The Effects of Periodical Cicadas on Food Web Dynamics

By

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Abstract

Arthropods play critical roles in food webs as both consumers and prey for higher trophic levels, including birds. Every 13 or 17 years, millions of periodical cicadas (*Magicicada spp.*) emerge from the ground and create a significant biomass pulse that disrupts food web dynamics. Little research has been conducted in North Carolina on the indirect effects that periodical cicadas can have on food web dynamics, and this study aims to bridge that gap by examining their impact. We predicted that the emergence of periodical cicadas would alter bird predation on caterpillars and vary across an urbanization gradient. We deployed clay caterpillar models to assess bird predation at five different study sites throughout the summer, surveyed arthropod populations at those five sites, and performed data analysis to assess whether periodical cicadas had an indirect positive effect on caterpillar populations. We found that caterpillar abundance increased significantly during the cicada emergence, indicating a shift in bird predation from caterpillars to cicadas, but the magnitude of the effect varied across sites. We found a marginal positive relationship between urbanization and caterpillar abundance ($p=0.056$), with greater increases in forested areas than in urbanized ones. These findings contribute to a deeper understanding of how resource pulses, such as periodical cicada emergences, can significantly alter food web dynamics. While our findings suggest a potential link between urbanization and changes in caterpillar abundance, further research is needed to confirm these patterns. This study also has broader implications for understanding urbanization's impact on ecosystem functions and its relevance to management strategies targeting invasive species.

Introduction

Arthropods play a critical role in ecosystems around the globe, functioning as both primary and secondary consumers. They contribute to nutrient cycling and serve as a critical nutrient source for many predators (Lewthwaite et al., 2024; Riggi et al., 2019). Insectivorous and omnivorous birds rely heavily on arthropods for nutrition, and in return, they provide critical top-down control in forest ecosystems, helping keep arthropod herbivory in check and regulating arthropod abundance (Leuenberger et al., 2021; Planillo et al., 2020). Caterpillars can significantly influence the ecological traits of birds, playing a crucial role in maintaining the delicate balance of ecosystems (Leuenberger et al., 2021).

Throughout much of the eastern United States, periodical cicadas (Magicicada spp.) emerge every 13 or 17 years, creating a massive influx of biomass into ecosystems, emerging in synchronized broods that have the potential to fundamentally alter trophic-level interactions. During emergence years, cicadas become an abundant alternative food source for foliage-gleaning birds that otherwise prefer caterpillars (Getman-Pickering et al., 2023), creating an indirect positive effect on caterpillar abundance by reducing predation pressure (Abrams & Matsuda, 1996). Previous research conducted in the Mid-Atlantic region has shown that avian predation on clay caterpillar models decreased during emergence years compared to non-emergence years (Getman-Pickering et al., 2023), highlighting cascading food web effects. Here, we examine whether cicada emergence has similar effects on caterpillar predation and abundance in North Carolina. Additionally, we build on previous work by exploring these effects across an urbanization gradient.

Urbanization has increased dramatically throughout the world, causing habitat fragmentation, promoting non-native species invasions, disrupting ecosystem functions, and influencing the decline of many species worldwide (López-Núñez et al., 2017; Nason et al., 2020). This dramatic increase in urbanization reduces arthropod diversity and abundance, creating urban ecosystems characterized by dramatic biodiversity and environmental filtering (Planillo et al., 2020; Roper-Edwards & Hurlbert, 2024). Understanding how cicadas alter food web dynamics across an urbanization gradient can help shed light on the impacts that non-native species can have on food web dynamics in the midst of the new epoch.

We hypothesize that cicada emergence will alter bird predation on caterpillars, and the extent of this effect will vary across sites based on the degree of urbanization. Specifically, we predict sites with more forest cover will have greater cicada density and, therefore, experience larger increases in caterpillar densities during the cicada emergence year compared to sites that are urbanized. Previous research has shown that bird predation on caterpillars decreases significantly during periodical cicada emergences (Getman-Pickering et al., 2023), suggesting a shift in predation. Given that lower arthropod diversity and abundance is associated with urbanization (Planillo et al., 2020; Roper-Edwards & Hurlbert, 2024), we expect to see a less pronounced shift in predation in more urban sites due to lower arthropod abundance and reduced bird populations. We conducted research at five sites across the Research Triangle of central North Carolina that range in degree of urbanization, and compared predation on clay caterpillar models to measure the switch from caterpillars to cicadas on an urbanization gradient. This study aims to link the ecological event of cicada emergence with urbanization, providing insights into how these two can interact to shape food web dynamics and influence predator-prey interactions.

Methods

Study Sites

We conducted this study at five sites in central North Carolina: UNC Chapel Hill, Johnston Mill, NC Botanical Garden, Prairie Ridge Ecostation, and Eno River State Park. These sites were selected based on varying levels of urbanization and were spread out across Orange and Wake counties. Cicada density varied across sites during the emergence, with UNC Chapel Hill, Johnston Mill, NC Botanical Garden, and Eno River State Park located within high-density emergence areas, while Prairie Ridge Ecostation was on the edge of the cicada emergence zone (Figure 1).

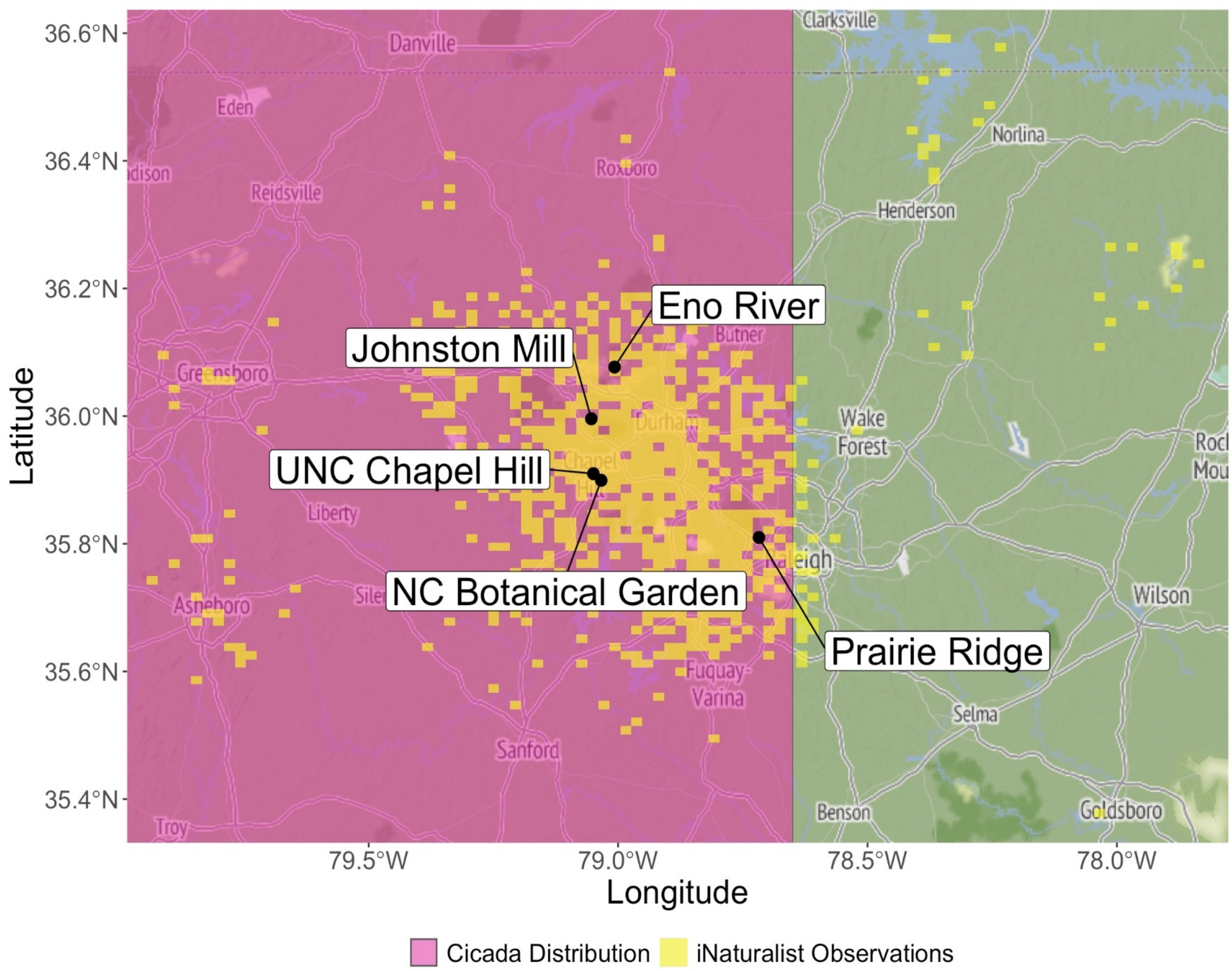

Figure 1: Cicada Density Across the North Carolina Triangle Region This map displays cicada density across the North Carolina Triangle region with yellow indicating iNaturalist observations that occurred from May 14 - June 13.

To account for urbanization across the study sites, we used forest cover data from 2022 that contained every site except for Prairie Ridge Ecostation. Prairie Ridge Ecostation forest cover data was calculated and allowed us to fully represent each site during the experiment. Furthermore, the mean cicada noise data was collected using an AudioMoth and analyzed in RStudio by Grace Layman, and was used to represent the noise levels at each site during and after cicada emergence (Table 1). The Cicada Index was calculated as the maximum running average amplitude between 1.0 and 1.2 kHz from ten-second intervals, and averaged across all sampling locations within a site (Layman, 2024).

Site	Site Code	Forest Cover	Peak Cicada Index
Eno River State Park	ERSP	93.83%	.088
UNC Chapel HIll	UNC	7.51%	.067
Johnston Mill	JM	72.52%	.170

NC Botanical Garden	NCBG	42.58%	.117
Prairie Ridge Ecostation	PR	10.68%	.021

Table 1: Site characteristics for the five study sites, including site codes, forest cover percentage within a 1 kilometer radius, and peak cicada volume during the 2024 cicada emergence.

Caterpillar Predation Assay

In the experiment, a total of 600 clay caterpillars were hand-rolled and deployed across five study sites. Each site contained circles that consisted of five survey trees used for arthropod surveys, and clay caterpillars were deployed at six circles within each site. Sites were assayed for predation rates four times between May 13, 2024, and June 28, 2024. During each assay, 30 clay caterpillars (30 mm long and 3 mm wide) were affixed to branches of survey trees that were being monitored for foliage arthropods using a thin metal wire (Castagneyrol et al., 2019). Clay caterpillars were deployed after arthropod surveys were completed to prevent possible distortion. They remained in place for one week before being collected and assessed for predation, allowing us to track temporal variation in predation pressure (Figure 2).

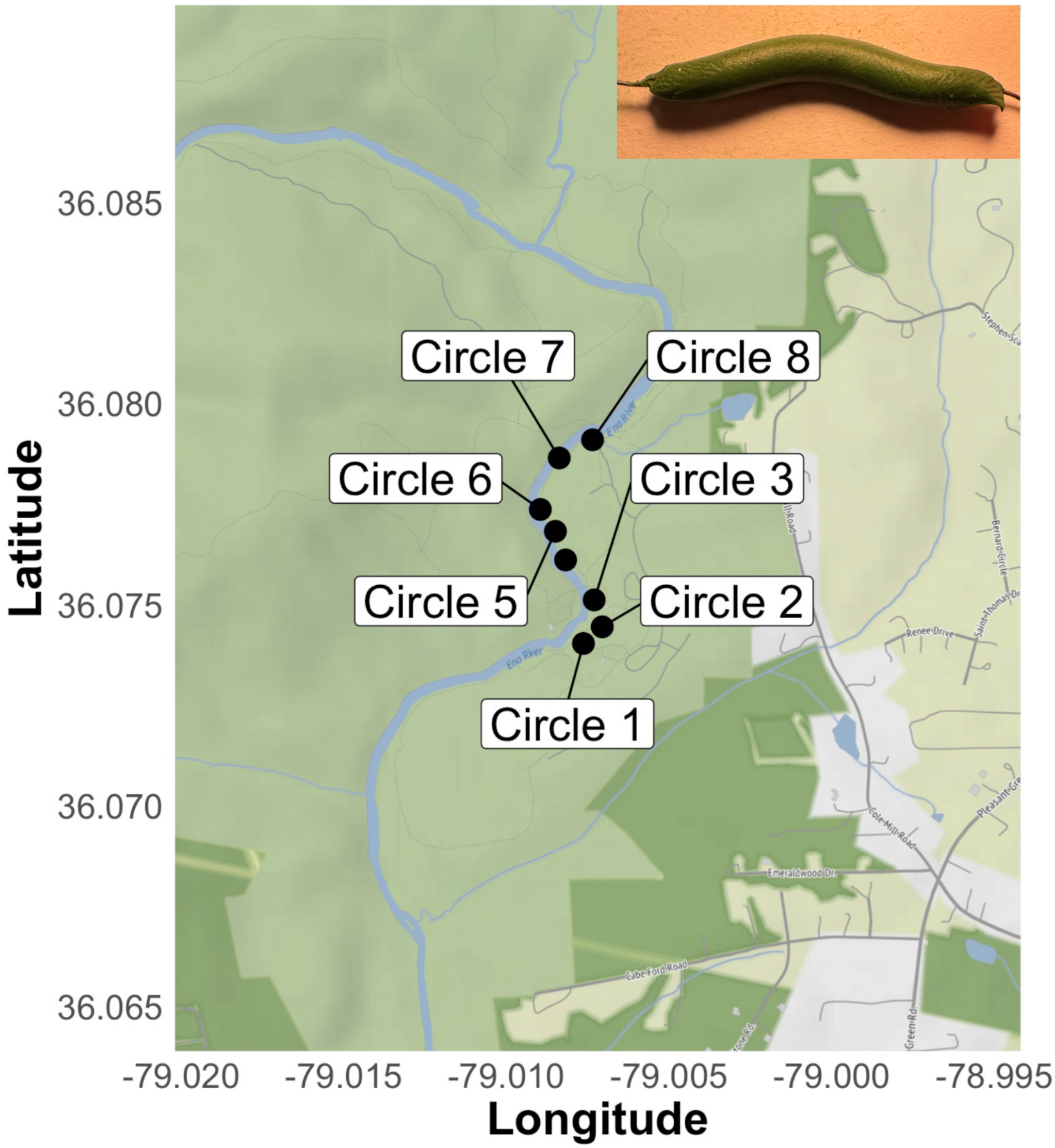

Figure 2: Survey Locations and Clay Caterpillar Deployment at Eno River State Park This map illustrates the eight survey locations at Eno River State Park. Circles 2 - 7 had five clay caterpillar models deployed at them after arthropod surveys were conducted.

Seven days after deployment, we collected the models and stored them individually inside of labeled vials to prevent distortion. There was a week between collection and the following deployment of clay caterpillar models to avoid skewing data collection, as repeated exposure could cause birds to become habituated to the presence of the models, potentially altering their predation behavior.

After collecting the clay caterpillar models in the field, pictures were taken using an iPhone 15 pro of each clay model that showed the sides, and the top. For each clay caterpillar model, we recorded the deployment date, collection date, and predation marks. A dissecting microscope was used to look over each model and predation was verified by other lab personnel. The reference collection from Low et al. (2014) was used to determine the type of predator that attacked the models and labeled whether they were predated on by insects, mammals, reptiles, or birds (Figure 3).

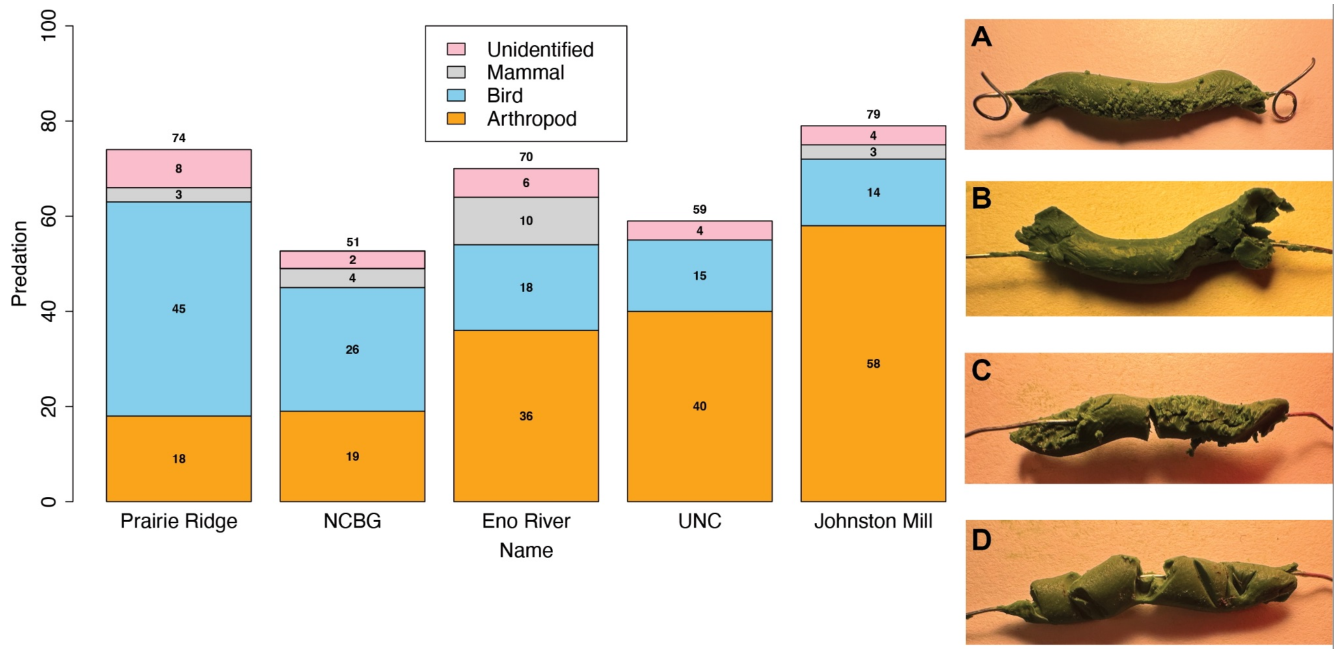

Figure 3: Types of Predation on Clay Caterpillar Models Stacked Bar Graph representing the different types of predation that was analyzed after collecting the clay caterpillar models. The images on the right depict predation marks left by different predators: (A) Arthropods, (B) Unidentified, (C) Mammals, and (D) Birds.

To assess the impact of cicada emergence on caterpillar abundance, we analyzed data from a GitHub repository containing survey results from 2021 through 2023 and conducted surveys in 2024 across five study sites. Data from 2021 through 2024 was used to compare caterpillar abundance across the five study sites. Eno River State Park and Johnston Mill were the only two sites that only had data consisting of two years, and the rest of the sites had data for all four years. We categorized data into pre-2024 and 2024, with May 14th through June 13th representing the cicada emergence period and June 14th through December 30th representing the post-cicada period, to compare differences in caterpillar abundance.

Data Analysis

To analyze the impact of cicada emergence on caterpillar abundance, we created multiple linear regression models. To directly test our hypothesis, we ran a generalized linear model comparing the percentage of surveys containing caterpillars between pre-2024 years and 2024 (Figure 4A). Additionally, we ran a linear regression model to examine the relationship between cicada and caterpillar density by comparing the difference in the fraction of surveys that had caterpillars to the cicada volume index (Figure 4B).

An additive linear regression model was used to assess the relationship between predation rates and weekly cicada noise levels at each site. To determine if urbanization had an impact on caterpillar abundance, we ran a linear model comparing the difference in the fraction of surveys that had caterpillars to the percentage of forest cover within 1 kilometer.

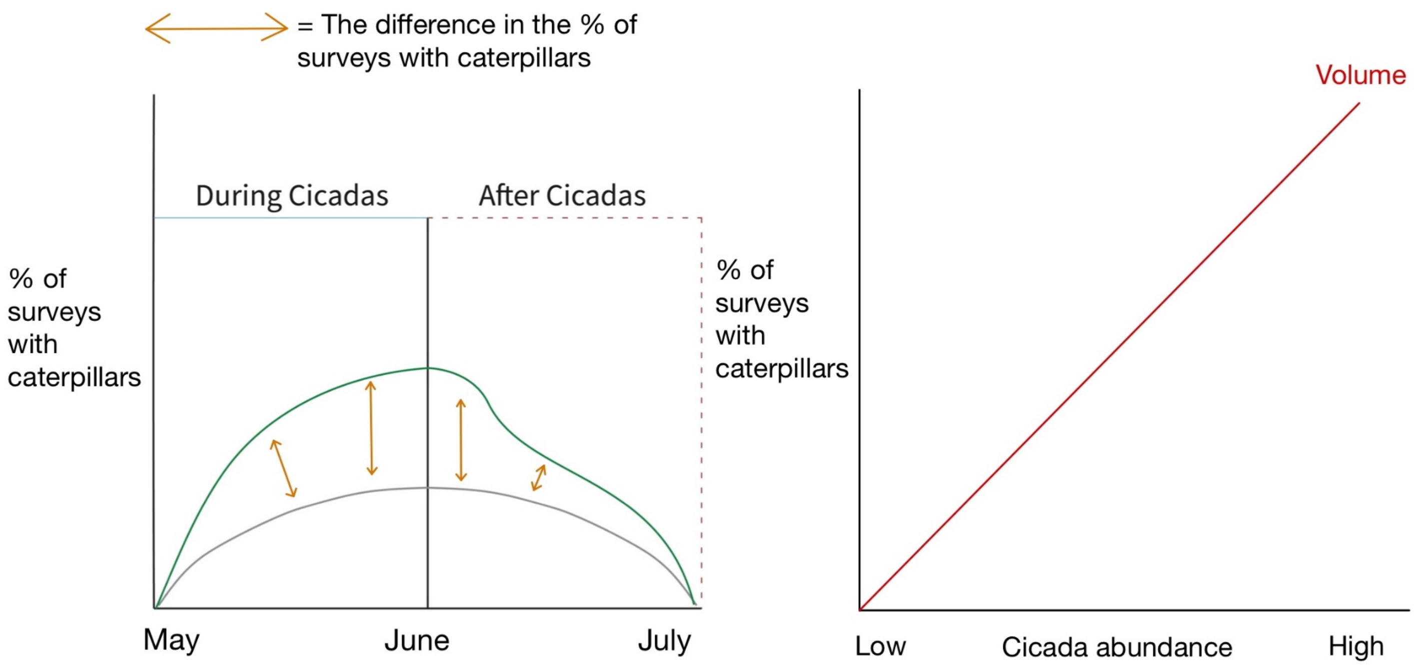

Figure 4: Expected Relationship Between Cicada Emergence and Caterpillar Abundance. The cartoon illustration on the left (Figure 4A) illustrates the difference in the percentage of surveys with caterpillars between previous years (gray line) and 2024 (green line), highlighting the expected increase due to the cicada emergence. The cartoon illustration on the right (Figure 4B) represents the expected relationship between cicada abundance and the percentage of surveys with caterpillars, where greater cicada density and noise levels correspond to higher caterpillar abundance.

Results

Caterpillar Abundance Across Sites During and After Cicada Emergence

To test if the periodical cicada emergence had an effect on caterpillar abundance, I quantified the difference in caterpillar abundance during and after the cicada emergence, comparing pre-2024 years with 2024. During the cicada emergence period (May 14 - June 13), caterpillar abundance increased compared to preceding non-cicada years ($P = 0.019$; Figure 5A). After the cicada emergence (June 14 - July 31), caterpillar abundance increased compared to preceding non-cicada years ($P = 0.013$; Figure 5B). The linear model indicated that the impact of periodical cicadas varied across sites, with Johnston Mill having a larger effect than North Carolina Botanical Garden, Prairie Ridge Ecostation, and UNC Campus ($P < 0.09$; Figure 5, Table S2)

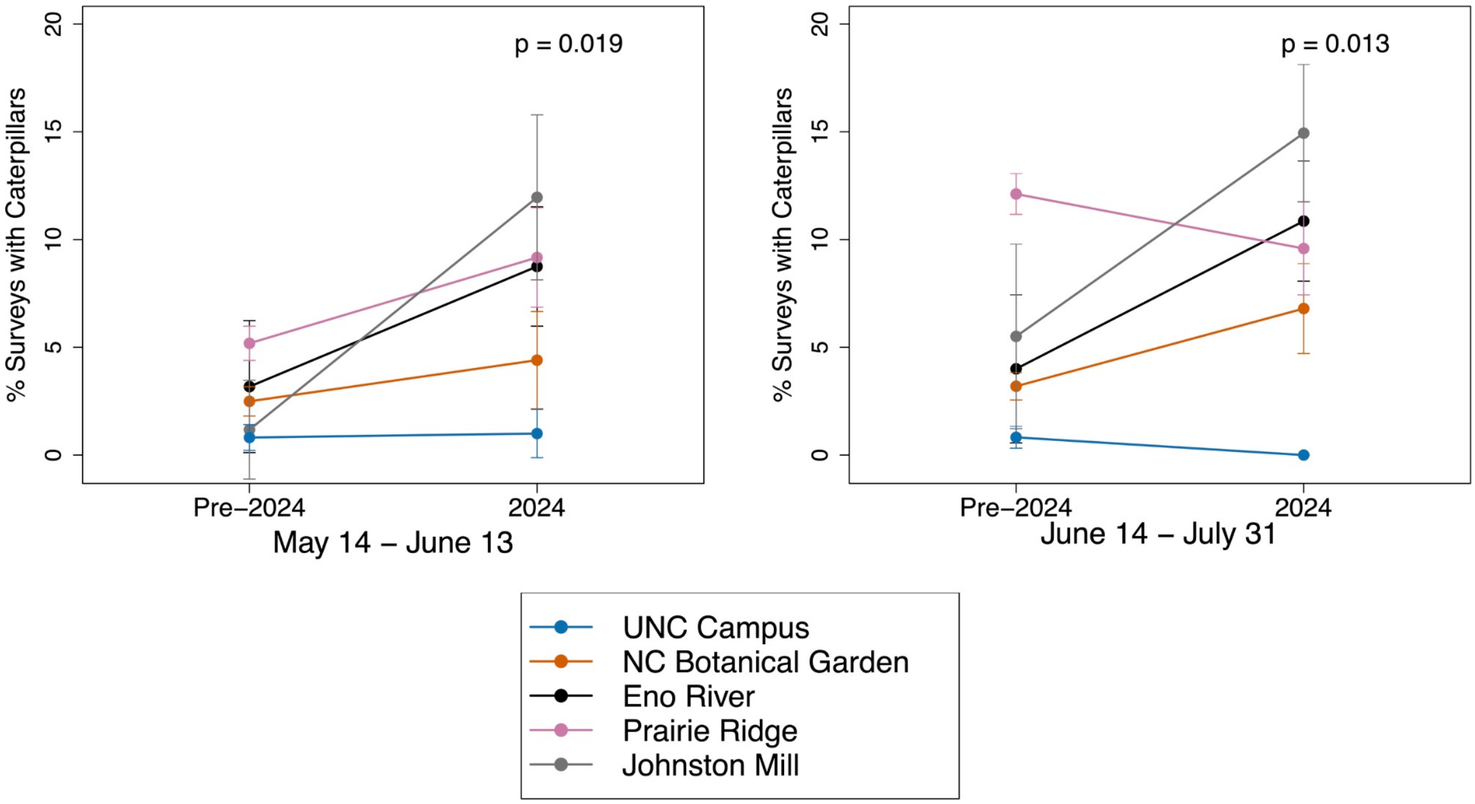

Figure 5: (A) **Caterpillar Abundance During the Cicada Emergence Period**. The percent of surveys with caterpillars at each site during the cicada emergence window (May 14 - June 13), comparing non-cicada years (pre-2024) to a cicada emergence year (2024). (B) **Caterpillar Abundance After the Cicada Emergence Period.** The percent of surveys with caterpillars at each site during the seasonal window after cicada emergence (June 14 - July 31), comparing non-cicada years (pre-2024) to a cicada emergence year (2024).

Cicada Emergence and Forest Cover Positively Correlates with Caterpillar Abundance

The difference in caterpillar occurrence between 2024 and pre-2024 non-cicada years at a site was positively related to the cicada index ($P = 0.0156$, $SE = 0.1765$, $R^2 = 0.8559$; Figure 6). That is, sites with more cicadas demonstrated a greater increase in caterpillars during the cicada year.

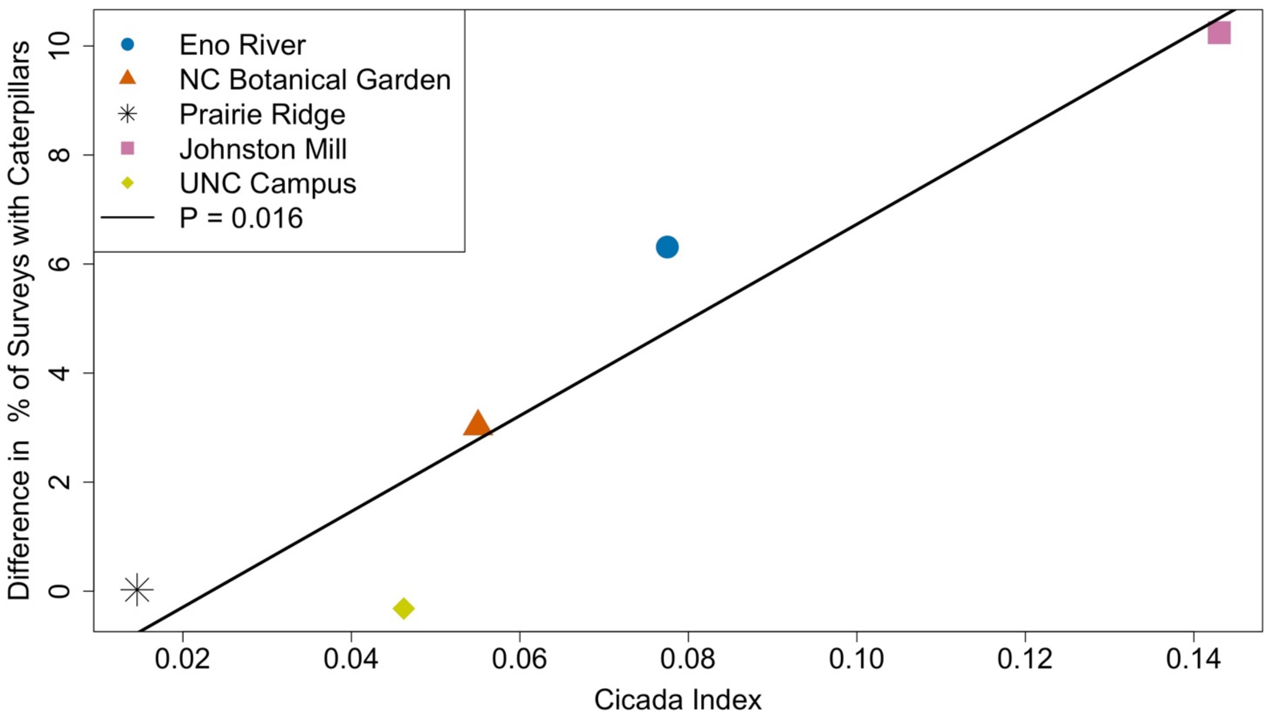

Figure 6: Relationship Between Cicada Index and Changes in Caterpillar Occurrence. Graph comparing the difference in the percent of surveys with caterpillars to cicada index. Each symbol represents a site, with sites varying in cicada volume.

Forest Cover Positively Correlates with Caterpillar Abundance

Urbanization can influence predator-prey dynamics across various ecosystems, and the extent varies across an urbanization gradient. To understand how urbanization can influence caterpillar abundance during the periodical cicada emergence, we employed a linear regression model to assess the relationship between forest cover and the percent of surveys with caterpillars. Results showed a positive relationship between forest cover and caterpillar abundance ($P = 0.056$, $SE = 0.0338$, $R^2 = 0.6729$) (Figure 7).

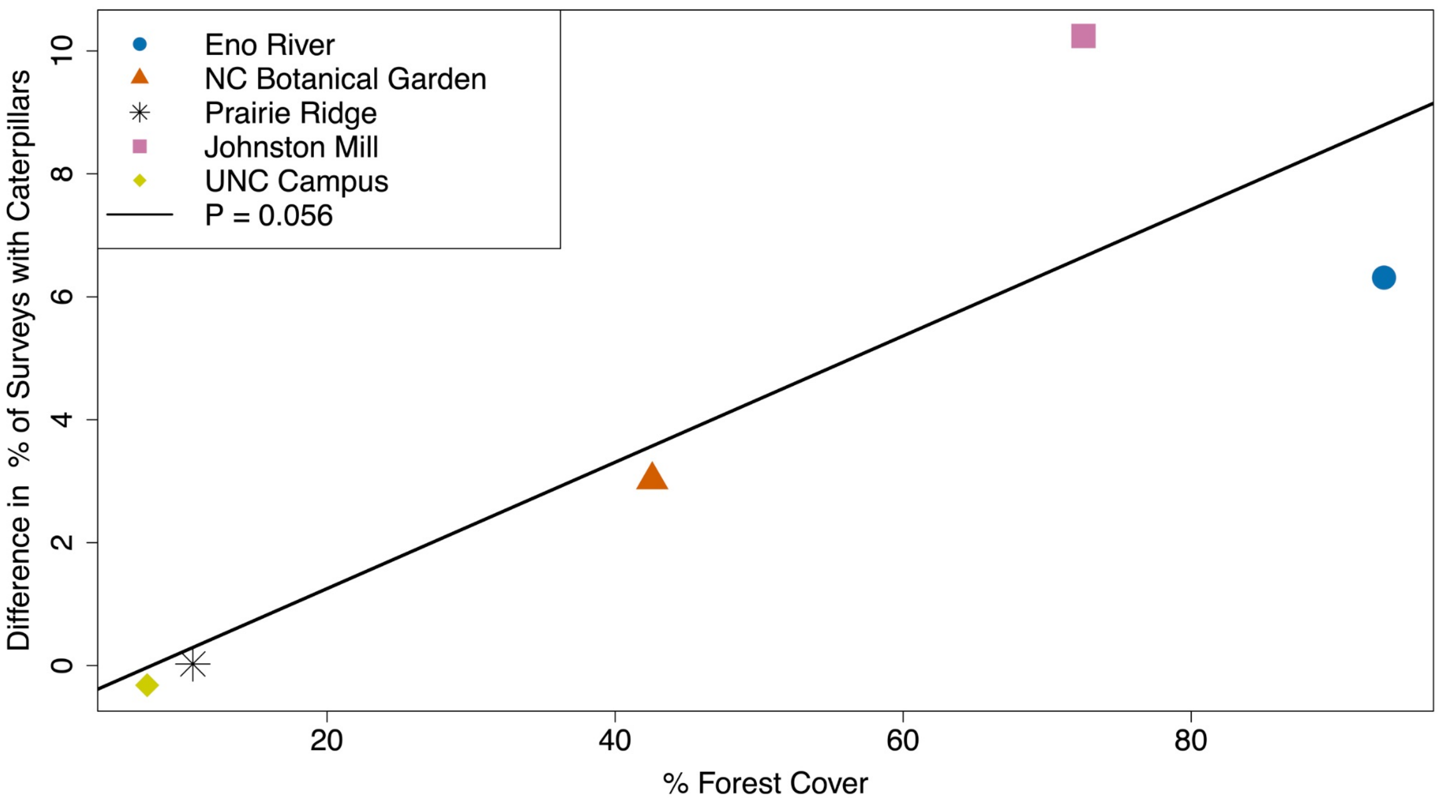

Figure 7: Relationship Between Forest Cover and Changes in Caterpillar Occurrence. This graph compares the difference in the percent of surveys with caterpillars to the percent of forest cover within a 1-kilometer radius at each site.

Bird Predation on Caterpillar Models Decreases During Cicada Emergence

To further assess the shifts in caterpillar abundance, we analyzed predation rates on clay caterpillar models. Clay caterpillar models revealed fewer predation marks during the cicada emergence period, and increased in bird strikes after the cicada emergence (Figure 8).

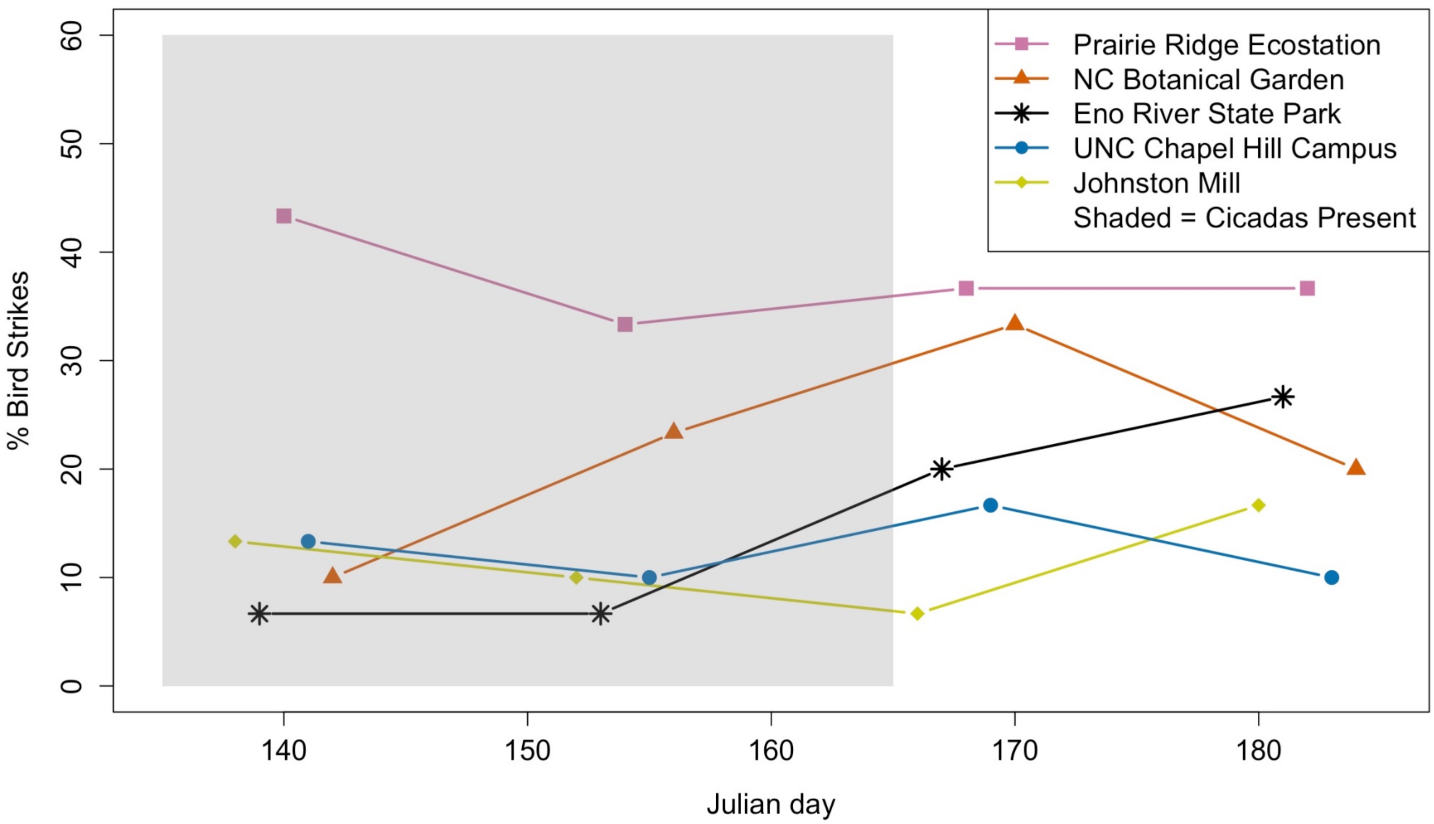

Figure 8: Bird Predation on Caterpillar Models Before, During, and After Cicada Emergence. This graph represents the percentage of bird strikes of each deployment from May through July at every site. The shaded area on the graph represents the period when cicadas were present (May 14 - June 13), and the non-shaded area represents the period after cicadas (June 14 - July 31).

Cicada Noise Reduces Predation on Caterpillars

bird predation rates were significantly influenced by cicada volume, and it varied across sites. The linear model revealed a general negative effect of cicada volume on bird predation (SE = 55.94, T = -2.21, P = 0.044), supporting our hypothesis that higher cicada volume corresponds with lower predation rates on caterpillars (Figure 9). Additionally, the linear model demonstrated variation in predation (R^2 = 0.79, F(5, 14) = 10.65, P = 0.0002), emphasizing that site-specific factors play a role in predation in clay caterpillars.

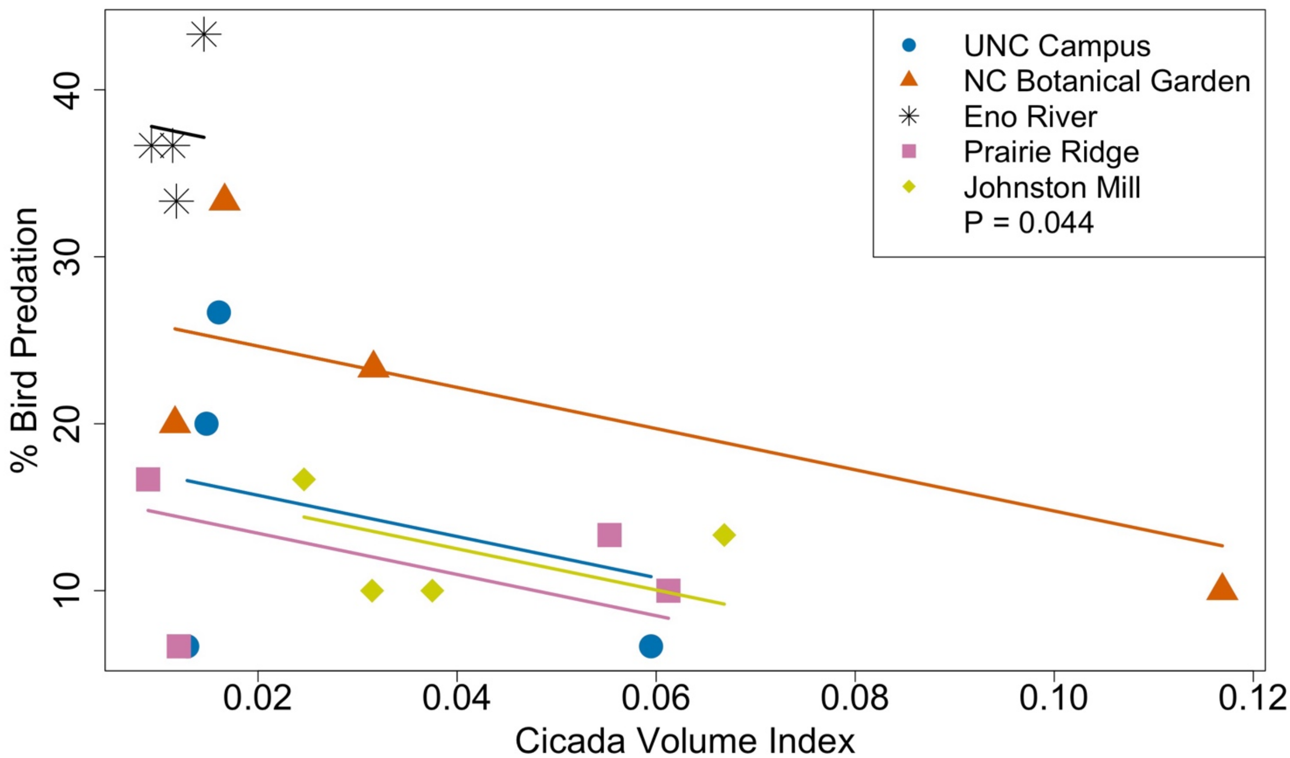

Figure 9: Relationship Between Bird Predation and Cicada Volume Across Study Sites. This graph illustrates the site-specific comparison of bird predation to cicada volume. The grey dashed line represents the regression line for the overall effect of bird predation to cicada noise, while solid color lines represent the regression lines for each site.

Discussion

Our findings highlight that bird predation on caterpillars decreased at sites with higher cicada density, suggesting that birds shifted their predation pattern from caterpillars to periodical cicadas, reducing predation pressure on caterpillars. These effects were evident both temporally and spatially. Caterpillar abundance increased during the emergence window compared to post-emergence and was higher at sites with greater cicada densities, reinforcing the link between cicada availability and shifts in bird foraging behavior.

Previous research by Getman-Pickering et al. (2023) demonstrated that cicada emergences alter avian foraging behavior, but these studies primarily focused on temporal comparisons between emergence and non-emergence years. Our study builds on this by incorporating a spatial dimension, comparing sites with varying cicada densities. This approach strengthens the evidence that resource pulses not only shift predator-prey interactions over time but also vary in magnitude across ecological gradients, providing a more comprehensive understanding of their impact on food web dynamics.

The significant relationship between mean cicada noise (our proxy for cicada abundance) and caterpillar abundance emphasizes the ecological impact that periodical cicadas can have on an ecosystem. Caterpillars at sites with higher cicada density experienced less predation pressure from birds, which resulted in increased caterpillar abundance. The relationship confirms that periodical cicadas have a positive indirect effect on caterpillar abundance.

When testing to see if urbanization had an effect on caterpillar abundance, we found a positive trend with forest cover, though the relationship was not strong. This could have been due to the low number of data points, impacting the significance of our model. Due to urbanization not being a significant factor, our study didn't align with previous research that highlighted the importance that habitat quality can have on predator-prey interactions along an urbanization gradient (Planillo et al., 2021). Furthermore, urbanization could have played a role in caterpillar abundance due to forested areas being a more suitable habitat for caterpillars, highlighting the importance of future research along urbanization gradients.

Comparing bird predation on clay caterpillar models to cicada volume with site-specific effects demonstrated that higher cicada volume reduced predation rates on clay models. Each site varied in different predation rates when compared to cicada volume. Predation at Eno River State Park and the North Carolina Botanical Garden decreased substantially when cicada volume increased. Predation at UNC campus, Prairie Ridge Ecostation, and Johnston Mill Nature Preserve didn't exhibit a relationship between predation and cicada volume. The overall model showed a significant effect, indicating that the periodical cicada emergence released predation pressure on caterpillars.

While percent forest cover and cicada abundance explained a large fraction of the variation in avian predation and caterpillar density, additional unmeasured site-specific factors may have influenced predation rates. Prairie Ridge Ecostation didn't have an emergence of periodical cicadas, so it was expected to have higher predation rates on clay models. UNC didn't show any correlation between predation and cicada volume, with little predation on clay models. This could have been due to UNC being the most urbanized site, having a smaller presence of predators, or human interference with models. Johnston Mill didn't exhibit a relationship between predation and cicada volume even though it had the highest cicada volume along with having the highest difference in the percent of surveys with caterpillars. Factors such as foot traffic on trails and a small presence of predators could have played a role in predation on clay models. These factors emphasize the importance of future research in site-specific effects.

This study expands upon the limited research in North Carolina on the indirect effects that periodical cicadas can have on food web dynamics across an urbanization gradient, highlighting their ecological significance in trophic interactions. Understanding how periodical cicadas cause cascading effects throughout the food web can help inform conservation strategies in combating invasive species. With climate change continuing to worsen, future research should investigate whether climate change alters the emergence of periodical cicadas. Caterpillars provide essential nutrients to fledglings and are crucial to their development and growth. Understanding how periodical cicadas influence the fitness of fledglings is essential in protecting bird populations, especially threatened species. Future studies should incorporate data from both cicada and non-cicada years to better quantify the impact of cicada emergence on avian predation, thereby strengthening our conclusion on the hypothesis. Furthermore, future research should examine the role that urbanization plays in population dynamics.

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Author Contributions

This thesis and its figures were developed by Alexander Smith, with Guidance from Dr. Allen Hurlbert. The experimental design was created by Alexander Smith with input from Dr. Hurlbert. The deployment and collection of clay caterpillar models were carried out by Alexander Smith with assistance from lab members Ivara Goulden, Grace Layman, and Isabella Nieri. Statistical analysis and R code development were conducted by Alexander Smith, with support from Ivara Goulden and Dr. Hurlbert. The cicada noise data used for the Cicada Index was collected and analyzed by Grace Layman. Dr. Hurlbert also provided feedback on data interpretation and manuscript development.

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Appendix

Site	Estimate	Std. Error	Statistic	P-Value
(Intercept - Johnston Mill)	-4.44	1	-4.44	9.13e-06
Eno River SP	1.00	1.12	0.9	0.37
NCBG	0.76	1.01	0.75	0.45
Prairie Ridge	1.5	1	1.5	0.13
UNC Campus	-0.37	1.07	-0.35	0.73
Cicada Year	2.38	1.02	2.34	0.02
Eno River * Cicada Year	-1.33	1.14	-1.16	0.24
NCBG * Cicada Year	-1.8	1.06	-1.7	0.09
Prairie Ridge * Cicada Year	-1.78	1.03	-1.74	0.08
UNC Campus * Cicada Year	-2.17	1.23	-1.77	0.08

Table S1: Generalized linear model results for caterpillar abundance during the cicada emergence period (May 14 - June 13).

Site	Estimate	Std. Error	Statistic	P-Value
(Intercept - Johnston Mill)	-2.87	0.41	-7.03	2.03e-12
Eno River SP	-0.33	0.61	-0.54	0.59
NCBG	-0.56	0.42	-1.32	0.19
Prairie Ridge	0.82	0.41	2.01	0.05
UNC Campus	-1.93	0.52	-3.73	0
Cicada Year	1.05	0.43	2.47	0.01
Eno River * Cicada Year	-0.01	0.63	-0.02	0.98
NCBG * Cicada Year	-0.27	0.47	-0.59	0.56
Prairie Ridge * Cicada Year	-1.3	0.44	-2.93	0.003
UNC Campus * Cicada Year	-13.73	218.38	-0.06	0.95

Table S2: Generalized linear model results for caterpillar abundance after the cicada emergence period (June 14- July 31).