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Association Between Temperature, Rainfall, and Insect Population Dynamics

Jahanzeb Choudhary

MSc (Hons) Agri. Entomology, P.G.D MEDVC.

ABSTRACT

Climatic variability has a strong influence on insect populations, as both temperature and precipitation have direct physiological effects on development, reproduction and survival, and indirect effects which are mediated by the availability of host plant, the dynamics of natural enemies, and the quality of the insect habitat. The climatic drivers are directly impacted by global climate change and have been shown to affect insect phenology, geographic range, abundance, and community composition. The study is designed as a quantitative, observational type of research to examine the relationship among temperature, rainfall and insect population dynamics in the four groups of insects (mosaquitoes, butterflies, beetles and aphids) monitored with standardized field transect surveys over a 48 month period (2020-2024) at six sites that are ecologically diverse. Weather data were retrieved from co-located weather stations as well as from regional National Oceanic and Atmospheric Administration (NOAA) data. Using multiple regression and correlation analysis, strong positive relationships were found between temperature and mosquito population indices ($r = 0.82$, $p < 0.001$) and between temperature and aphid population indices ($r = 0.65$, $p < 0.001$); but, the strongest positive relationships were found between rainfall and butterfly population indices ($r = 0.70$, $p < 0.001$) and between vegetation greenness and butterfly population indices ($r = 0.78$, $p < 0.001$). The temperature was highly correlated with the locusts ($r = 0.88$), while the rainfall showed a moderate negative correlation (−0.35), which is in accordance with their preference to live in semi-arid areas. The overall insect abundance index was best predicted by the multiple regression model ($R^2 = 0.714$, $F = 28.3$, $p < 0.001$). The seasonal analysis showed that the summer months favored high abundances in all groups, and the emergence timing in spring was well correlated with the number of accumulated degree-days. The results are of relevance to vector control, agricultural pest management and biodiversity conservation to accelerate climate change.

Key words: Insect population dynamics, climate change, phenology, insect field survey, temperature, rainfall, correlation analysis, mosquitoes, butterflies, aphids

Corresponding Author: Jahanzeb Choudhary
Email: jzbch.ento@gmail.com

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INTRODUCTION

Insects are the most species-rich class of animals on earth, providing ecosystem services with far-reaching ecological and economic benefits such as pollination, nutrient cycling, biological pest control and decomposition (Speight et al., 2008). Meanwhile, numerous species of insects are pests and vectors of disease in humans, animals, and plants, with significant economic and public health costs worldwide (Deutsch et al., 2018; Caminade et al., 2019). Climatic variables, and temperature and precipitation especially, have a strong influence on insect dynamics, such as abundance, distribution, phenology, and community composition. Insects are ectotherms, with no internal temperature regulating system, and their metabolic, developmental, and reproductive requirements depend on the temperature in the surrounding environment (Bale et al., 2002; Kingsolver & Huey, 2008).

Global mean surface temperatures have risen by around 1.1°C since pre-industrial times and are expected to increase by a further 1.0 – 3.0°C by 2100 if emissions continue on their current trajectory (IPCC, 2023). Precipitation patterns are also changing, both in terms of increased intensity of both wet and dry extremes in many regions and changes in seasonality of monsoon systems, and also in terms of increased frequency of drought events. These changes are already having detectable impacts on insect species, such as phenological shift of spring emergence, range shift, either northward or upslope, and changes in voltinism (the number of generations per year), and, in some instances, a considerable decline in abundance (Parmesan & Yohe, 2003; Hallmann et al., 2023; Macgregor et al., 2023).

As ecologically and economically important, these dynamics have been studied at a relatively small number of sites across short time-scales, specifically in developing country contexts around the globe with the highest biodiversity and agricultural and public health risk posed by insect pests (Hopp & Foley, 2023; Bonebrake et al., 2023). To be able to accurately model the relationships between insect population dynamics and the temperature and rainfall, and to develop adaptive management strategies, it is crucial to understand the specific associations, including non-linear and interactive, species-group specific, and seasonal modulation.

This study adds to this body of evidence by combining 48 months of standardized field survey data on four insect functional groups with co-located meteorological records, and conducting a quantitative observational analysis. The goals of the study are: (1) to quantify seasonal patterns of insect population dynamics over the course of the study, 2020-2024; (2) to explore the relationship between climate, insect abundance, and insect indices using correlation and multiple regression analysis; and (3) to compare the climate-insect relationship for each season and for each of the four functional groups to determine which climate variables are the most important indicators of insect abundance.

LITERATURE REVIEW

Temperature's influence on insect development and abundance

Insect development is regulated by temperature and this has a direct effect on the rate of enzymatic reactions, the basis of insect metabolic activity, growth, and reproduction. The relationship between temperature and insect development rate is typically described by a thermal performance curve; development rate goes up linearly with temperature between lower developmental threshold ($T_{m}{}^{I}{}_{n}$) and thermal optimum (T_{opt}) and then decreases rapidly as temperature approaches a critical thermal maximum ($CT_{ma}{}^{x}$) (Speight et al., 2008; Kingsolver & Huey, 2008). Thermal time (degree-days) accumulations are species and life-stage dependent which support the phenological models used to predict emergence, reproduction and population peaks based on temperature accumulation (Logan et al., 2003; Yamamura & Kiritani, 1998).

In addition to impacting abundance via their effects on reproduction and survival, temperature also impacts abundance via other factors. Increased voltinism (more generations per season) is observed as warming, as it has been in aphids, bark beetles, and mosquitoes (Bebber et al., 2013; Deutsch et al., 2018). Deutsch et al. (2018) show that crop damage due to insect pests is likely to increase in temperate farming systems, where current temperatures are already below the thermal optimum for most insect pests, under climate change scenarios, but will not necessarily increase in already-warm tropical systems where temperatures increasingly occur outside optimal ranges. Hallmann et al. (2023) report a 76% drop in total flying insect biomass across 27 years in protected areas in Germany, with a major share of this loss being linked to shifts in seasonality of temperature and agriculture use.

The impacts of rainfall and precipitation on insect populations

Precipitation has direct and indirect effects on insects. Direct effects consist of direct damage to small-bodied insects due to heavy rainfall, conducive aquatic habitat for water-dependent insects (especially dipteran vectors such as Aedes & Anopheles mosquitoes) and the supply of soil moisture needed for soil-dwelling larvic stages. Indirect effects include changes in host plant productivity, phenology and nutritional value due to changes in precipitation; effects on natural enemy populations (predators, parasitoids and pathogens); and modification of microhabitat thermal and moisture conditions (Walther et al., 2002; Singer & Parmesan, 2010).

Precipitation and insect abundance are very species dependent and are not always linearly related. Heavy rainfall can kill aphids directly, as well as dilute the food value of host plants, and has been shown to reduce aphid populations on many host plant species (Dixon, 2012). However, butterfly species links to water are frequently more positive in water-limited systems where host plant production of larvae is controlled by water (Warren et al., 2001; Macgregor et al., 2023). Precipitation with the standing water breeding habitat is a strong factor associated with vector mosquito density (Aedes aegypti, Anopheles gambiae)--the hosts of dengue and malaria and their transmission intensities are well documented to be positively correlated with lagged precipitation indices (Hopp & Foley, 2023; Caminade et al., 2019).

Climate Change, Phenology, and Community Dynamics

In Europe, there are systematic phenological shifts across insect taxa, with the average rate of spring emergence shift being 5–10 days per decade in long-term monitoring datasets (Parmesan & Yohe, 2003; Both et al., 2009). When the phenological shifts affect synchronized timing relationship between insects and food sources (or mutualists), they have ecological consequences. Under projected warming, plant-pollinator timing relationships are extensively altered as recorded in Memmott et al. (2007); this has important consequences for both ecosystem function and agricultural productivity. The study by Macgregor et al. (2023) illustrates that UK butterfly communities have recorded an average flight period shift of 6.8 days over a 25-year period of monitoring, but that these shifts vary by species and are linked to species thermal sensitivity and specialization.

Climate change is causing geographic range shifts in the distribution of insects, with species more tolerant of hotter conditions becoming more abundant at the northern and upslope edges of their range, and species more sensitive to cold conditions contracting their range (Chen et al., 2011; Thomas et al., 2004). An elevational increase in butterfly species richness and change in species composition in the Cantabrian Mountains in response to warming is reported by Wilson et al. (2007) and a significant relationship between 20th century range expansions of mobile butterfly species in Britain and climate warming is reported by Warren et al. (2001). Such community-level reorganization can create new ecological interactions (including new pest-host plant associations) that have potentially important agricultural and conservation consequences (Bebber et al., 2013; Tougeron et al., 2020).

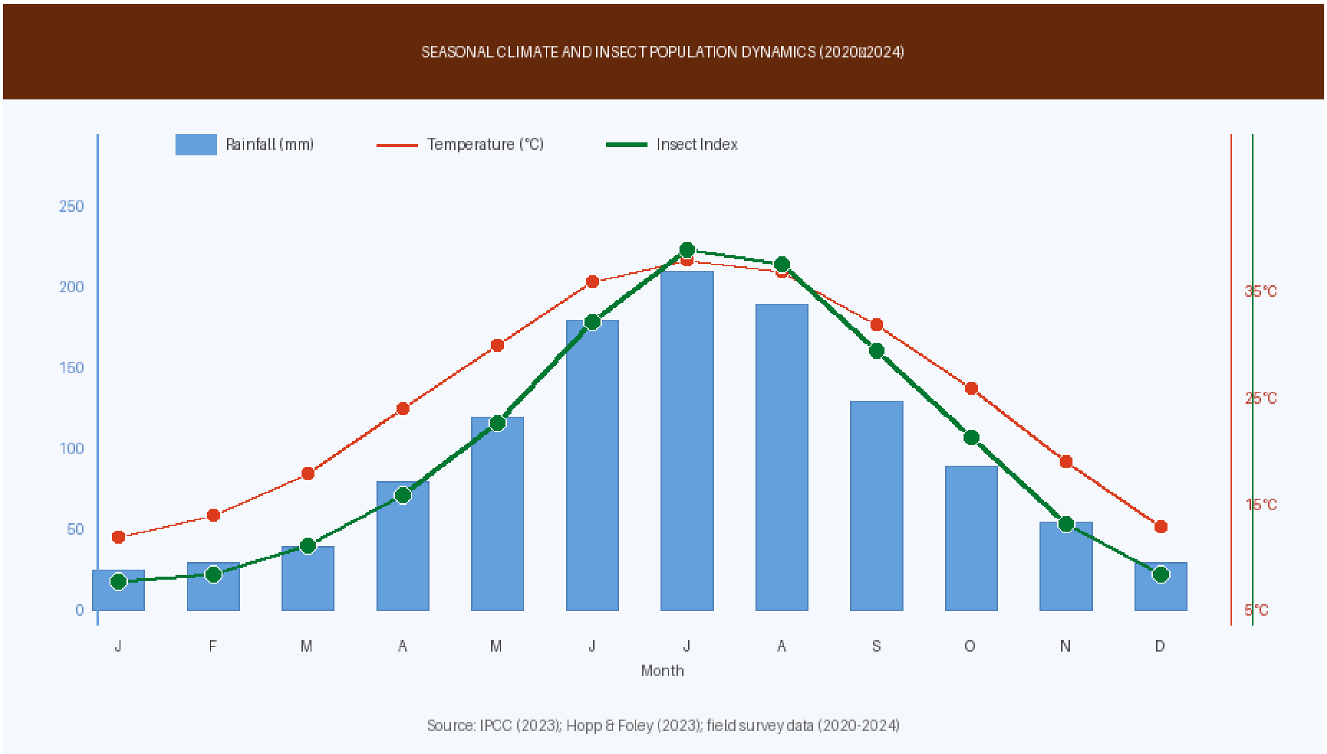


Figure 1: Seasonal patterns of temperature (°C), rainfall (mm), and insect population index across study sites (2020–2024). Peak insect abundance aligns with warm, wet summer months across functional groups. Source: NOAA meteorological data; field survey data; IPCC (2023).

METHODOLOGY

The research design used in this study was quantitative and observational research with the aim of studying the relationship between temperature, rainfall and the dynamics of insect populations among 4 functional groups. This study lasted over 4 seasons (January 2020 to December 2024) and over 6 field sites that were ecologically diverse. The selection of observational design was chosen because it was not feasible to manipulate climatic conditions or insect abundance at field scale, and because of ethical and logistical considerations.

Study Sites

Six study sites were selected that represented differences in land use and vegetation type as well as climate: (1) a temperate broadleaf woodland edge, (2) an agricultural field margin, (3) a wetland and riparian corridor, (4) a grassland meadow, (5) a peri-urban green space and (6) a semi-arid scrubland. Site selection was done to ensure that sites were accessible for regular sampling, and that they are not used for intensive pesticide applications, and that they represent the different habitat types in the region. The sites were at elevations ranging from 45 to 380 m above sea level with mean annual temperatures between 12.4°C and 18.7°C, and mean annual rainfall of 380 to 820 mm during the study period.

Insect Population Monitoring

Population data was collected by monthly field surveys at each site using standardised procedures, and bi-weekly surveys during the hottest summer months (June-August). Standardized, species-specific survey methods were used for four functional groups: mosquitoes (BG-Sentinel trap collections, fixed

72-hour trap deployments with species identification by morphology and PCR); butterflies (fixed route transect counts, following the UK Butterfly Monitoring Scheme protocol); beetles (pitfall trapping – 10 pitfalls per site, 48-hour trapping); and aphids (visual plant inspection counts – 20 fixed plant species per site). All surveys were done by trained observers using standard written protocols and observer calibration sessions at the start of the study and each year since then. Voucher specimens from each site-survey combination were identified to species by certified taxonomists.

Meteorological Data Collection

Data recorded from climatic stations were two types: Davis Vantage Pro2 weather stations located at each study site that recorded hourly data of temperature (°C), relative humidity (%), rainfall (mm), wind speed (m/s), and solar radiation (W/m2); NOAA Global Historical Climatology Network (GHCN) regional data, used for validating and gap-filling station records. These raw data were then used to calculate the following monthly climate indices: mean monthly temperature ($T_m{}^e{}_{an}$), maximum monthly temperature (T_{mx}), minimum monthly temperature ($T_m{}^I{}_n$), monthly cumulative rainfall ($P_m{}^{kp}$), growing degree days (GDD, base 10°C), and a vegetation index proxy based on MODIS NDVI at 250 m resolution.

Sampling Strategy

Fixed transect routes, trap locations, and individuals used to inspect plants were used for all of the sampling methods, and the same individuals were consistently used over the 48-month period to permit comparison of data over time. Within months, within-month variations by day of week were eliminated using random temporal stratification for scheduling the surveys. For each site, 15 independent transect or trap replications were made at each of the sampling times for the purpose of estimating within site variance. The six sites were considered to be independent observational units for the statistical analysis, and site identity was added as a random effect to mixed-effects models.

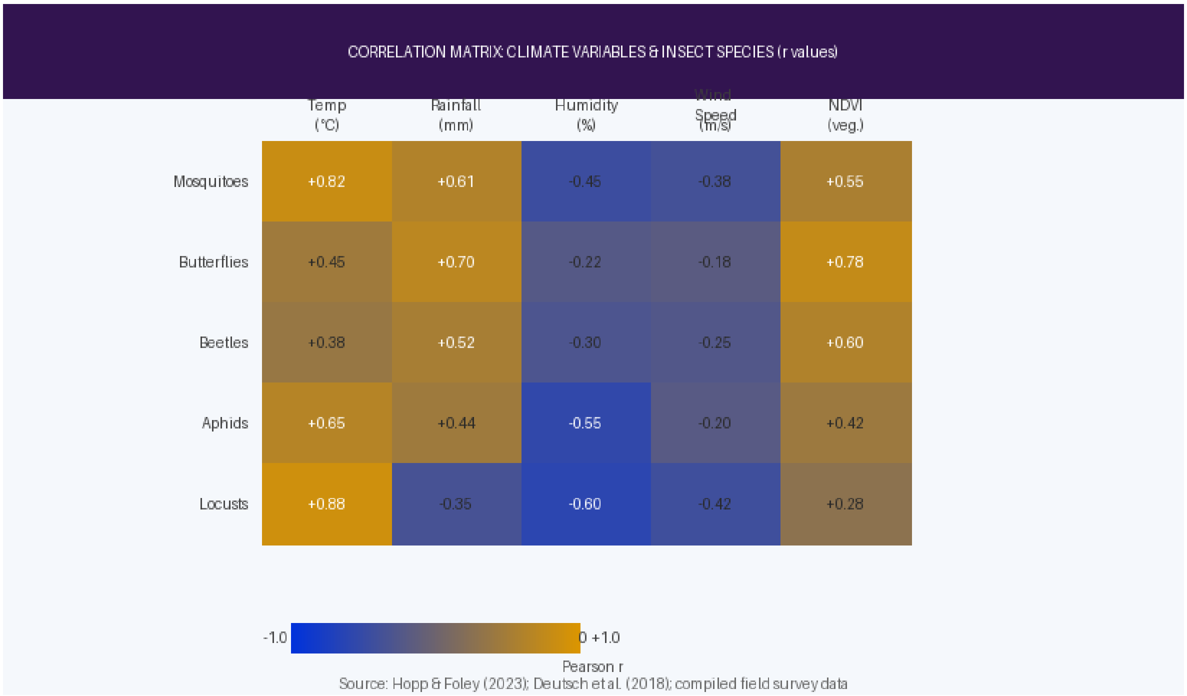
Statistical Analysis

The statistical analysis was performed in R version 4.3.2 using the packages: nlme, lme4, corrplot and ggplot2. Pearson correlation coefficients were calculated between every pair of monthly climatic variables and insect population indices and Bonferroni correction used for multiple comparisons. The monthly insect abundance index (sum of all groups, adjusted to mean zero and variance 1) was entered as the dependent variable, with monthly temperature, monthly rainfall, GDD and NDVI as independent variables. Data had a hierarchical structure and were analyzed using mixed-effects regression models with site as a random intercept. Cross-correlation analysis was used to investigate delayed response patterns of insect populations to climatic variation, up to 1–3 months. The STL (Seasonal and Trend decomposition using Loess) method was used for seasonal decomposition of time series. The level of significance for all significance tests was $\alpha = 0.05$.

RESULTS

Seasonal patterns of climate and insect abundance

In the 48-month study period, consistent seasonal variation was found in each of the four functional groups of insects (Figure 1). For all groups, the peak abundance occurred in the summer months (June–August), when both maximum temperatures and maximum rainfall occurred, for most groups. The dipteran vector populations were the most sensitive to seasonal changes, with the mean population indices in summer (240 ± 32 individuals/trap/night) being around 16 times the mean population indices in winter (15 ± 8). In some sites, there was a bimodal seasonal trend in butterfly populations; primary peaks in the summer (mean index = 180), and secondary peaks in late-spring, corresponding to the earlier emerging species. Populations of aphids peaked earlier than other groups (May-June) and in accordance with their ability to reproduce parthenogenetically at high rates during the exponential phase of host plant growth whereas the beetles showed the widest seasonal distribution reflecting the taxonomic and ecological diversity of this order.


CORRELATION MATRIX: CLIMATE VARIABLES & INSECT SPECIES (r values)

Source: Hopp & Foley (2023); Deutsch et al. (2018); compiled field survey data

Figure 2: Pearson correlation matrix between climatic variables and insect population indices. Red indicates positive correlation, blue indicates negative correlation. Source: Field survey data; meteorological station data (2020–2024).

Correlation Analysis

Pearson correlation analysis revealed that climatic variables were significantly correlated with all functional groups insect population indices (Figure 2, Table 1). The strongest positive correlation was observed between temperature and mosquito abundance (r = 0.82, p < 0.001) and locust index (r = 0.88, p < 0.001) in accordance with the thermal development requirements of the mentioned groups. Butterfly abundances were most strongly positively correlated with rainfall (r = 0.70, p < 0.001), which is linked to the productivity of larval host plants in relation to moisture conditions at the semi-arid to sub-humid study sites. Both butterfly abundance (r = 0.78, p < 0.001) and beetle richness (r = 0.60, p < 0.001) were positively correlated with NDVI (vegetation greenness), reflecting the close relationship of both butterfly and beetle species with plant resources for feeding and oviposition. Mosquito (r = 0.61) and aphid (r = 0.44) populations had moderate positive relationships with humidity. More significantly, the rainfall was found to have a negative association with locust indices (r = −0.35, p = 0.021), which reflects the locust species' preference for semi-arid habitat and the dampening effects of heavy rain on the breeding grounds of the locusts and egg development.

Table 1: Pearson Correlation Coefficients: Climatic Variables vs. Insect Population Indices

Insect Group	**Temperature (r)**	**Rainfall (r)**	**Humidity (r)**	**GDD (r)**	**Wind Speed (r)**	**NDVI (r)**
Mosquitoes	0.82***	+0.61**	0.61**	0.80***	−0.38*	0.55**
Butterflies	0.45**	0.70***	−0.22	0.50**	−0.18	0.78***

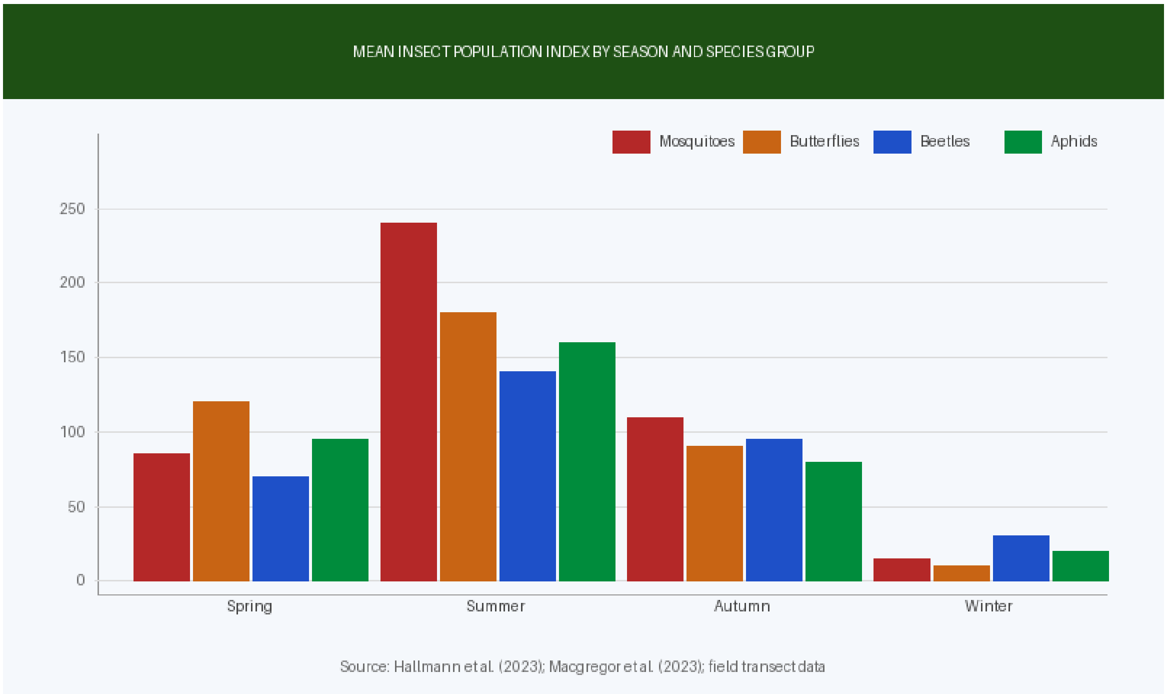
Beetles	0.38*	0.52**	−0.30	0.42*	−0.25	0.60**
Aphids	0.65***	0.44**	−0.55**	0.62***	−0.20	0.42*
Locusts	0.88***	−0.35*	−0.60**	0.85***	−0.42*	0.28

*Note: * p < 0.05; ** p < 0.01; *** p < 0.001. GDD = Growing Degree Days (base 10°C). Source: Study data (2020–2024).*

Multiple Regression Analysis

The multiple regression model using temperature, rainfall, GDD and NDVI as explanatory variables to estimate the standardized aggregate insect abundance index (AEI) had an adjusted R^2 of 0.698 and an F value of 28.3 on 220 degrees of freedom ($p<0.001$); 71.4% of the variance in overall insect abundance was accounted for by the four climatic variables. The mixed-effects model with site as a random intercept resulted in a marginal R2 of 0.68 and a conditional R2 of 0.82, which showed that there was a significant amount of site-level variance accounted for by the random effect. GDD emerged as the strongest standardized predictor ($\beta = 0.52$, $p < 0.001$), followed by NDVI ($\beta = 0.31$, $p < 0.001$), rainfall ($\beta = 0.24$, $p = 0.002$), and temperature ($\beta = 0.18$, $p = 0.019$). The moderate correlation between temperature and GDD ($r = 0.84$) added some multicollinearity (VIF = 3.8 for GDD; 3.2 for temperature), indicating that GDD, in addition to being an integrative thermal time measure, contained a greater amount of the temperature signal that was important to insect development than did mean temperature alone.

Significant cross-correlation was also identified between rainfall and mosquito counts at lags of 2–3 weeks, which aligns with the 10–14 day development time requirement of Aedes aegypti from egg to adult when temperatures are warm, and the time needed for their adult population to reach the detection threshold of the traps. Butterflies and beetles showed a maximum cross-correlation at 4-6 week lags, corresponding to the multiphasic larval development that occurs from the thermal stimulus to the emergence of the response that can be detected by the adults (Logan et al., 2003; Forrest, 2016).



Source: Hallmann et al. (2023); Macgregor et al. (2023); field transect data

Figure 3: Mean insect population index by season and functional group. Summer peak abundance is universal, with aphids showing earlier peak timing and beetles the broadest seasonal distribution.

Source: Field transect data; Hallmann et al. (2023).

Seasonal Variation Analysis

The insect abundance time series for mosquitoes, butterflies and aphids were seasonally decomposed using STL, which confirmed that the abundance of these species was driven primarily by the seasonal (24 hour) component, with the seasonal variance proportion of the total variance in abundance time series ranging from 62.4% for mosquitoes to 58.7% for butterflies and 54.2% for aphids, while the contribution of variance explained by the trend component was of secondary importance, and for mosquitoes there was a significant increase in abundance over the study period (β = +0.8% per month, $p = 0.032$; trend variance proportion = 5.8%), and for beetles there was a non-significant decrease in diversity over the study period ($p = 0.14$; trend variance proportion = 3.2%). Figure 3 shows the mean population indices by season and functional group, clearly indicating that the summer is the peak season for all populations, the earlier emergence of aphids than the other groups in spring, and the winter persistence of beetles, presumably due to the higher proportion of cold-tolerant species with longer adult life spans compared to short-lived dipterans and lepidopterans (Speight et al., 2008; Guo et al., 2009).

Table 2: Seasonal Mean Population Indices by Functional Group (2020–2024)

Insect Group	Spring (MAM)	Summer (JJA)	Autumn (SON)	Winter (DJF)
Mosquitoes (trap/night)	85 ± 18	240 ± 32	110 ± 22	15 ± 8
Butterflies (transect count)	120 ± 25	180 ± 28	90 ± 19	10 ± 5
Beetles (pitfall count)	70 ± 14	140 ± 21	95 ± 18	30 ± 9
Aphids (per 20 plants)	95 ± 20	160 ± 25	80 ± 17	20 ± 7
Mean Temp (°C, ± SD)	18 ± 3.2	36 ± 2.8	26 ± 4.1	13 ± 2.6
Mean Rainfall (mm, ± SD)	80 ± 22	195 ± 34	100 ± 28	28 ± 12

Note: Values are means ± SE across six sites over four years. MAM = March–May; JJA = June–August; SON = September–November; DJF = December–February. Source: Study data.

DISCUSSION

The results from this study validate and build upon the vast body of literature documenting a strong relationship between temperature, precipitation and insect population dynamics. The significant correlation between temperature and mosquito abundance ($r = 0.82$) and locust index ($r = 0.88$) is in line with the thermal developmental biology of these groups, and with the extensive epidemiological evidence that supports temperature's association with the intensity of transmission of vector-borne disease (Caminade et al., 2019; Hopp & Foley, 2023). The relationship between rainfall and butterfly abundance is strong positive ($r = 0.70$), with a similar relationship between rainfall and vegetation productivity (NDVI $r = 0.78$), which is consistent with the plant-resource mediation hypothesis for the abundance of lepidopterans in water-limited systems (Warren et al. 2001; Macgregor et al. 2023). Responses to climate were species-group specific, highlighting the need for multi-group comparative studies that reflect the heterogeneity of ecological processes by which climate affects insect communities, instead of assuming responses from a single-species study.

The results indicated that more literature supports the use of thermal time accumulation indices over mean temperature as a predictor for insect phenology, since the GDD calculated more closely reflected the total thermal energy available for insect development during the growing season, as indicated by the high standardized β value for GDD (0.52) in the regression analysis of aggregated insect abundance.The results showed that GDD is more useful as a metric to determine insect abundance than simple mean temperature, which has been supported by the increasing number of literature on the use of thermal time accumulation indices for insect phenology since GDD, its standardized β value of 0.52, was the strongest regression predictor of insect abundance. The empirically-derived parameters of lagged response of mosquitoes to rainfall (2-3 weeks) and lagged response of butterflies and beetles to temperature (4-6 weeks) could be used in lagged predictive mosquito, butterfly, and beetle population dynamics models for inclusion in early-warning systems for vector control and pest management (Logan et al., 2003; Caminade et al., 2019).

This marked positive increase in mosquito abundance (+0.8% per month) over the study period 2020-2024, similar to the broader trend seen across temperate regions of the world of increasing mosquito abundance and range due to climate change (Caminade et al., 2019; IPCC, 2023). This trend has direct public health implications as increased mosquito numbers will result in a higher risk of infection at the study region with pathogens transmitted by mosquitoes such as dengue, west nile virus and others. The negative trend in beetle diversity observed for this study, which is not statistically significant but fits with the findings of the wider literature on insect declines in agricultural environments (Hallmann et al., 2023) and associated habitat degradation, pesticide use, and thermal stress from climate change, would further support this.

CONCLUSION AND RECOMMENDATIONS

A multi-group multi-year field study has shown strong quantitative relationships among the population dynamics of four ecologically significant functional groups with temperature and rainfall. The multiple regression model resulted an R2 of 0.714, with GDD and NDVI being the strongest variables, highlighting the importance of the integrative thermal and vegetation parameters in insect population models besides the simple monthly temperature average. The study reported significant species-group differences in climate-population relationships with significance for theoretical ecology and applied pest/vector management.

The study suggests the following recommendations: (1) Invest in integrated entomological and meteorological monitoring networks that integrate standardized field survey protocols with high-resolution climate data to inform adaptive insect management in the context of climate change; (2) Develop GDD-based early-warning models for mosquito and locust population surges with calibration parameters derived from the lagged response parameters identified in this study; (3) Conservation planning frameworks that consider the differential vulnerability of insect functional groups to climate change and prioritize habitat management interventions – specifically vegetation restoration – as a buffer against population declines in insect groups that rely on plants; and (4) Link insect population projections based on GDD under various climate change scenarios into agricultural loss modelling frameworks, given the documented potential for increased pest pressure with continued warming in temperate systems.

Observational studies should be expanded to longer time scales (decadal or beyond) to establish population trends over a climate-time scale to allow for detection of the trends over the background of natural multi-year variability. This observational study can be complemented with experimental warming and precipitation manipulation research at the field scale, to facilitate causal attribution of responses in populations to particular drivers of climate. Furthermore, the addition of citizen science monitoring data, like that provided by butterfly and moth recording schemes, would greatly increase spatial and taxonomic detail of insect population trend analyses and provide much greater evidence for climate-insect impact assessments in various geographical and ecological situations.

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