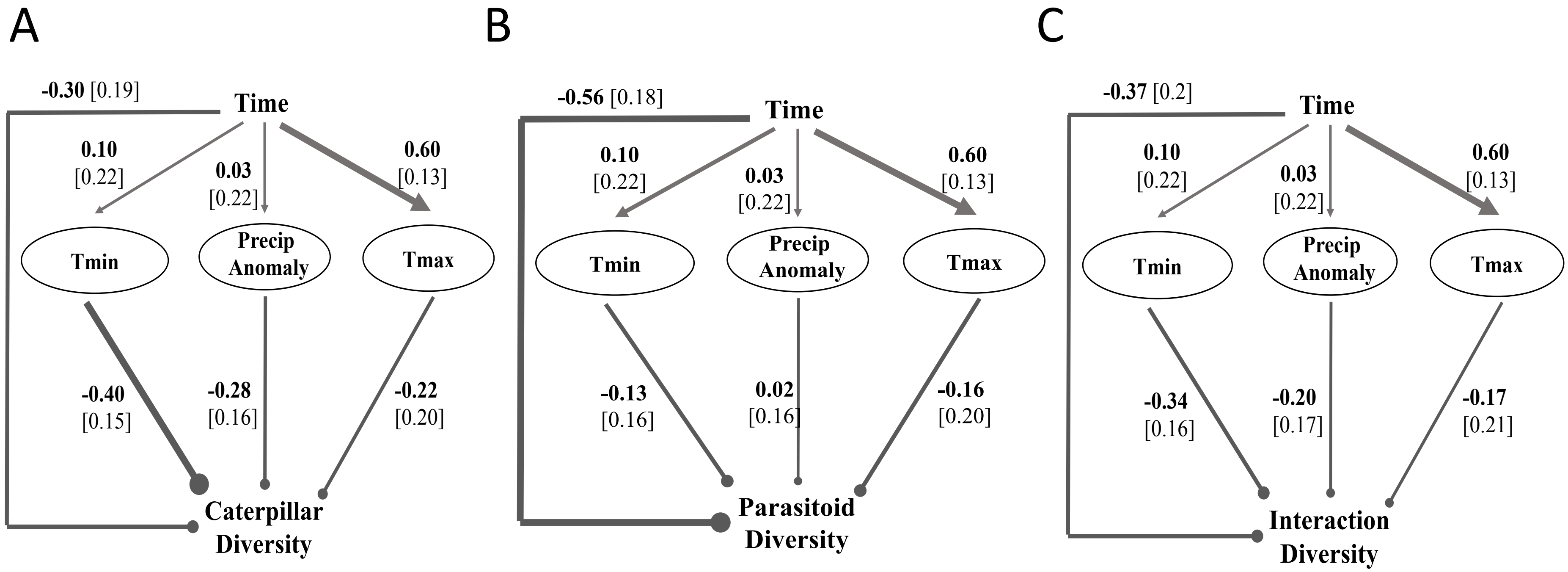

Fig. S11. Structural equation models (SEM) testing the effects of minimum temperature (Tmin), maximum temperature (Tmax) and precipitation anomalies on caterpillar (A), parasitoid (B) and interaction (C) richness . Time is an exogenous variable representing year and the endogenous variables include richness, Tmin, Tmax and precipitation anomalies. Path coefficients are standardized and width of arrows are scaled based on magnitude of path coefficients. Arrows represent positive associations and lines with circle represent negative associations. Model fit: SEM1: (χ^2=0.044, p=0.833, df=1).

Tables S1-S4

Table S1. Estimates of standardized and unstandardized beta coefficients and associated 80% credible intervals for each Lepidoptera genera nested in a hierarchical Bayesian model that modeled frequency across years.

	Standardized Coefficients				Unstandardized Coefficients		
Lepidoptera Genera	**Esitmate**	**CI l_{ower}**	**CI_{upper}**	**Probability**	**Estimate**	**CI_{Low}**	**CI_{High}**
Saliana	0.1412	-0.0528	0.3529	0.1778	0.0356	-0.0133	0.0890
Eucereon	0.1364	-0.0579	0.3485	0.1866	0.0344	-0.0146	0.0879
Malocampa	0.0561	-0.1385	0.2636	0.3579	0.0141	-0.0349	0.0665
Achlyodes	0.0363	-0.1409	0.2211	0.3977	0.0092	-0.0355	0.0557
Memphis	0.0255	-0.1588	0.2179	0.4305	0.0064	-0.0400	0.0549
Zanola	0.0219	-0.1642	0.2169	0.4409	0.0055	-0.0414	0.0547
Cropia	0.0193	-0.1649	0.2119	0.4473	0.0049	-0.0416	0.0534
Dioptis	0.0142	-0.1678	0.2035	0.4604	0.0036	-0.0423	0.0513

	Standardized Coefficients				Unstandardized Coefficients		
Lepidoptera							
Genera	**Esitmate**	**CI l_{ower}**	**CI_{upper}**	**Probability**	**Estimate**	**CI_{Low}**	**CI_{High}**
Euptychia	0.0077	-0.1565	0.1765	0.4763	0.0019	-0.0394	0.0445
Pachydota	0.0064	-0.1886	0.2104	0.4835	0.0016	-0.0476	0.0531
Dunama	0.0045	-0.2107	0.2329	0.4893	0.0011	-0.0531	0.0587
Parides	0.0027	-0.1856	0.1987	0.4927	0.0007	-0.0468	0.0501
Scotura	0.0002	-0.1892	0.1970	0.4995	0.0000	-0.0477	0.0497
Telemiades	**-0.0096**	-0.1971	0.1845	0.5258	-0.0024	-0.0497	0.0465
Anomis	**-0.0175**	-0.2028	0.1734	0.5478	-0.0044	-0.0511	0.0437
Thracides	**-0.0193**	-0.2269	0.1973	0.5469	-0.0049	-0.0572	0.0497
Megalopyge	**-0.0219**	-0.2072	0.1692	0.5599	-0.0055	-0.0522	0.0427
Eueides	**-0.0247**	-0.2066	0.1623	0.5684	-0.0062	-0.0521	0.0409
Isanthrene	**-0.0285**	-0.2090	0.1562	0.5800	-0.0072	-0.0527	0.0394
Euclea	**-0.0287**	-0.2157	0.1637	0.5773	-0.0072	-0.0544	0.0413
Protambulyx	**-0.0339**	-0.2400	0.1800	0.5825	-0.0085	-0.0605	0.0454

	Standardized Coefficients				Unstandardized Coefficients		
Lepidoptera							
Genera	**Esitmate**	**CI l_{ower}**	**CI_{upper}**	**Probability**	**Estimate**	**CI_{Low}**	**CI_{High}**
Acharia	**-0.0420**	-0.2226	0.1417	0.6166	-0.0106	-0.0561	0.0357
Temenis	**-0.0471**	-0.2533	0.1646	0.6147	-0.0119	-0.0639	0.0415
Pericopis	**-0.0480**	-0.2601	0.1702	0.6137	-0.0121	-0.0656	0.0429
Heliconius	**-0.0515**	-0.2312	0.1313	0.6429	-0.0130	-0.0583	0.0331
Consul	**-0.0599**	-0.2490	0.1324	0.6574	-0.0151	-0.0628	0.0334
Talides	**-0.0624**	-0.2479	0.1260	0.6667	-0.0157	-0.0625	0.0318
Hypothyris	**-0.0632**	-0.2466	0.1226	0.6708	-0.0159	-0.0622	0.0309
Tithraustes	**-0.0690**	-0.2756	0.1408	0.6657	-0.0174	-0.0695	0.0355
Chlosyne	**-0.0808**	-0.2558	0.0951	0.7234	-0.0204	-0.0645	0.0240
Hamadryas	**-0.0919**	-0.2877	0.1040	0.7281	-0.0232	-0.0726	0.0262
Dubiella	**-0.0933**	-0.2933	0.1070	0.7268	-0.0235	-0.0740	0.0270
Automeris	**-0.0946**	-0.2640	0.0751	0.7638	-0.0238	-0.0666	0.0189
Gamelia	**-0.0975**	-0.2897	0.0946	0.7436	-0.0246	-0.0730	0.0238

	Standardized Coefficients				Unstandardized Coefficients		
Lepidoptera							
Genera	**Esitmate**	**CI l_{ower}**	**CI_{upper}**	**Probability**	**Estimate**	**CI_{Low}**	**CI_{High}**
Epimecis	**-0.1017**	-0.2948	0.0908	0.7523	-0.0256	-0.0743	0.0229
Phaeoblemma	**-0.1043**	-0.3068	0.0977	0.7475	-0.0263	-0.0774	0.0246
Spodoptera	**-0.1052**	-0.2831	0.0724	0.7774	-0.0265	-0.0714	0.0183
Hypercompe	**-0.1154**	-0.3246	0.0915	0.7638	-0.0291	-0.0818	0.0231
Anacrusis	**-0.1211**	-0.3104	0.0658	0.7976	-0.0305	-0.0783	0.0166
Quentalia	**-0.1337**	-0.3443	0.0727	0.7981	-0.0337	-0.0868	0.0183
Olceclostera	**-0.1397**	-0.3259	0.0428	0.8374	-0.0352	-0.0822	0.0108
Phoebis	**-0.1458**	-0.3630	0.0654	0.8126	-0.0368	-0.0915	0.0165
Milanion	**-0.1488**	-0.3407	0.0387	0.8459	-0.0375	-0.0859	0.0097
Antichloris	**-0.1490**	-0.3827	0.0762	0.8027	-0.0376	-0.0965	0.0192
Cyclomia	**-0.1530**	-0.3144	0.0062	**0.8910**	-0.0386	-0.0793	0.0016
Oraesia	**-0.1553**	-0.3526	0.0368	**0.8505**	-0.0392	-0.0889	0.0093
Astraptes	**-0.1567**	-0.3104	-0.0055	**0.9080**	-0.0395	-0.0783	-0.0014

	Standardized Coefficients				Unstandardized Coefficients		
Lepidoptera							
Genera	**Esitmate**	**CI l_{ower}**	**CI$_{upper}$**	**Probability**	**Estimate**	**CI$_{Low}$**	**CI$_{High}$**
Adelphia	**-0.1656**	-0.3466	0.0110	**0.8852**	-0.0418	-0.0874	0.0028
Tigridia	**-0.1667**	-0.3600	0.0210	**0.8725**	-0.0420	-0.0908	0.0053
Caligo	**-0.1693**	-0.3602	0.0161	**0.8791**	-0.0427	-0.0908	0.0041
Myscelus	**-0.1695**	-0.3919	0.0437	0.8460	-0.0427	-0.0988	0.0110
Desmia	**-0.1730**	-0.3511	0.0007	**0.8992**	-0.0436	-0.0885	0.0002
Tarchon	**-0.1738**	-0.3430	-0.0078	**0.9102**	-0.0438	-0.0865	-0.0020
Pachylia	**-0.1806**	-0.3751	0.0073	**0.8909**	-0.0455	-0.0946	0.0018
Agaraea	**-0.1881**	-0.3765	-0.0056	**0.9067**	-0.0474	-0.0949	-0.0014
Papilio	**-0.1915**	-0.3888	-0.0016	**0.9018**	-0.0483	-0.0980	-0.0004
Dysschema	**-0.1961**	-0.3827	-0.0159	**0.9185**	-0.0494	-0.0965	-0.0040
Apatelodes	**-0.2129**	-0.3964	-0.0364	**0.9391**	-0.0537	-0.0999	-0.0092
Gonodonta	**-0.2186**	-0.3808	-0.0606	**0.9622**	-0.0551	-0.0960	-0.0153
Hylesia	**-0.2266**	-0.4096	-0.0512	**0.9513**	-0.0571	-0.1033	-0.0129

	Standardized Coefficients				Unstandardized Coefficients		
Lepidoptera							
Genera	**Esitmate**	**CI l_{ower}**	**CI_{upper}**	**Probability**	**Estimate**	**CI_{Low}**	**CI_{High}**
Pantographa	**-0.2532**	-0.4322	-0.0816	**0.9713**	-0.0638	-0.1090	-0.0206
Dysodia	**-0.2554**	-0.4555	-0.0672	**0.9595**	-0.0644	-0.1149	-0.0169
Emesis	**-0.2768**	-0.4933	-0.0768	**0.9630**	-0.0698	-0.1244	-0.0194
Xylophanes	**-0.3059**	-0.4798	-0.1401	**0.9916**	-0.0771	-0.1210	-0.0353

Table S2. Quantitative comparisons among observed network metrics summed for the first (1997-2001) and last (2012-2018) five years of data. Values represent network properties summarized at the level of taxonomic families, and (in square brackets) at the level of species.

Network Property	**1997-2001**	**2012-2018**
Node Richness		
Host plant	109 [325]	79 [216]
Herbivore	32[941]	24 [257]
Parasitoid	10 [385]	2 [67]
Total	151 [1651]	105 [540]
Link Richness		
Host Plant-Herbivore	442 [1654]	199 [409]
Herbivore-Parasitoid	83 [547]	19 [80]
Total	525 [2201]	218 [489]

Table S3. Linear model estimates and fit for various climate variables collected from 1983-2018.

	Climate Variable	Estimate	Std.Error	P.Value	R.squared
Annual Mean	Precip (mm)	0.036	0.035	0.315	0.029
	Tmin	0.028	0.005	0.000	0.475
	Tmax	0.021	0.007	0.005	0.200
	Avg. Temp.	0.013	0.005	0.014	0.217
Anomaly	Extreme Precip. Event	0.011	0.034	0.749	0.003
	Drought Events	-1.165	0.229	0.000	0.426
	Tmin	0.061	0.023	0.012	0.166
	Tmax	0.123	0.040	0.004	0.211
	Avg. Temp.	0.128	0.106	0.241	0.054
Coefficient of Variation	Precip (mm)	1.000	0.000	0.000	1.000
	Tmin	0.000	0.002	0.950	0.000
	Tmax	0.000	0.000	0.508	0.013
	Avg. Temp.	0.001	0.000	0.000	0.559

Table S4. Linear model estimates and fit for various climate variables collected from 1983-2018. Data is displayed for wet (May-December) and dry(January-April) seasons separately.

	Climate Variable	Estimate	Std. Error	P.value	R.squared
Wet Season					
Annual Mean	Precip (mm)	0.030	0.039	0.440	0.017
	Tmin	0.028	0.005	0.000	0.452
	Tmax	0.019	0.007	0.009	0.177
	Avg. Temp	0.013	0.005	0.011	0.230
Anomaly	Days of Extreme Precip.	-0.002	0.032	0.942	0.000
	Dry Days	-0.894	0.197	0.000	0.370
	Tmax	-0.006	0.012	0.605	0.008
	Tmin	0.012	0.021	0.560	0.010
	Avg. Temp	-0.032	0.013	0.023	0.190
Coefficient of Variation	Precip (mm)	1.000	0.000	0.000	1.000
	Tmin	0.001	0.002	0.760	0.003
	Tmax	0.000	0.000	0.220	0.043
	Avg. Temp	0.001	0.000	0.000	0.579
Dry Season					
Annual Mean	Precip (mm)	0.081	0.049	0.102	0.077
	Tmin	0.028	0.008	0.002	0.250
	Tmax	0.039	0.012	0.002	0.248
	Avg. Temp	0.014	0.010	0.165	0.079

Anomaly	Days of Extreme Precip.	-0.001	0.009	0.881	0.001
	Dry Days	-0.234	0.072	0.003	0.235
	Tmax	-0.003	0.004	0.377	0.023
	Tmin	0.007	0.008	0.385	0.022
	Avg. Temp	-0.005	0.005	0.331	0.039
Coefficient of Variation	Precip (mm)	1.000	0.000	0.000	1.000
	Tmin	-0.015	0.008	0.059	0.101
	Tmax	0.001	0.000	0.007	0.201
	Avg. Temp	0.000	0.000	0.702	0.006

References and Notes:

1. Vitousek, P.M., Mooney, H.A., Lubchenco, J., Melillo, J.M. Human domination of Earth's ecosystems. *Science* **277,** 494-499 (1997).
2. Parmesan, C., Ecological and evolutionary responses to recent climate change. *Annu. Rev. Ecol. Evol. Syst.*, ***37***, 637-669 (2006).
3. Tylianakis, J.M., Didham, R.K., Bascompte, J., Wardle, D.A. Global change and species interactions in terrestrial ecosystems. *Ecology letters*, ***11***, 1351-1363 (2008).
4. Poisot, T., Stouffer, D.B., Gravel, D. Beyond species: why ecological interaction networks vary through space and time. *Oikos*, ***124***, 243-251 (2015).
5. Clarke, D.A., York, P.H., Rasheed, M.A., Northfield, T.D. Does biodiversity–ecosystem function literature neglect tropical ecosystems?. *Trends in ecology & evolution*, ***32***, 320-323 (2017).

6. Pereira, H.M., Navarro, L.M., Martins, I.S. Global biodiversity change: the bad, the good, and the unknown. *Annual Review of Environment and Resources*, ***37***, 25-50 (2012).
7. Dirzo, R., Young, H. S., Galetti, M., Ceballos, G., Isaac, N. J., & Collen, B. Defaunation in the Anthropocene. *Science*, *345*(6195), 401-406 (2014).
8. Lister, B.C., Garcia, A. Climate-driven declines in arthropod abundance restructure a rainforest food web. *Proceedings of the National Academy of Sciences*, ***115***, E10397-E10406 (2018).
9. Hance, T., Van Baaren, J., Vernon, P., Boivin, G. Impact of extreme temperatures on parasitoids in a climate change perspective. *Annu. Rev. Entomol.*, ***52***, 107-126 (2007).
10. Jamieson, M.A., Burkle, L.A., Manson, J.S., Runyon, J.B., Trowbridge, A.M., Zientek, J. Global change effects on plant–insect interactions: the role of phytochemistry. *Current opinion in insect science*, ***23***, 70-80 (2017).
11. Cornelissen, T. Climate change and its effects on terrestrial insects and herbivory patterns. *Neotropical Entomology*, ***40*,** 155-163 (2011).
12. Bonebrake, T.C., Deutsch, C.A. Climate heterogeneity modulates impact of warming on tropical insects. *Ecology*, ***93***, 449-455 (2012).
13. Corlett, R.T. Impacts of warming on tropical lowland rainforests. *Trends in ecology & evolution*, ***26***, 606-613 (2011).
14. Forister, M.L., Novotny, V., Panorska, A.K., Baje, L., Basset, Y., Butterill, P.T., Cizek, L., Coley, P.D., Dem, F., Diniz, I.R., Drozd, P. The global distribution of diet breadth in insect herbivores. *Proceedings of the National Academy of Sciences*, ***112***, 442-447(2015).
15. McKinney, M.L.,Lockwood, J.L. Biotic homogenization: a few winners replacing many losers in the next mass extinction. *Trends in ecology & evolution*, ***14*,** 450-453 (1999).

16. Van Bael, S. A., Aiello, A., Valderrama, A., Medianero, E., Samaniego, M., Wright, S. J. General herbivore outbreak following an El Nino-related drought in a lowland Panamanian forest. *Journal of Tropical Ecology*, ***20*,** 625-633(2004).
17. Whitfield, S.M., Bell, K.E., Philippi, T., Sasa, M., Bolaños, F., Chaves, G., Savage, J.M., Donnelly, M.A. Amphibian and reptile declines over 35 years at La Selva, Costa Rica. *Proceedings of the National Academy of Sciences*, ***104***,8352-8356 (2007).
18. Cleary, K.A., Waits, L.P., Finegan, B. Agricultural intensification alters bat assemblage composition and abundance in a dynamic Neotropical landscape. *Biotropica*, ***48***, 667-676 (2016).
19. Sigel, B.J., Sherry, T.W., Young, B.E. Avian community response to lowland tropical rainforest isolation: 40 years of change at La Selva Biological Station, Costa Rica. *Conservation Biology*, ***20***, 111-121 (2006).

20. Dyer, L., Letourneau, D. Can climate change trigger massive diversity cascades in terrestrial ecosystems?. *Diversity*, ***5***,479-504 (2013).
21. Valiente-Banuet, A., Aizen, M.A., Alcántara, J.M., Arroyo, J., Cocucci, A., Galetti, M., García, M.B., García, D., Gómez, J.M., Jordano, P., Medel, R. Beyond species loss: the extinction of ecological interactions in a changing world. *Functional Ecology*, ***29***, 299-307 (2015).
22. Tylianakis, J.M., Didham, R.K., Bascompte, J.,Wardle, D.A. Global change and species interactions in terrestrial ecosystems. *Ecology letters*, ***11*,** 1351-1363 (2008).
23. Tylianakis, J.M., Tscharntke, T.,Lewis, O.T. Habitat modification alters the structure of tropical host–parasitoid food webs. *Nature*, ***445***, 202 (2007).

24. Poisot, T., Guéveneux-Julien, C., Fortin, M.J., Gravel, D., Legendre, P. Hosts, parasites and their interactions respond to different climatic variables. *Global ecology and biogeography*, ***26***, 942-951(2017).

25. Finke, D.L., Snyder, W.E. Niche partitioning increases resource exploitation by diverse communities. *Science*, ***321***, 1488-1490 (2008).

26. Poisot, T., Mouquet, N., Gravel, D. Trophic complementarity drives the biodiversity–ecosystem functioning relationship in food webs. *Ecology letters*, ***16***, 853-861(2013).

27. Costanza, R., d'Arge, R., De Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'neill, R.V., Paruelo, J., Raskin, R.G. The value of the world's ecosystem services and natural capital. *Nature*, ***387***, 253 (1997).

28. Costanza, R., de Groot, R., Sutton, P., Van der Ploeg, S., Anderson, S.J., Kubiszewski, I., Farber, S., Turner, R.K. Changes in the global value of ecosystem services. *Global environmental change*, ***26*,**152-158 (2014).

29. J. Stireman *et al*., Climatic unpredictability and parasitism of caterpillars: implications of global warming. *Proc. Natl. Acad. Sci. U. S. A.* **102**, 17384-17387 (2005).

30. Howson, C., Urbach, P. *Scientific reasoning: the Bayesian approach*. (Open Court Publishing), 2006.

31. Sánchez-Bayo, F., Wyckhuys, K. A. Worldwide decline of the entomofauna: A review of its drivers. *Biological Conservation*, ***232***, 8-27 (2019).

32. Thomas, C.D., Jones, T.H. and Hartley, S.E.“Insectageddon”: a call for more robust data and rigorous analyses. *Global change biology*, (2019).

33. Gentry, G.L., Dyer, L.A. On the conditional nature of neotropical caterpillar defenses against their natural enemies. *Ecology*, ***83***, 3108-3119 (2002).

34. Dyer, L.A., Singer, M.S., Lill, J.T., Stireman, J.O., Gentry, G.L., Marquis, R.J., Ricklefs, R.E., Greeney, H.F., Wagner, D.L., Morais, H.C., Diniz, I.R.Host specificity of Lepidoptera in tropical and temperate forests. *Nature*, ***448*****,** 696, (2007).

35. Jost, L.Partitioning diversity into independent alpha and beta components. *Ecology*, ***88*****,** 2427-2439 (2007).

36. Chao, A., Jost, L. Estimating diversity and entropy profiles via discovery rates of new species. *Methods in Ecology and Evolution*, ***6***, 873-882 (2015).

37. Clark, D.A. NPP Tropical Forest: La Selva, Costa Rica, 1975-1994, R1. Data set. Available on-line [http://daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, USA. doi:10.3334/ORNLDAAC/218

38. Plummer, M. JAGS: A program for analysis of Bayesian graphical models using Gibbs sampling. In *Proceedings of the 3rd international workshop on distributed statistical computing*. **124** (2003).

39. Brooks, S.P., Gelman, A. General methods for monitoring convergence of iterative simulations. *Journal of computational and graphical statistics*, ***7*****,** .434-455(1998).

40. Rosseel, Y. Lavaan: An R package for structural equation modeling and more. Version 0.5–12 (BETA). *Journal of statistical software*, ***48***, 1-36(2012).