North American Moth Populations & the Effects of Changing Climate

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Silk Moths	Michelle	Zoë & Michelle
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Results	Zoë	Michelle
Discussion	Zoë & Michelle	Michelle & Zoë
Conclusion	Zoë	Michelle

Abstract

While the thought of moths for most might conjure up images of closet infestations, chewed-up clothes, and the flapping of gray wings, these nocturnal creatures uphold vital roles and provide many services to the ecosystem. Moth species unfortunately have been declining in recent decades due to many reasons, including climate change. In this study, we analyze the datasets of four different moth species derived from iNaturalist, a growing platform of both professional and citizen scientists that enables people to document observations of plants and animals in the natural world. We proceeded to look for trends in the proportion of moth observations by latitude and month as well as how these trends corresponded, if at all, to climate data for the Northeastern United States. We found that average monthly precipitation was more positively associated to the proportion of observations by latitude than was average monthly temperature, as well as noticed general decreases in proportions for latitude group 40 and increasing trends for groups 25 and 30. We saw a general increase in the proportion of observations for March, April, and September and decreases for May and June. While more in-depth research is needed to explain exactly why these trends are occurring, rising global temperatures and extreme precipitation are two major geographically pervasive stressors that interact with all other factors. With the help of apps like iNaturalist, we can monitor and better grasp the impacts of environmental changes on moth and other insect populations.

Acknowledgements

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We would also like to extend our thanks to State Ornithologist Andrew Vitz for their fieldwork help in the early stages of our project, as well as those who've contributed observations to the datasets we analyzed from iNaturalist.

Table of Contents

List of Figures

List of Tables

Introduction

While the thought of moths for most might conjure up images of closet infestations, chewed-up clothes, and the flapping of gray wings, these nocturnal heroes uphold vital roles in the environment and provide a variety of services to both humans and the ecosystem. Unfortunately, as with countless other insects, moth communities are declining in the face of climate change and other human-induced afflictions to the planet (Wagner 2020). In this paper, we will dive further into the topic of moth decline, highlight their importance to both research and their environment, and focus specifically on the impacts that shifting climate in the northeast has on native silk moth populations using data from iNaturalist.

Global Moth Decline

Moth populations in the northeastern United States are experiencing a significant decline, mirroring global trends observed in regions such as Great Britain, Scotland, Sweden, and the Netherlands. A comprehensive review from the Munis International Entomology and Zoology Research Journal reveals alarming statistics, with declines ranging from 27% to a staggering 71% in different countries (Dar and Jamal 2021). For example, in Great Britain, a 35-year study of common macro-moth species discovered a 54% decline in the abundance of the 338 species surveyed, with grassland specialists faring the worst (Conrad et al. 2004). Changes in the country's grassland management over recent years aligns with the results of the study and supports the sentiment that changes to, and overall poor land management poses a serious threat to insect communities (Dengler et al. 2014; Alison et al. 2017). Habitat specialists and oligophagous herbivores— common traits of most moth larvae— oftentimes are found to be more sensitive to environmental changes due to their heavy dependance on local host plant quality and abundance (Dennis et al. 1992; Steffan-Dewenter and Tscharntke 2004). Another study in Sweden found that out of the 597 butterfly and moth species present at the Kullaberg Nature Reserve in the 1950s, a drastic 70% of those deemed habitat specialists were extirpated from the area in 2004 due to fewer patches and reduced area of suitable habitat (Franzén and Johannesson 2007).

More research is needed to investigate the intricacies of moth and other insect decline, as the main drivers are multifaceted and vary for different species. In addition to poor land management as mentioned previously, habitat loss resulting from commercial forestry, intensive agriculture, urbanization, and industrial development is a leading suspect for moth decline (Wagner 2021). Biomes around the globe are in a constant state of change and have been altered by humans for a variety of reasons. For example, deciduous and hardwood forests— ecosystems that are of great importance to the silk moths we are focusing on— are heavily affected by human activities like logging and intensive agriculture. Forests all over North America have been impacted by human infrastructure for centuries; in the United States alone, roughly 90% of its original forests have been logged and/or exploited since 1600 (Vasseur 2012). Copious species of moths rely heavily on the invaluable resources that forests provide, from a diversity of food sources and shelter/breeding sites to niche microclimates and even pheromone communication (Kotze et al. 2022). This complexity of forest resources significantly impacts the life cycle, behavior, and overall survival of moths. Their relationship with forests is so interconnected that they even have specific niches within the vertical stratification of temperate deciduous forests (DeSmedt et al. 2019).

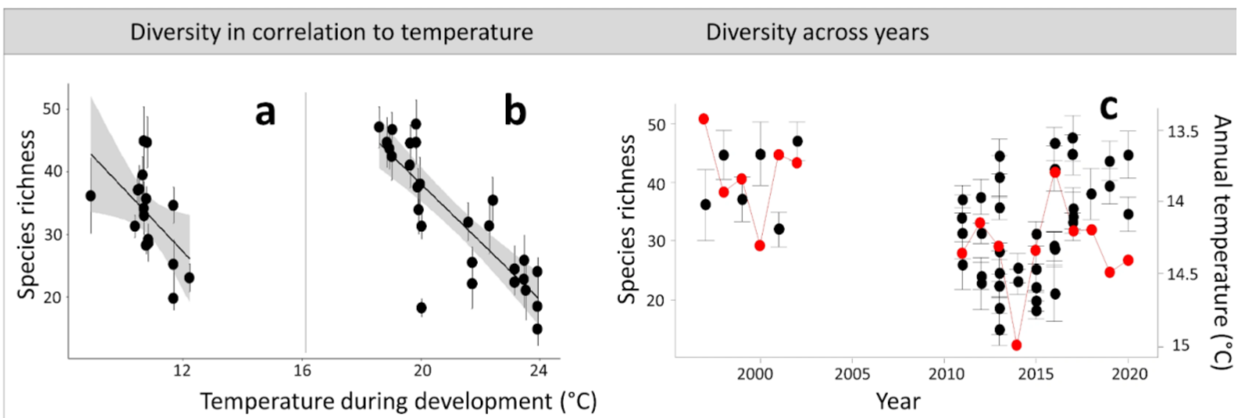
It is undeniable that the ongoing alteration of these ecosystems from human use is having a severe impact on moth and other insect communities. Especially in the age of climate change, it is imperative we continue to research and understand the drivers of global insect decline as they play vital roles in the food chain, influencing individuals across lower and higher trophic levels.

Climate Change

In the long term, the effect of rising global temperatures on moth communities may be catastrophic. Every species has a temperature optimum, and if global warming persists at such an increased rate, the once ideal habitats for moths will soon exceed these optima (Uhl 2022). Additionally, increased temperatures will reduce both quantity and quality of native plants (Raza 2019), limiting the vital growing stage of moth larvae.

While studies have shown that the egg and adult life stages of some moth species react either favorably or with dormancy in response to increased temperature changes, the caterpillar often reacts negatively (Uhl 2022). For example, a slight increase in temperature has been shown to improve adult moth flight time, but laboratory studies have found that caterpillars have high mortality rates with increasing temperature and drought (Uhl 2022). Rising temperatures can also lead to warm and wet winters— providing ample conditions for fungal infections, to which many overwintering caterpillars, such as *Arctia caja,* are prone to (Conrad et al. 2002). In a study on the effects of temperature and drought on coastal Mediterranean moth larvae, exposure to increased temperatures during larval development resulted in decreased species richness, especially for summer-developing larvae as shown in *figure 1* (Uhl 2022). On the other hand, studies on larvae with summer dormancy have shown that some smaller species will exhibit reduced fecundity in response to warmer temperatures, whereas larger species tend to retain egg production at equal levels (Haeler et al. 2014).

Fig. 1: Species Richness of Moth Larvae in Relation to Temperature Over Time

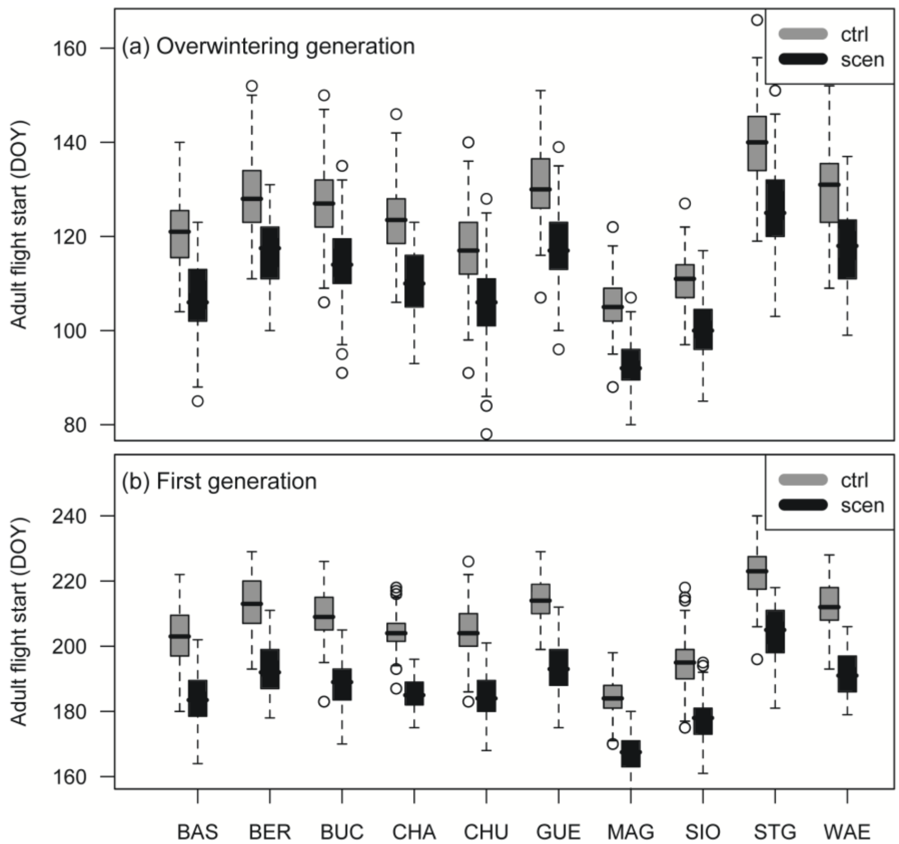


The graph on the left describes the relationship between observed moth species richness and temperatures during larval development. The graph is separated, and section (a) includes overwintering larvae while graph (b) describes summer-developing larvae. The graph on the left (c) describes inter-annual species richness fluctuations (black points) might be influenced by temperature (red points). Each of the black points represents a standardized species richness value which is a result of species interpolation-extrapolation of multiple samples.
"Changes in Species Richness in Relation to Temperature" by Britta Uhl is licensed under [CC BY 4.0](#).

Above all, caterpillar survival is heavily dependent on the abundance and quality of native plants for food. Thus, even the slightest changes in temperature can affect the growth of native plants, and in turn the entire food chain. In this age of increasing global temperatures, the seasonal timings of plants are advancing at an average of about 4 times faster than that of insects, which causes moth emergence and food plant maturation to fall out of sync (Forrest 2016). Moth development has evolved to be synchronized with the cycles of food plants they are reliant upon, and as rising temperatures cause plant growing seasons to become longer and warmer, this synchronization becomes misaligned (Harvey et al. 2023). As plants grow in these altered timeframes, they require more water and nutrients from the environment which creates a positive feedback loop of rising temperatures and plants shifting their seasonality (Forrest 2016).

Climate change is also advancing phenology, as reflected by instances of early insect emergence. In a study on the impacts that climate change exerts on the voltinism and phenology of Codling moths (*Cydia pomonella*), Swedish biologists simulated future climactic conditions for 2045-2074 using a stochastic weather generator to estimate risk levels for the emergence of a second generation. They found that as temperatures rise with time, the projected risk of a pronounced second generation of Codling moths in Sweden could increase from the current 20% to a shocking 70-100% (Stoeckli et al. 2012). They also identified a significant two-week shift towards earlier phenological stages under future conditions, as portrayed by the advanced adult moth flight starts in *figure 2*. What this shows is that earlier flight times can lead to extended reproductive periods for moths, resulting in additional broods and of course the cascading effects on the ecosystem that accompany them. Shifts in voltinism and phenology pose potential repercussions for plant-pollinator relationships, predator-prey dynamics, and overall ecosystem stability (Visser et al. 2006; Kuta 2023). The consequences of such shifts underscore the interconnectedness of species and the vulnerability of ecosystems to climate-induced disruptions. Understanding and addressing these shifts is thereby essential for effective environmental management and conservation efforts in the face of ongoing climate change.

Fig. 2: Simulated Effect of Climate Change on Codling Moth Voltinism & Phenology



The graph above was produced from a Swedish study on Codling moth voltinism and phenology in response to climate change, reflecting earlier adult moth flight dates under future conditions for all 10 study sites. Adult moth flight start (DOY) is defined as the day of year when >1% of adult moths emerge. Projected moth flight dates under climactic conditions for 2045-2074 are represented by the black boxes and current flight dates by the grey boxes. Graph A represents the "overwintering generation", or first generation, and B represents the second generation.

Moth Importance

Environmental

With about 160,000 species worldwide, moths are incredibly diverse and have great ecological significance— especially to the terrestrial food web (Moths 2020). In agricultural landscapes, macro-moths can provide unique and highly complex pollen transport links, making them vital components of wild plant–pollinator networks in agroecosystems (Walton et al. 2020). Moths are also essential pollinators in that some species continue to pollinate nocturnally while many other pollinators rest. Nocturnal moths contribute vital services for both wild plants and agricultural crops, as well as providing resilience to diurnal networks (Walton et et al. 2020). Moths pollinate a wider variety and quantity of plants, notably night-blooming varieties, that daytime pollinators might have missed. Crops such as strawberries, stone fruit, peas and Brassica/Raphanus sp. (a complex which includes the highly valuable crop oil-seed rape) are largely pollinated by moths (Macgregor 2019).

Moths play an essential role in the food chain, serving as a critical food resource at virtually every point in their lifecycle for various animals including songbirds, bats, small mammals, and other insects (Barbaro et al. 2011). In fact, some predatory insects and multiple bird species have adapted their predatory skills to target specific life stages of certain moths. For example, ants and hornets prey on moth caterpillars, spiders and beetles feed on moth pupae, and small rodents, lizards, skunks, and even bears feed on moths during virtually every life stage (Barbaro et al. 2011). Moths also serve as hosts for many parasitic species such as wasps. *Trichogramma pretiosum*, a common parasitoid wasp, lay their eggs inside host moth eggs using an ovipositor, which prevents moths from hatching and breaks their life cycle (Teerink 1979). Above all, moths are the most important food source for birds as nearly ninety-six percent of all terrestrial birds raise their young on insects, especially butterfly and moth caterpillars (Brenner 2018). Notably during the breeding season, birds cannot reproduce on berries and seeds alone; birds that typically eat seeds switch to insects (primarily moth caterpillars) when feeding chicks as they provide most fat and protein while excluding the hard chitin that comes with other insects (Mwansat 2015). Most adult insects contain 50-75% protein and 5-35% lipid whereas larvae of moths and butterflies are about 40-70% protein and 10-40% lipid (Kim et al. 2019). The higher protein concentration in moths improves predators' muscle growth and maintenance while the high fat concentration serves as a concentrated energy source. Aside from their environmental niches, moths also are vital resources for scientists and researchers.

Moths as Bioindicators

Lepidoptera is undoubtedly one of the most thoroughly studied insect lineages, backed by an ongoing, extensive repertoire of studies showcasing the life histories of countless butterfly and moth species (Hill et al. 2021). Existing literature provides valuable insights into how processes, including community-level (trophic interactions), population-level (geographic ranges), organismal (behavior, physiology, morphology, genetics), and phenological (voltinism), all interact and respond to environmental changes. This makes moths ideal models for monitoring the effects of climate change, particularly in investigating connections between species traits and distribution due to the wide availability of distributional data obtained from citizen science monitoring programs (Hill et al. 2021).

Moths have also been proven to be useful indicators of biodiversity. It is difficult for ecologists to accurately measure biodiversity in ecosystems as many species, especially insects, are understudied or remain undiscovered. Thus, most attempts to monitor insect diversity involve generalizations and large extrapolations from few well-studied taxa (Thoman 2015). In addition to the lack of long-established datasets and studies, biodiversity indicators are difficult to select as many sampling techniques tend to be too arduous or aren't cost-effective for certain species. Fortunately, moths possess essential characteristics for being practical indicators of biodiversity; not only are they are easy to identify and trap, but they also have a high alpha diversity, extended seasonal activity, and a strong ecological association with specific plants and habitats (Duran et al. 2022). Ecosystem health and resilience is often reflected in the responses of species with distinct environmental preferences and requirements (specialists), as stress can lead to visible changes in their distribution ranges, population sizes, and extinction rates (Franzén et al. 2023). A recent study analyzed Saturniidae moths as bioindicators for seasonality and precipitation patterns in the Brazilian savannah, finding a strong positive correlation between rainfall seasonality and Saturniidae abundance primarily due to their physiological tolerance (Braga and Diniz 2018). Moths have been underutilized as an essential taxon for rapid biodiversity assessments despite being able to do so effectively and with limited resources (Duran 2022). Their distribution and abundance patterns are valuable metrics proven useful in assessing ecosystem health and may also be indicative for other terrestrial invertebrates (Merckx et al. 2022). Thus, the continued research and investigation into moth communities and their responses to environmental stress is imperative to understanding the effects climate change has on biodiversity and ecosystem health.

Citizen Science

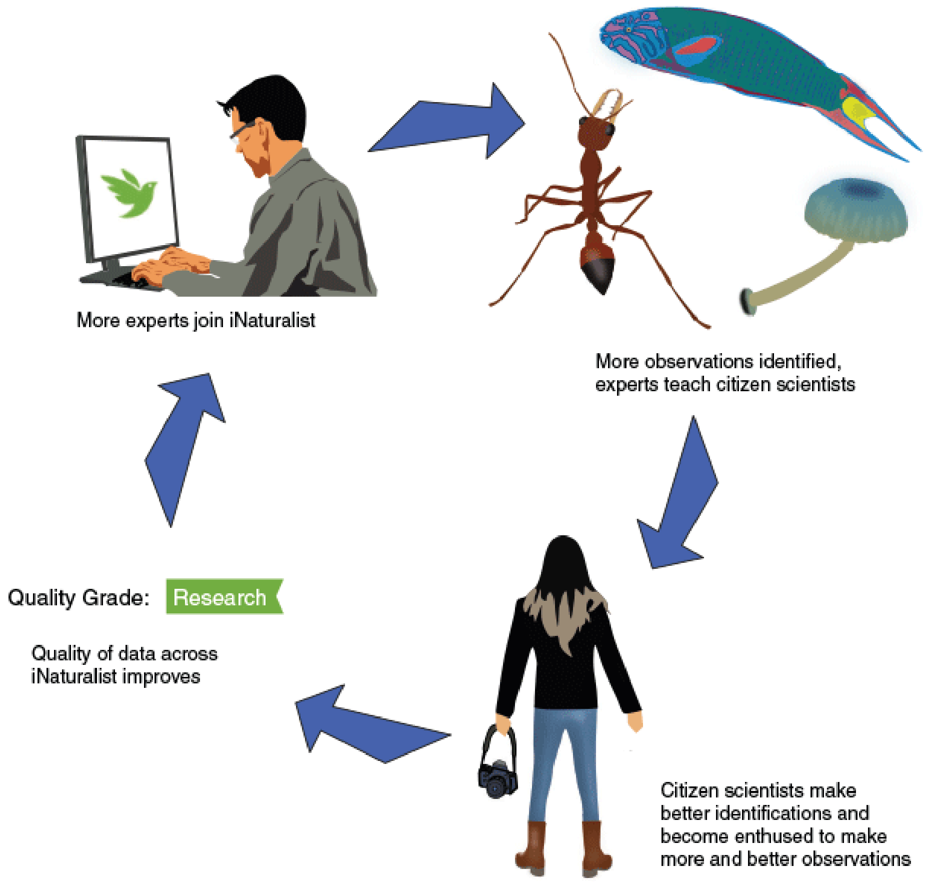
One such source of data and research that has contributed considerably to moth population and distribution tracking are citizen science monitoring programs. Citizen science, also known as community science or voluntary biological monitoring, is the collection and analysis of data by members of the public, usually in collaboration with professional scientists. Citizen science is essential as it not only helps collect large amounts of diverse data, but also increases awareness about science and issues among the general public. When used properly, citizen science can enhance an organization's abilities to conserve protected areas, monitor natural resources, and track species (Pocock 2017). The Florida LAKEWATCH is an example of a citizen science program, where volunteers that live near Florida rivers, lakes, and estuaries annually contribute to over 1.5 million hours to monitor the lake waters of Florida (Conrad et al. 2011). This program is a collaboration between government agencies and communities in which the keys components of its success are maintaining consistent long-term funding and integrating professionals and volunteers (Communications n.d.).

The effectiveness of citizen science lies in its organization and structure of the project, which we can see clearly when looking at citizen science projects targeted towards moth communities. We looked at three separate citizen science programs focused on moths and their ecosystems: The Garden Moth Scheme (GMS), the UK's Butterflies for the New Millennium project, and the National Moth Recording Scheme (NMRS). The GMS was a program conducted in Britain where participants ran garden light traps and answered a questionnaire. This proved to be incredibly successful as it had a defined protocol and guidelines, resulting in more accurate data and more participants each year (Bates et al. 2013). On the other hand, the Butterflies for the New Millennium project and NMRS were unsuccessful citizen science programs. These programs had no sampling protocols, resulting in a large variety between different UK sampling groups (Fox et al. 2019). While citizen science is an important part of scientific discovery, it must be done properly in order to reach effective and accurate results.

In the age of technology, our mobile devices and associated apps serve as powerful tools in collecting data and enable millions of people worldwide to contribute to ecological research. For our research paper, we focused on data from the app iNaturalist, a platform of naturalists, biologists, and citizen scientists who map and share observations of biodiversity around the world. The iNaturalist app was founded in 2008 to serve as a global community for nature observation and identification where users can upload images and other media of their plant, animal, or fungi observations (iNaturalist n.d.). These can then be identified and verified by the rest of the iNaturalist community and biodiversity data can be collected to create a crowdsourced species identification system. As their mission statement, iNaturalist claims “to connect people to nature and advance biodiversity science and conservation” (Loarie 2023). iNaturalist aims to create a world in which biodiversity information is open and accessible, so much so it has even been used as an educational tool to teach and promote curiosity about biology in schools. Inquiry-based and hands-on approaches are known to have positive impacts on student learning, and iNaturalist does just that by creating an immersive learning experience (Eden 2023).

Even beyond educational initiatives, citizen science programs and the data that is collected from them are increasing at an exponential rate. As a result of this, biodiversity research is becoming increasingly dependent on citizen science (Pocock 2017). Programs such as iNaturalist and eBird provide enough scientific data to understand ecological patterns at temporal and spatial scales not possible decades ago. Australia is the top contributing nation of iNaturalist observations in the southern hemisphere, and top four contributing nations globally. Studies have found that iNaturalist in Australia significantly drives research in conservation, spatial ecology, and macro-ecology as well as contributes to broad-scale ecological databases (Mesaglio et al. 2021). Ideally, iNaturalist popularity and research effectiveness would create a positive feedback loop with each other as illustrated in *figure 3*. Unfortunately, Australian (and many other countries’) scientific policies are led not by quality biological observation but by the cost associated with said research. This can lead to negative repercussions for biodiversity. Citizen science data tends to be very cheap (Cavalier et al. 2016) and thus provides incentivization for policymakers to use this data to make more accurate and meaningful policies. Many papers suggest that a blend of community science data with long-term surveying by experts could serve as a more reliable method to biodiversity monitoring (Sumner et al. 2019).

Fig. 3: The Positive Feedback Loop Created by iNaturalist



As more taxonomic experts join iNaturalist, the greater the amount and accuracy of observations identified. This in turn leads to users and the general population being encouraged to increase the bio-literacy of the data, and the improved quality of iNaturalist data will encourage more experts to join (Mesaglio et al. 2021).

For our paper, we chose to analyze silk moth data retrieved from the iNatualist database. The data was open-access, easy to filter and download, and contributed to an aspect of sustainability in our project. Citizen science is an inherently sustainable practice, and iNaturalist exemplifies this through its engaging of global communities in documenting and understanding biodiversity, which simultaneously promotes environmental conservation, education, and collaboration and aligns with several UN sustainable development goals.

By advocating for environmental conservation, restoration, and sustainable use of terrestrial ecosystems, iNaturalist directly supports SDG 15 “Life on Land”. While most observations are of terrestrial organisms, a portion of them are aquatic, thus also contributing to SDG 14 “Life Below Water” which promotes the conservation and sustainable use of marine resources (United Nations 2015). SDG 4 “Quality Education” is also met, as iNaturalist provides a platform for all individuals to learn more about the environment around them while enabling them to contribute directly to ecological research. Collaboration is built into the platform's nature, as data from the public is met with affirmations and/or revising from licensed biologists and other experts. SDG 17 "Partnerships for the Goals" emphasizes the importance of partnerships for sustainable development, so by facilitating the sharing of biodiversity data between various groups, iNaturalist contributes to the broader effort to achieve this goal. Lastly, and although not its primary focus, iNaturalist indirectly supports SDG 13 "Climate Action" by raising awareness of how climate change can impact biodiversity (United Nations 2015).

Silk Moths

Lepidoptera, the order of winged insects encompassing butterflies and moths, houses the superfamily *Bombycoidea*, which encapsulates all silk moths. The most common conception of silk moths is the domestic silk moth (*Bombyx mori*), which has been historically bred to specialize in silk production and played an incredible role in the distribution of silk throughout human history (Panthee et al. 2017). However, *Bombycoidea* encompasses much more than this one species, including ten other families such as giant silk moths (*Saturniidae*), and sphinx moths (*Sphingidae*) (Kitching et al. 2018).

Silk moths are vital components of the ecosystem as they are herbivores and serve as prey for other insects and animals. The mouthparts of adult silk moths are vestigial, and their digestive tracts are absent, resulting in stored fatty reserves and ultimately very short lifespans (Campos-Domínguez 2017). Their nutrient composition is a vital source of fats and proteins for birds, bats, and other predators and accounts for a large portion of insect biomass. For the purpose of this research paper, each of our moths belongs to the *Saturniidae* family, which contains the largest members of silk moths including emperor moths (*Saturnia pavonia*), royal moths (*Citheronia regalis*), and giant silk moths (*Hyalophora cecropia*). Moths in the *Saturniidae* family are often brightly colored and are some of the largest extant insects, ranging from 1-6 inches and up to 12 inches. Our four focal species are cecropia moths (*Hyalophora cecropia),* luna moths (*Actias luna*), polyphemus moths (*Antheraea polyphemus*), and rosy maple moths (*Dryocampa rubicunda*).

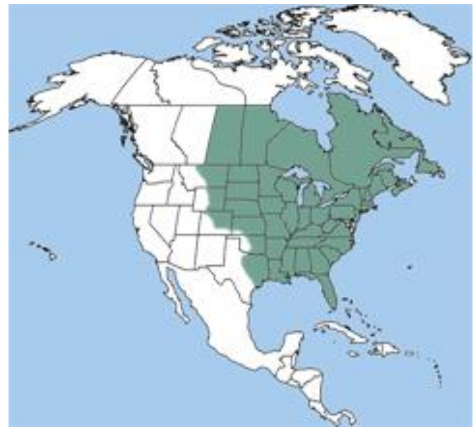
Cecropia Moths

The cecropia moth (see *figure 3*) is North America's largest native moth and it belongs to the genus *Hyalophora*. They are a Nearctic species with a wide range throughout the United States and Canada, as shown in *figure 4*, in which they are commonly found in temperate forests, urban, and rural areas (Cecropia 2023). They can be found on young hardwood trees, in backyards, woodland areas, orchards, and new housing developments. Their cocoons are typically found under turfs of grass or shrubs to help avoid predation (Geoffrey 2010).

Adult cecropia moths have a massive wingspan of 110 to 180 cm (about 5.91 ft) and as seen in *figure 3*, the wings are black and red with dispersed white scales (Johnstone 2020). There is no sexual dimorphism other than slight differences in the size of the antennae: males have a larger quadripectinate antennae which assists in detection of female pheromones (Vance 2023).

The larvae are polyphagous folivores that feed on a large variety of deciduous shrubs and trees. These plants include apples (*Malus*), ashes (*Fraxinus*), beeches (*Fagus*), birches (*Betula*), cherries (*Prunus*), dogwoods (*Cornus*), maples (*Acer*), larch (*Larix*), poplars (*Populus*), and willows (*Salix*) (Cecropia 2023). Based on past records of moth collectors, it's been estimated that current populations of cecropia moths are much less dense than they were in the 19th century (Vance 2023). Potential causes are complex and multifaceted, ranging anywhere from an increase in urban development and use of pest control, to the destruction of host trees and the introduction of parasitoid species such as the tachinid fly. The cecropia moth is considered a stable population however, and there are no known conservation efforts (Vance 2023).

Fig 3 & 4. Cecropia Moth and its Distribution



Pictured on the left is a cecropia moth photo by Mark Beckemeyer licensed under CC BY-NC 2.0 (Johnstone 2020). The image on the right shows the distribution of cecropia moths across North America, with the green area indicating regions where cecropia moths are native to. (Cecropia Moth 2023).

Luna Moths

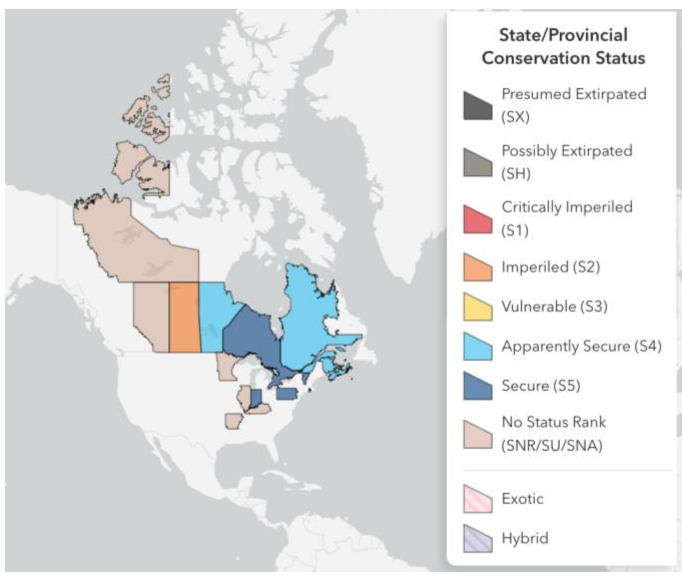
The luna moth (see *figure 5*), also known as the American moon moth, belongs to the genus *Actias*. *Figure 6* maps their distribution throughout the United States and parts of Canada, in which they are commonly found in deciduous hardwood forests (iNaturalist n.d.). They are a nocturnal species and have an incredibly short adult lifespan of 7-10 days (Schweitzer 2005).

Their pale green wings are lined in a deep pink hue on the uppermost edge, and they possess four crescent-like eyespots to ward off predators (Ausmus 2000). They mimic living and dead leaves on the ground and it’s essentially impossible to see them during the daytime when they are roosting on sycamore trees. Southern populations tend to prefer eating pick walnuts, hickories, sumacs, sweetgum, and persimmon while northern populations prefer white birch (Kavalerskaia 2023). Males and females do not have much sexual dimorphism; the main differences are that males have larger antennas and females have larger abdomens because of deposited eggs. Their wingspan typically ranges from 75 to 105 mm (about 4.13 in), (Hall 2007) but can grow up to 178 mm (about 7.01 in), making the luna moth one of the largest moths in North America. Due to human behavior, wild silk moth numbers have declined since the 1960’s. Luna moths often face habitat destruction and disrupted mating due to the increased use of bright vapor lights. We can see in *figure 7* that luna moth populations tend to be secure.

Fig. 5 & 6: Luna Moth and its Distribution

Pictured on left is a photograph of a luna moth by ggallice (Geoff Gallice), CC BY-NC 2.0 (Ausmus 2000). The image on the right depicts its distribution across the United States-the yellow dots representing individual moth observations collected via iNaturalist (iNaturalist, n.d.).

Fig. 7: Conservation Status of Luna Moths Across North America

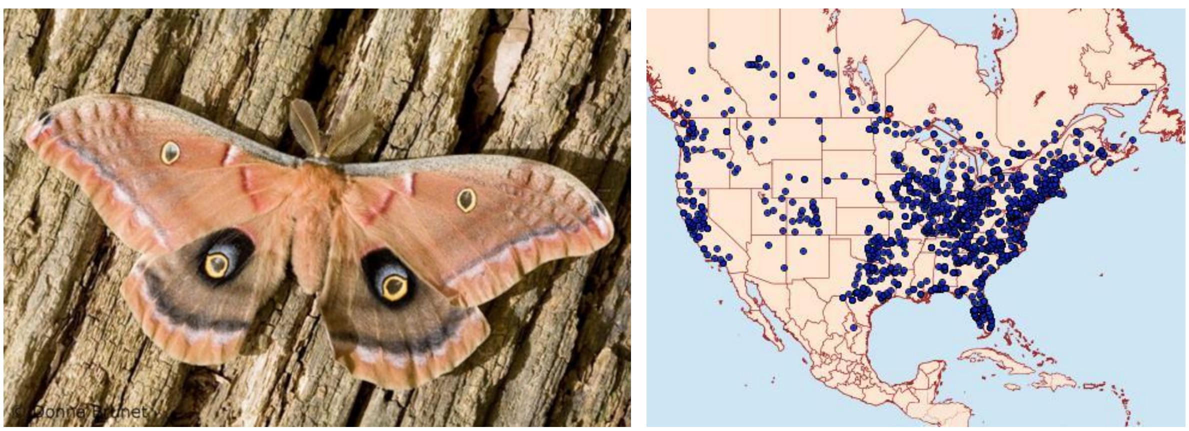


The map above illustrates the state/provincial conservation status of the luna moth population across North America (primarily the United States and Canada). The key on the right indicates what status each colored section pertains to. The luna moth tends to be secure/apparently secure in most regions except the Canadian province, Saskatchewan, where it is deemed imperiled (Schweitzer 2005).

Polyphemus Moths

The polyphemus moth (see *figure 8*) is a North American moth belonging to the genus *Antheraea*. Their distribution is heavily concentrated along the east coast of the United States and parts of the Midwest, though they are also present in some areas of the west coast and Canada as shown by the distribution map in *figure 9.* Within these areas, polyphemus moths inhabit urban areas, deciduous hardwood forests, wetlands, and orchards. Their wings are multitoned, with pale and darker brown sections and yellow-ringed, eye-like markings present on each wing. Adult polyphemus moths have wingspans ranging from 10 to 15 cm (about 5.91 in). There is essentially no sexual dimorphism other than ornamental in which the male polyphemus moths have bushy antennae for detecting pheromones and females have slender antennae (Kalola 2011). The caterpillars feed on the leaves of sweetgum (L*iquidambar)*, birch (*Betula*), grape (*Vitis*), hickory (*Carya*), maple (*Acer*), oak (*Quercus*), willow (*Salix*), and members of the rose family (*Rosaceae*) (Moth 2023).

Fig. 8 & 9: Polyphemus Moth and its Distribution



Pictured on the left is a photograph of a polyphemus moth by Wildreturn and is licensed under CC BY-NC 2.0. (Openverse 2023). The image to the right illustrates the distribution of polyphemus moth across North America, with the blue points representing regions where polyphemus moths have been observed (Moth Photographers Group 2023).

Rosy Maple Moths

The rosy maple moth (see *figure 10*) is a small North American moth belonging to the genus *Dryocampa*. Their distribution within the United States is approximately the whole right half of the country, extending into the lower east regions of Canada (see *figure 11)*. In these locations, the rosy maple moth inhabits temperate deciduous forests. As the name implies, they are often associated with maple trees such as box elder maples (*Acer negundo*), silver maples (*Acer saccharinum*), sugar maples (*Acer saccharum*), and red maples (*Acer rubrum*). Depending on where these host trees are, the rosy maple moth has also been spotted in suburban areas (Bouseman et al. 2002).

Their wing coloration can range from bright yellow and pink to unmarked white. This wide range of appearances is linked to polymorphism occurring within different geographic regions. For example, uniquely in Missouri the rosy maple moth is all white with minimal faint pink maculation (Damele 2013). Sexual dimorphism is present in wing size and shape; males tend to have narrower and less rounded wings when compared to females, though both sexes have an average wingspan of 32 to 55 mm (about 2.17 in). There are also differences in ornamentation as males have bipectinate antennae while females have simple antennae (Damele 2013). Their caterpillars, also known as green-striped maple worms, also have different coloration depending on their stage of development. They are florivorous (specificity in eating leaves), and early larvae feed in union but eventually become solitary feeders. While it is difficult to find the direct correlation between climate change and the rosy maple moth populations, it should be noted that these moths are very sensitive to temperature (Bailey 2023). Adults become active in the warmer months of the year, and they have a high prevalence with high temperatures. This may be since their subfamily *Ceratocampinae* has tropical origins or their lack of efficient body temperature control due to their small size.

Fig. 10 & 11: Rosy Maple Moth and its Distribution

Pictured to the left is a photograph of a rosy maple moth (Southern Living 2023) and the left shows the distribution map of rosy maple moths across North America. The green areas indicate regions where rosy maple moths are native to (Dziedzic 2019).

Methodology

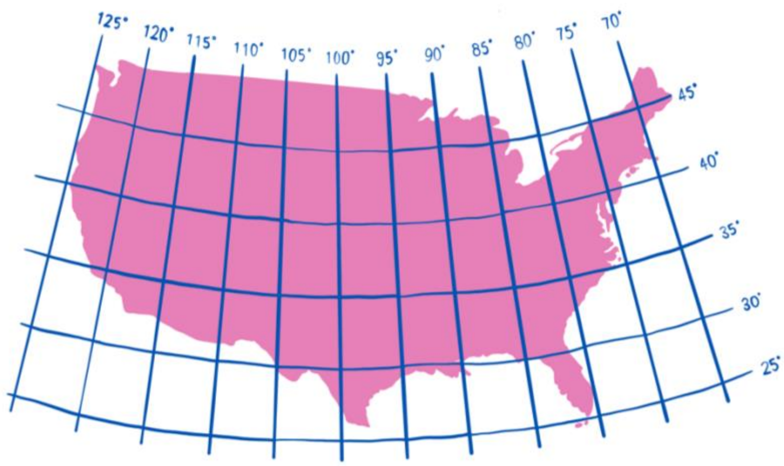
The aim of our study was to analyze iNaturalist datasets for four silk moth species recorded in the contiguous United States across varying latitudinal groups. We chose to focus our research solely on species observed in the United States as that was where a majority of iNaturalist observations were documented. We specifically looked at silk moth species as they were both abundant in data and play important roles as bioindicators of climate and other environmental change (Chowdhury et al. 2023).

Data Collection

In choosing which silk moth species to further investigate, we browsed the different species information pages on iNaturalist, paying specific attention to the interactive seasonality graphs at the top right of each page. In efforts to see if peak months are changing over time for moth communities, we chose species with varying seasonality and later mimicked these graphs using our narrowed data.

After choosing our target moths (luna, cecropia, polyphemus, and rosy maple), we used iNaturalist's export tool (iNaturalist 2023) to download csv files for each species. To narrow the results, we applied several filters to the data before exporting. We wanted only research-grade observations recorded in the wild, so we chose "Research" for quality grade and "No" for the captive/cultivated option. We then chose "United States (country)" for the place, "25" for SW latitude, and "50" for NW latitude to limit observations to the contiguous United States that fall between the 25 and 50th parallels (which we later divide into latitude groups as outlined in *figure 13*). By clicking the "Create Export" button at the bottom of the page, we were able to download the data and continue our analysis in both R and Microsoft Excel.

Fig. 13: Map Blueprint of Latitudinal Sections



The image above illustrates a blueprint of the way we created our latitudinal groups for data analysis. The sections we created are as follows: Latgroup 25: 25-29°N, Latgroup 30: 30-34°N, Latgroup 35: 35-39°N, Latgroup 40: 40-44°N, and Latgroup 45: 45-50°N. Figure created by M. Kirtich.

Data Analysis

Two of our main research goals were to analyze the moth data in terms of latitude group and in terms of month of the year. We first assigned each observation a latitude group based on their coordinates (see latitude group details in *figure 13*) and separated the date of each observation into day/month/year columns for convenience. Rather than working with the actual number of moth observations, we converted this data into proportions and created two pivot tables: one for proportion of observations by latitude and the other proportion of observations by month. In doing so, we were able to better visualize the distribution of observations over time and found that most observations were recorded from 2012 onward. We therefore decided to narrow our data to observations recorded from 2012-2022, as 2023 was not yet a full year of data. Because iNaturalist has been growing in popularity and use in more recent years it was essential to use proportions of moths as it provided a more holistic viewpoint of the data. From here, we created line graphs for each moth species illustrating the relationship between proportion of observations and latitude group and proportion of observations by month for 2012-2022.

Statistical Analysis

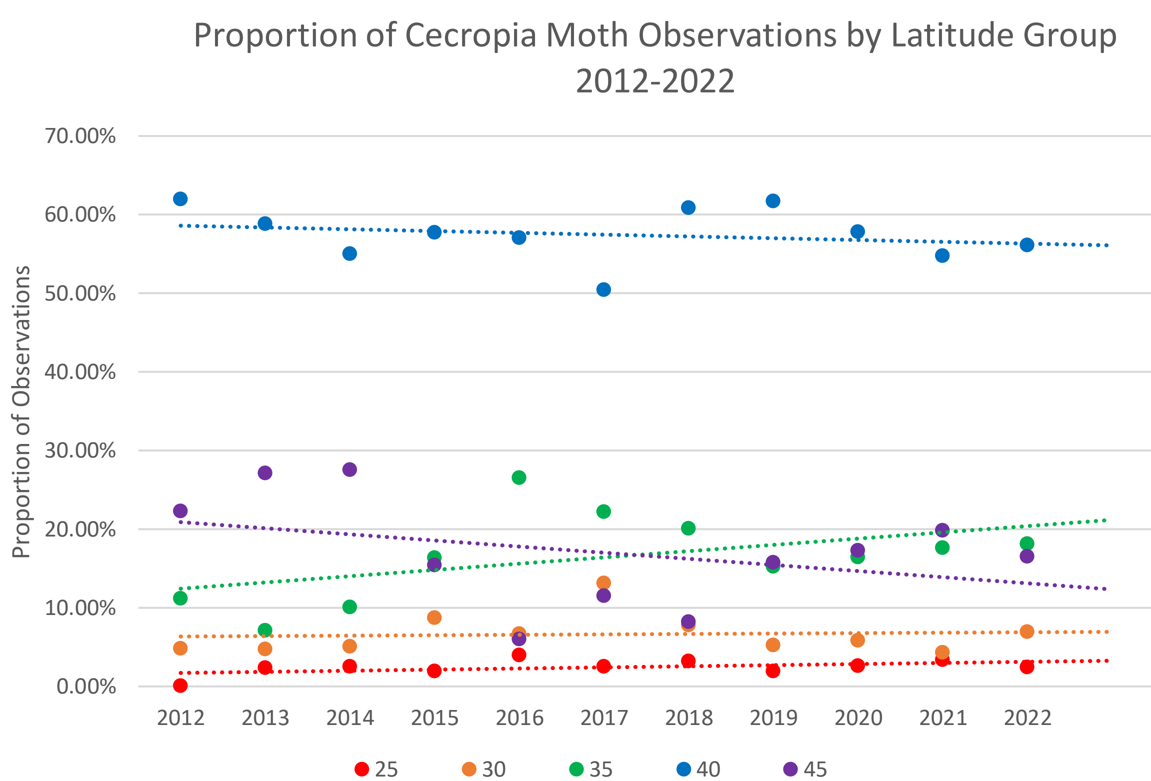
To examine if the proportion of observations was related to latitude or month, we ran separate ANOVA analyses in R for each moth species. We then incorporated climate data into our analysis using the NOAA Regional Time Series Climate Monitoring Tool (Climate 2023) and downloaded CSV sheets of 2012-2022 average temperatures, min/max temperatures, and precipitation for the Northeast United States (see Appendix F for which region NOAA defines as Northeast). We first ran a correlation test in Excel between each of the weather variables and we found that average, minimum, and maximum temperatures were all strongly correlated with one another (each $r > 0.7$). Thus, we chose average temperature to move forward with further analyses in addition to precipitation, as it was only slightly positively correlated to the other weather variables ($r < 0.7$). We ran correlation tests between these variables and proportions by latitude but not by month, as it is already common knowledge that weather data corresponds to time of year.

Results

Latitude

On average, the highest proportions of observations for each of the moth species were recorded within latitude groups 35 and 40 whereas groups 25 and 45 on average contained the lowest proportions of observations (aside from cecropia moths, in which groups 25 and 30 were the lowest). Even though groups 35 and 40 contain the highest proportion of observations, they have been slightly decreasing over time as shown by the graphs in appendix A. Cecropia moths however saw a spike in observations for latitude group 35 in 2016, hence the positive slope ($y = 0.008x + 0.1163$), but they've been decreasing ever since (see *figure 14*).

Fig. 14: Proportion of Cecropia Moth Observations by Latitude Group for 2012-2022



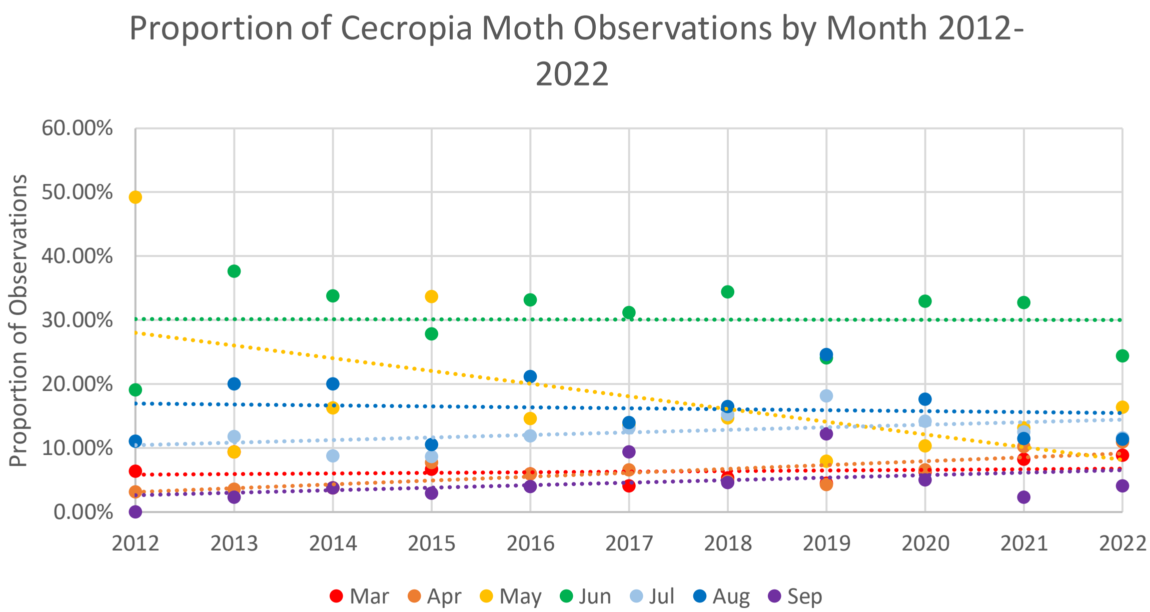
The image above contains a graph depicting the proportion of Cecropia moth observations recorded within the different latitude groups across the contiguous United States for the years 2012-2022. Latitude groups are defined as 25 (25'N to 29'N, shown in red), 30 (30'N to 34'N, shown in orange), 35 (35'N to 39'N, shown in green), 40 (40'N to 44'N, shown in blue), and 45 (45'N to 49'N, shown in purple). General trends in proportions are illustrated by their respective trendlines and corresponding slopes can be found in Appendix A.

For cecropia moths (on average in decreasing order), the proportion of observations was greatest in latitude groups 40, 45, 35, 30, and lastly 25. The most prominent pattern seen in the data was that all latitude groups besides 40 had proportions that remained below 30% whereas group 40 ranged 50-62%. Most latitude groups for cecropia moths had proportions that were approximately the same over the ten-year span, aside from a slight increase in group 35 (7% increase) and slight decreases in groups 40 (5.8% decrease) and 45 (5.78% decrease). The proportion of luna moth observations was greatest in latitude group 35 followed by 40, 30, 45, and 25. While group 35 had a steady trend in proportions, groups 25, 30, and 45 all showed slight increases over time (1.73%, 9.48%, 1.85% increase respectively). Group 40 was the only one to decrease over time at a sharp 13.87%. Polyphemus moths had proportions greatest in groups 35 and 40, then 30, 45, and lastly 25. Group 35 again remained consistent whereas groups 25 and 30 increased (9.64% and 8.77%) and groups 40 and 45 decreased (16.77% and 7.94%) from 2012 to 2022. Lastly, rosy maple moths exhibited highest proportions of observations in latitude groups 35 and 40 (ranging 25.33-63.56%) while the remaining groups all generally fell below the 20% range. Most groups had steady trends, though the most notable ones were 30 with a 6.12% increase and 40 with a 4.57% decrease. Graphs for each moth's observation proportions by latitude can be found in Appendix A, and the respective R^2 values and slopes are contained in Appendix B.

Month

On average, the highest proportions of observations for each moth were recorded during the month of June from 2012-2022 aside from polyphemus moths which experienced the highest proportions in August. July and August were close seconds for most moths, though May also displayed some high numbers especially for cecropia and rosy maple. March and September were generally the months with the lowest proportions of observations except for polyphemus moths in which September consistently had higher numbers than March, April, most of May, and occasionally even June. General trends in proportions of observations by month are illustrated in the graphs contained in Appendix C, with corresponding slopes and R^2 values in Appendix D. A sample graph for cecropia moths is shown below in *figure 15.*

Fig. 15: Proportion of Cecropia Moth Observations by Month for 2012-2022

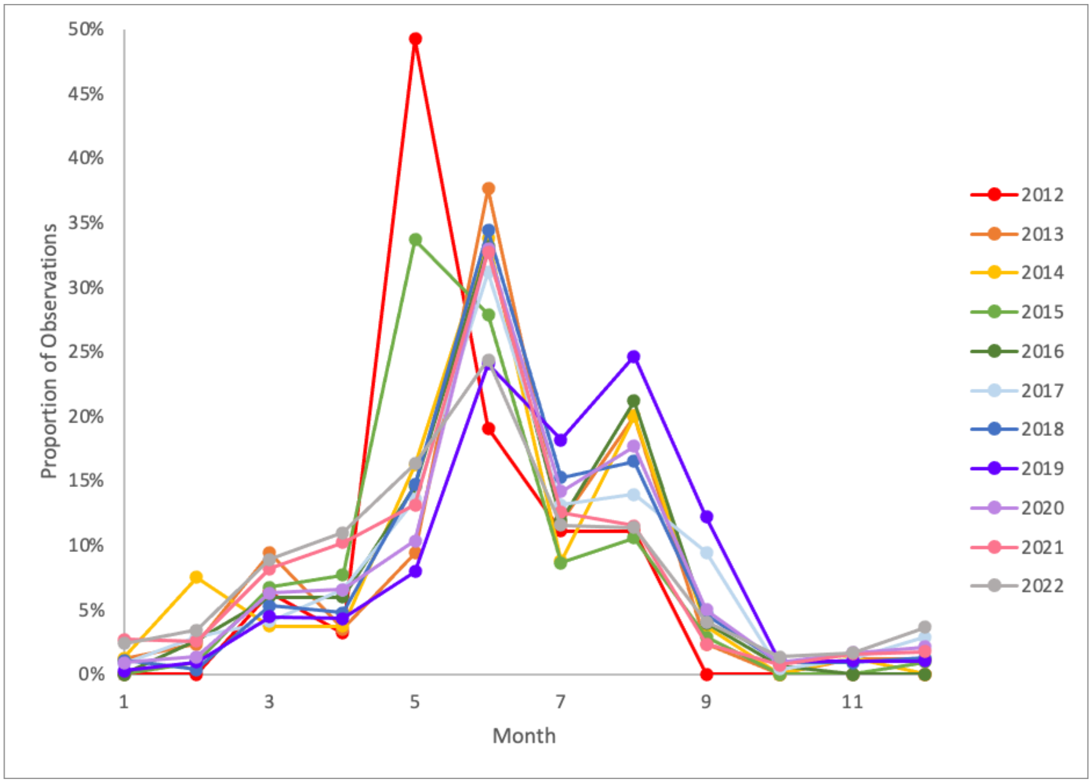


The graph above depicts the proportion of cecropia moth observations recorded within each month for the years 2012-2022 across the contiguous United States. Months were narrowed to March (red), April (orange), May (yellow), July (light blue), August (dark blue), and September purple) as they contained the most data recordings. General trends in proportions are illustrated by their respective trendlines and corresponding slopes can be found in Appendix D.

The majority of 2012-2022 cecropia moth observations were recorded in June (proportions ranging 19.05%-37.65%) aside from 2012 and 2015 where May saw the highest proportions (49.21% and 33.65%). Most months were extremely consistent in their yearly proportions (i.e. y= 0.006x-12.111, R^2= 0.5762 for June) though the most prominent change was seen in May as the proportion of observations dropped from 49.21% in 2012 to 16.33% in 2022 (32.88% decrease). Proportions for the months March, April, July, and September remained below 20% for all 10 years. Similarly, March, April, May excluding 2012, and September all had proportions remaining below 20% for luna moths. They've also experienced high proportions of observations in June though they've been decreasing over time (13.3% decrease since 2012). Aside from the sharp decrease in June, luna moths have shown slight increases for the months April (1.9%), July (9.1%), August (7.5%), and September (4.4%). Polyphemus moths on the other hand had almost an even split between increased and decreased proportions. Four out of the seven months saw increases (March 3.56%, April 2.12%, August 10.4%, and September 4.13%) while the remaining three saw decreases (May 8.04%, June 12.09%, July 9.4%). Unlike the other moth species, polyphemus moths on average had highest proportions of observations in August. Lastly, rosy maple moths displayed highest proportions in June and July ranging from 25.22%-40.57%. The rest of the months on average had proportions remaining below 20%, with March and September being the lowest (below 5%). The proportions for June have been decreasing with time (10.36% decrease since 2012) whereas proportions for April, August, and September have all shown slight increases (3.72%, 9.50%, and 1.86% respectively).

To illustrate which months exhibit peaks in moth observations over time, we created seasonality graphs inspired by the interactive graphs listed on the homepage of each species on the iNaturalist website. We mimicked the general style of this graph for each of our species of interest, but instead used proportion of observations as our dependent variable as opposed to actual number of observations like iNaturalist does. A sample seasonality graph for cecropia moths is pictured below in *figure 16*, and the rest can be found in Appendix E. We can see that there has been a slight shift in peak months for all moths besides cecropia.

Fig. 16: Cecropia Moth Seasonality for the Years 2012-2022



The above graph depicts the proportion of cecropia moth observations in each month for the years 2012-2022 across the contiguous United States. This helps illustrate the shifts in peak months for moths over time and enables us to make predictions about shifting population dynamics in response to changing climate.

In 2012 and 2015, cecropia moths peaked in observations for the month of May and in 2019 they peaked in August, but June was the top month for all other years between 2012-2022. *Figure 16* depicts proportions dropping for the month of July and peaking a second time in August for most years. For luna moths, there was a slight shift in seasonality to later months (July and August) between 2017-2019 but otherwise has consistently experienced peaks in June with the occasional second spike in August. Polyphemus moths experienced peaks on the later end, with peaks in August for 2017, 2019, and 2022 and in July for 2012. The rest of the years peaked in June, with 2013, 2016, 2020, and 2021 showing a second spike in August. Rosy maple moths had no second spikes in proportion of observations and saw a shift towards later months for 2017-2019 and 2022, where peaks occurred in July whereas previous years saw peaks in June.

Climate Data & Statistical Analysis

After graphically examining the proportions of observations in respect to latitude group and month, we decided to further analyze these relationships through statistical analysis and compare them to northeastern climate data. We first examined if proportion of observations differs by latitude or month by running separate, single-factor ANOVA tests for each species in R. We also ran descriptive statistics in Excel for each moth's proportion of observations by latitude for 2012-2022 as well as by month. Table 1 lists these metrics along with the results from each ANOVA test. It was found that for all moth species, there was statistical significance between proportion of observations and both latitude and month ($p < 0.001$).

Table 1: Descriptive Statistics and ANOVA Results for Proportion of Moth Observations

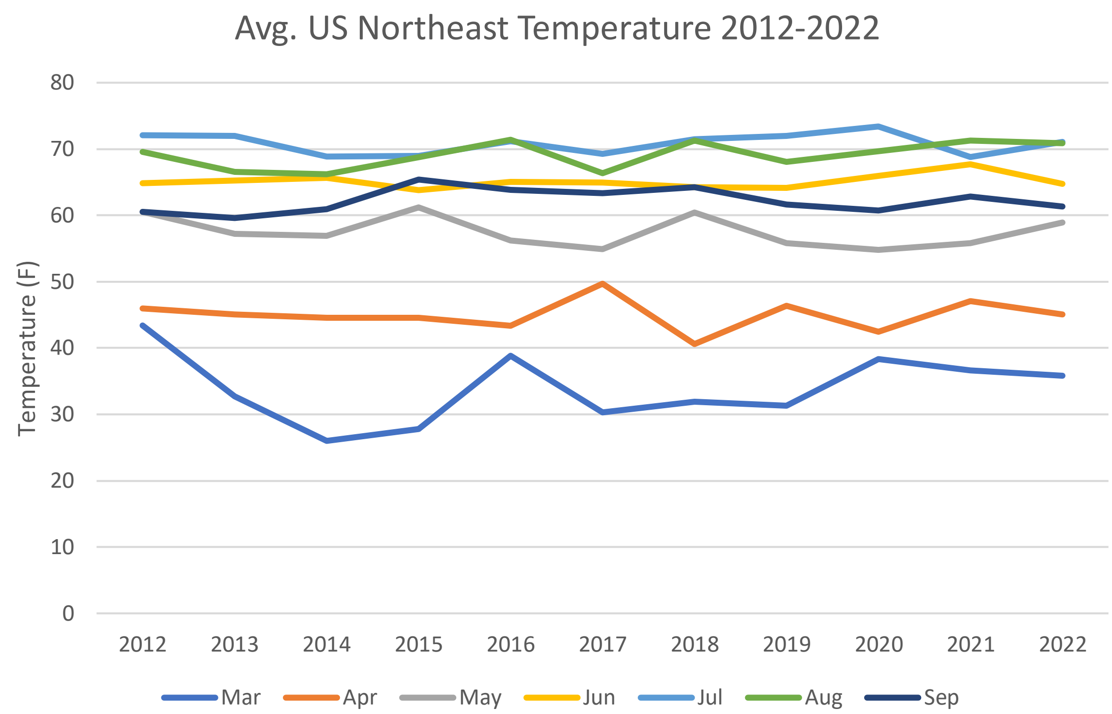
Descriptive Statistics for Proportion of Observations								
Moth	*Cecropia*		*Luna*		*Polyphemus*		*Rosy Maple*	
	Lat	Month	Lat	Month	Lat	Month	Lat	Month
Min	0.00	0.00	0.02	0.03	0.02	0.01	0.00	0.00
Max	0.62	0.49	0.44	0.35	0.42	0.27	0.64	0.41
Range	0.62	0.49	0.42	0.33	0.40	0.26	0.64	0.41
Std. D	0.20	0.11	0.13	0.08	0.11	0.06	0.20	0.13

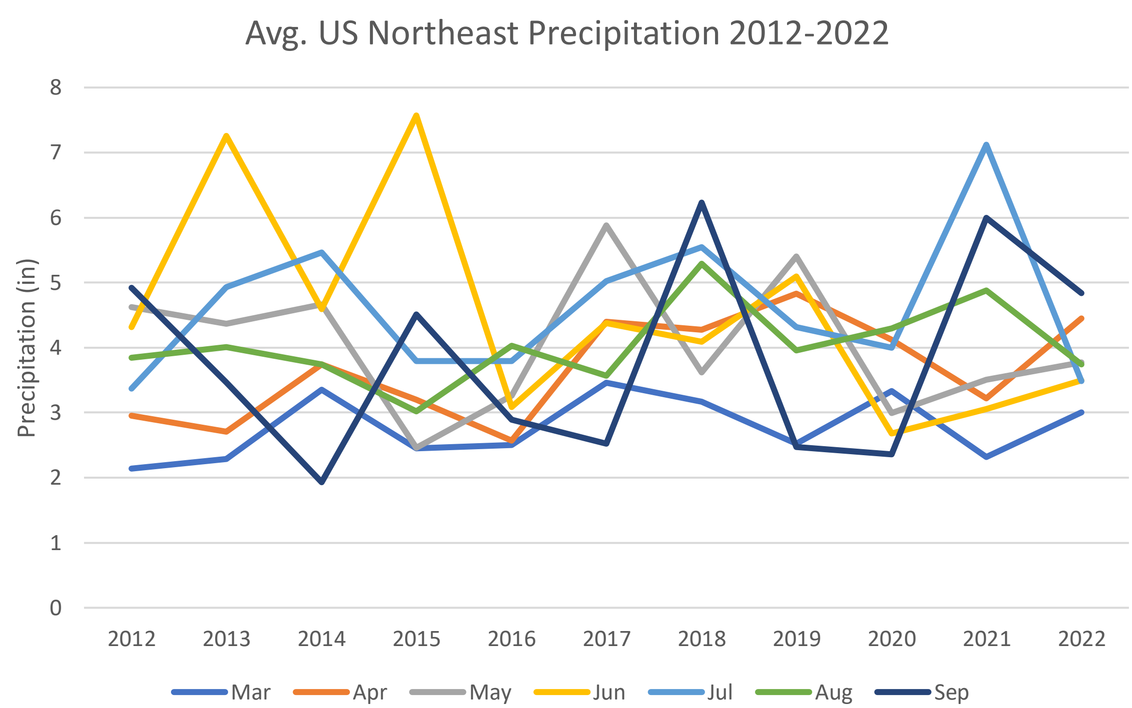
Results for Single-Factor ANOVA								
Moth	*Cecropia*		*Luna*		*Polyphemus*		*Rosy Maple*	
	Lat	Month	Lat	Month	Lat	Month	Lat	Month
df	4	6	4	6	4	6	4	6
F	267.5	26.58	140.9	42.55	80.6	32.83	131.9	131.3
p-value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

The above table shows descriptive statistics and ANOVA test results for proportion of observations by latitude and by month for the years 2012-2022. Highlighted in grey are the results for the monthly proportions and in white are the results for proportions by latitude.

Once we understood how the proportions of observations for each moth species related to latitude and month, we then compared them to the average temperatures and precipitation for the northeastern United States, whose region is defined by the NOAA map listed in Appendix F. Below are *figures 17 & 18,* which contain graphs of average monthly temperature and average monthly precipitation of the northeastern United States over the years 2012-2022. As expected, we see the lowest average temperatures occurred during March and the highest average temperatures were recorded for July and August. Though changes in average temperature over time may be miniscule and difficult to see in such a particular area/timeframe, it has been proven by countless climate scientists and is generally agreed upon that average global temperatures have been on the rise (Butler 2018). As for precipitation, the trajectory of the graph is less predictable. The greatest average precipitation values occurred during June of 2013 and 2015 (7.26in and 7.57in respectively) and the lowest during September of 2014 (1.93in). Overall, it appears that most months are increasing in average precipitation levels as time goes on, which aligns with current trajectories of increased extreme weather (Jentsch 2007).

Fig. 17 & 18: Average Temperature and Precipitation in the Northeastern United States Over Time





The graphs above depict monthly trends in average temperature (F) and precipitation (in) for the northeastern United States during the years 2012-2022.

Knowing that temperature varies by latitude, we were curious as to how proportions of observations in our chosen latitude groups correlate to temperature. To do so, we chose to run correlations in Excel between average temperature, precipitation, and proportion of observations by latitude for each separate year. We found that for cecropia moths, proportion of observations by latitude had a strong, positive correlation to average temperature for the years 2014 ($r = 0.733$) and 2021 ($r = 0.758$) as well as to precipitation for 2013 ($r = 0.943$) and 2015 ($r = 0.957$). For luna moths, proportion of observations had no strong correlations to average temperature but had strong, positive correlations to precipitation for the years 2012, 2019, and 2022 ($r = 0.906$, 0.886, and 0.719). Proportion of polyphemus moth observations only showed a strong, positive correlation to 2012 precipitation ($p= 0.867$). Lastly, proportion of rosy maple moth observations had strong, positive correlations to precipitation for the years 2012, 2013, and 2019 ($r = 0.779$, 0.784, and 0.74) and a strong, negative correlation in 2020 ($r = -0.816$). An interesting observation we noted here is how average temperature was strongly correlated only to cecropia moth proportions during 2014 and 2021, whereas precipitation was strongly correlated to proportion of observations for every species for at least one year (see *Table 2* below).

Table 2: Proportion of Observations by Latitude in Relation to Climate Data

Is Proportion of Observations Correlated to Climate Data?								
Moth	*Cecropia*		*Luna*		*Polyphemus*		*Rosy Maple*	
	Avg. T	**Precip.**	**Avg. T**	**Precip.**	**Avg. T**	**Precip.**	**Avg. T**	**Precip.**
2012	No	No	No	Yes	No	Yes	No	Yes
2013	No	Yes	No	No	No	No	No	Yes
2014	Yes	No	No	No	No	No	No	No
2015	No	Yes	No	No	No	No	No	No
2016	No	No	No	No	No	No	No	No
2018	No	No	No	No	No	No	No	No
2019	No	No	No	Yes	No	No	No	Yes
2020	No	No	No	No	No	No	No	Yes
2021	Yes	No	No	No	No	No	No	No
2022	No	No	No	Yes	No	No	No	No

The table above lists the results of each correlation test ran between proportion of observations by latitude and both average temperature and precipitation for 2012-2022. Highlighted in yellow are the instances where proportion and a weather variable were strongly correlated to each other (r > 0.7).

Discussion

Dataset

Before diving into potential explanations for trends in our selected data, we want to first preface that the datasets we analyzed, though they contained hundreds of thousands of observations, are only a select portion of actual moth populations to exist during our chosen timeframe. This is mainly because these observations are only what have been recorded in iNaturalist, which launched in 2008 and relies heavily on everyday people and scientists to collect data. Since its launch date, the number of overall observations each year has been roughly doubling, and according to the nonprofit's 2018 year in review, the site had not passed the 100,000 observations a year threshold until 2012— hence our focus on the years 2012-2022 (Loarie 2018). Seeing as the popularity and general use of this resource required some time to gain traction, the number of moth observations closer to their launch date may not reflect actual population abundances (Möglich et al. 2023). Even nowadays when observations are at an all-time high, results can still not entirely be representative of actual moth communities due to increased user activity during certain times of the year or even by latitude group. For example, nature observation projects such as eBird and iNaturalist have the highest number of observations in June. When looking at overall (not just nature-based) citizen science projects, we can also see a direct and positive correlation between contribution and seniority among participants (Strasser 2023). While such variability correlates to the seasonality and individuals' skill level, we can begin to see how biases may impact the data collection process.

The data itself has many biases just due to its nature. While it has been thought that citizen science programs are helping in reflecting the wants and needs of citizens, citizen science appears to concentrate on affluent municipalities while excluding highly marginalized regions (Fernández-Álvare 2022). iNaturalist data comes from citizens who log observations they make in nature using their mobile device or computer. One, this limits data collection to only those with internet or access to a device, making areas with less access prone to lower numbers of observations than there may be (Scheibner 2021). Thus, remote and/or disadvantaged communities may be underrepresented, especially in our proportions by latitude data. Studies have found that marginalized groups in society are also underrepresented from citizen science.

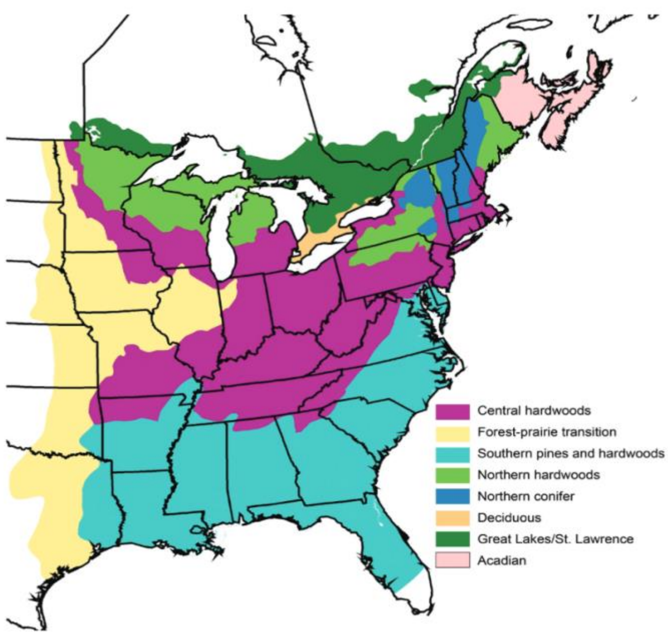
This includes people with lower social, human, and economic capita (Pateman et al. 2021). Two, there is room for user and/or artificial intelligence (AI) error in accurately identifying the organism. Users have the option to choose between AI-suggested species after uploading photos of their organism, and even though photos and descriptions are provided with suggested species, users still may choose an incorrect option that can go unresolved by scientists. Additionally, photos uploaded by users may also be too blurry for the AI system to provide accurate identification options and for scientists to agree/disagree with. This is another reason we chose the four silk moths we did, as they're easily identifiable and have few lookalikes (Luna n.d.; Giant n.d.; Roads 2014), thereby potentially reducing the risk of false positives. As mentioned in our methods, we narrowed the data to only "research grade" observations, which are observations that 2/3 of the community voters agree on. This filter does a sufficient job at eliminating additional false positives from our dataset (i.e., a different moth species incorrectly identified as a cecropia etc.), though there is always a small potential for error (Koch et al. 2022). The influence of AI in causing inconsistencies in datasets within the biological research community is becoming a common topic of interest, especially in genome sequencing research where it is increasingly difficult to avoid false positives when analyzing datasets using AI (Mallick et al. 2009). Unfortunately, there is no easy way for us to pinpoint false positives in our datasets due to their sheer sizes; we would have to look at the tens of thousands of observations one by one and compare them with their associated photo file— if one is even provided. It is for all these reasons that we recognize the trends and correlations we report may not be entirely representative of the actual trends in these moth populations, but rather what trends are arising in the iNaturalist community that can help inform us about potential trends.

Even though these trends may not entirely be true to what is happening in the wild, they still hold some validity especially as the app grows in popularity. What these trends can show us is the potential shifting of peak months for proportion of moth observations. The datasets iNaturalist and other citizen science-based programs possess are incredibly helpful to the scientific community as they are very large and cover areas in which professionals may not have the time or resources to collect data (Strasser et al. 2023). Through documenting observations, citizens are directly contributing to biodiversity research by providing data that scientists can use to track species distribution and abundance, monitor the effects of environmental changes, and ultimately make informed decisions for biodiversity conservation (Duncan et al. 2017). As climate change affects the distribution of species, iNaturalist data can be used to track these shifts and adapt conservation strategies accordingly. Community scientists provide hundreds of thousands of valuable insect observations annually, and several studies have already shown how said data has informed ecologists on insect abundances, distributions, and phonologies (Prudic et al. 2023). One such study in South Africa formed a citizen science project titled the "Baboon Spider Atlas" (BSA) in which community members upload photos to the BSA website of baboon spider encounters. As a result of citizen science, the BSA assembled the largest database of baboon spider information in Southern Africa and discovered not only that their ranges are expanding and are limited by cold/wet climactic conditions, but also documented new behavior in adult females and immatures that challenged the previous notion that baboon spiders are sedentary (Campbell 2017). While the BSA is an ongoing project, the Campbell paper was only based on data from the initiative's launch date in 2013 to October 2017— a dataset nearly half the size of the ones we analyzed, yet still incredibly accomplished in its findings and insights into baboon spider ecology. Other studies have reached similar conclusions that citizen science monitoring programs are effective tools in collecting large quantities of data that scientists would require tenfold the amount of time and resources to accomplish. Another study in the UK found that two weeks' worth of community-collected wasp data generated coverage comparable to over four decades of recordings by experts (Sumner et al. 2019). Seeing as each of our moth datasets is ten years' worth of data, the shifts we noted in proportions by latitude and peak months provide constructive insights into long-term species distribution and phenology.

Impact of Latitude on Moth Communities

Latitude plays a crucial role in shaping the diversity, distribution, and behavior of nearly all organisms, and moths are no exception. Moth species are not evenly distributed around the world as their diversity and composition vary with latitude (Antão 2020). This aligns with the Latitudinal Diversity Gradient Theory, which claims that there is high taxonomic, phylogenetic, functional, genetic, or phenetic biodiversity near the equator, and less such biodiversity as you move towards the poles (Willing 2018). While the specific causes of this phenomenon are unknown, the primary cause is thought to be temperature (influenced by solar radiation) on evolutionary speed (Rohde 1992). We documented that latitude groups 35 and 40 exhibited on average the highest proportions of observations for each moth, meaning that states falling between the 35th and 45th parallel seem to be the hotspots for our moths of interest. On the East Coast, the border between North Carolina and Georgia marks the 35th parallel, and the 45th parallel runs through New York, Vermont, New Hampshire, and Maine (see *figure 13*). This region falls within the distribution patterns for each moth (see *figures 4,6,9, & 11*), and the latitude groups with the lowest proportions of observations (groups 25 and 45) mark the bottom and top portions of these distribution map. It makes sense that groups 35 and 40 showed the highest proportions of observations because the region between the 35th and 45th parallel has a large availability of preferred host plants, as biodiversity tends to increase as latitude declines (Ha et al. 2023). Cecropia moth caterpillars feed mainly on the leaves of birch, cherry, and maple trees common to this area (Hoffman 1978). Luna moth caterpillars also feed on the leaves of a variety of native hardwoods, primarily hickory and birch (Patlan 2000), and polyphemus caterpillars feed on broad-leaved trees and shrubs such as sweetgum, birch, maple, and oak (Kalola 2011). As implied by its name, rosy maple caterpillars feed on the leaves of maple trees, especially those of red and sugar maples widely distributed in this region (Damele 2013*). Figure 19* below illustrates the major forest regions of the Eastern United States (Dey et al. 2012).

Fig. 19: Major Forest Regions of the Eastern United States



The graph above depicts the major forest regions of the Eastern United States. Our moths of interest feed mostly on the leaves of deciduous, hardwood trees which can be seen between the 35th and 45th parallel (Dey 2012).

Another interesting trend we noticed was that each moth species experienced both a slight decline in proportion of observations for latitude group 40 and a slight increase in groups 25 and 30 from 2012-2022. The increase in lower latitudes surprised us, as we know most preferred host plants were found in the 35th to 45th range. In addition, many new studies that address moth populations in terms of latitude and climate change are hypothesizing that in response to warming, species are expanding their ranges poleward regardless of their latitudinal range extent and habitats (Burner et al. 2021; Antão 2020). While this might not make sense for groups 25 and 30, this can be a potential explanation as to why there was a general decreasing trend in latitude group 40, as moths from this region may be traveling north. However, this may not be exactly the case as the decreases from latitude 40 were not directly reflected in latitude group 45, seeing as there was a 50/50 split in terms of increasing and decreasing trends.

Based on our correlations between proportion of observations and climate data, we saw that precipitation appeared to have a closer-knit relationship to proportion of observations than did temperature, though relative importance of temperature and precipitation can vary based on a region's specific climate or habitat. For example, the effects of precipitation on species abundance may arguably outweigh those of temperature in arid regions where even minor rainfall events may have profound impacts on moth communities as moisture availability is usually a limiting factor (Brehm et al. 2007). Perhaps proportions are increasing in groups 25 and 30 due to the region experiencing increased precipitation over time, though we cannot say for sure as we only analyzed weather data for the Northeast (see Appendix F) and do not possess latitudinal weather data. However, plenty of current climate studies report trends of increased precipitation levels globally, thus it is entirely possible these latitudes experienced such trends (Harp et al. 2022; Myhre et al. 2019). In contrast, temperature may be a more consistent factor influencing moth development and activity in more tropical or temperate regions (Uhl 2022). While average environmental temperature is still an incredibly important factor that influences everything from life cycle timing to insect behavior and basic metabolic processes, precipitation ultimately can have more immediate, conspicuous influences that directly impact population dynamics. Precipitation dictates facets like resource availability and breeding conditions, which are essential to moth survival and proliferation. Adequate rainfall leads to the increase in plant growth and production of new leaves, serving as both an essential diet for moth caterpillars and favorable breeding conditions for adult moths, as they often lay their eggs on or near preferred host plants (Bertea et al. 2020). In addition to this, precipitation can deter moth predators such as bats and birds which allows moths a greater chance at survival and reproduction. It is for these reasons that we believe precipitation tended to correlate more with the proportion of moth observations than average temperature.

Conclusion

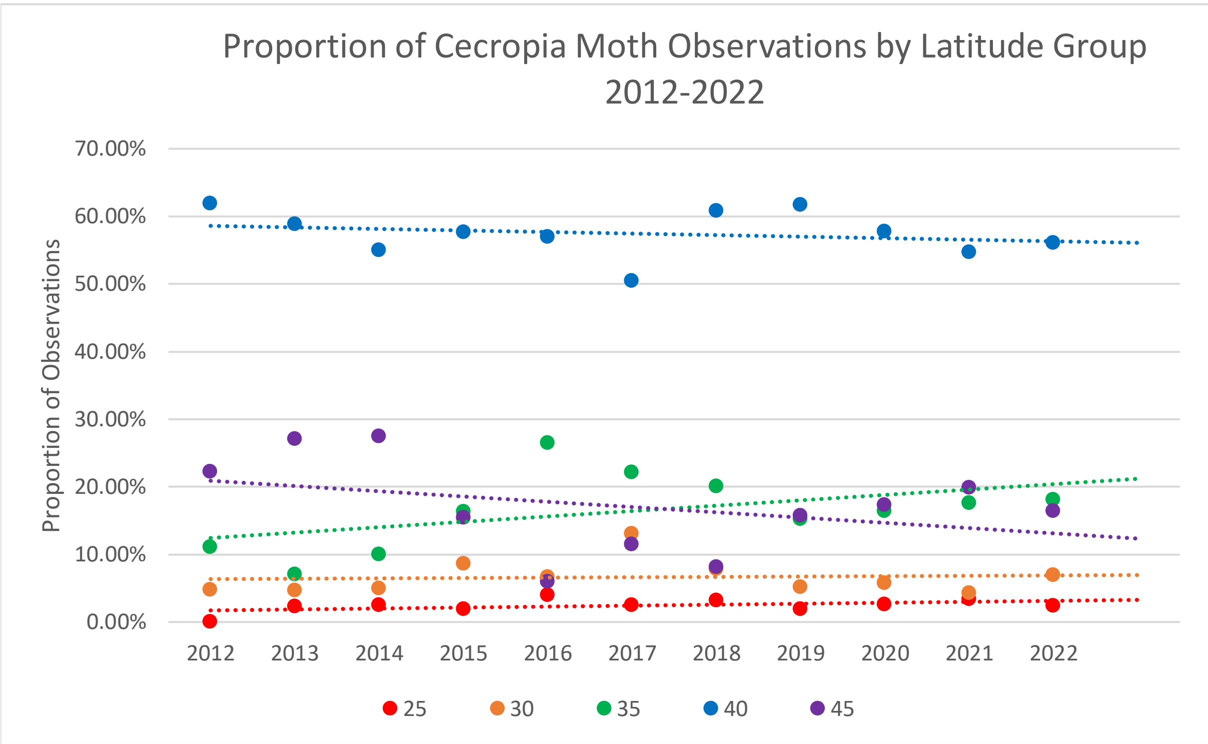
While more in-depth research is needed to explain exactly why these trends are occurring, rising global temperatures and extreme precipitation are two major geographically pervasive stressors that interact with all other factors. As climate change continues to alter our ecosystems, understanding the responses of wildlife like moths is essential for informed conservation strategies and biodiversity preservation. With the help of apps like iNaturalist, we can monitor and better grasp the impacts of environmental changes on moth and other insect populations.

The survival of moth and other pollinator species is directly tied to our own survival. While the control of rising global temperatures may be out of individual civilians' hands, there are still ways to help native moth populations. As previously discussed, moths are essential pollinators and food sources. The rising temperatures of climate change are hurting moth populations, especially those at high latitudes and elevations that are even more susceptible to changing temperatures (Moth 2014). The most effective method for increasing local moth diversity and population is increasing the amount of wildflower species found in your backyard, garden, or around your neighborhood (Blumgart et al. 2023). In addition, increased participation in citizen science programs, such as iNaturalist, can help the scientific community understand moths and their patterns.

Appendices

Appendix A: Proportion of Observations by Latitude Group 2012-2022

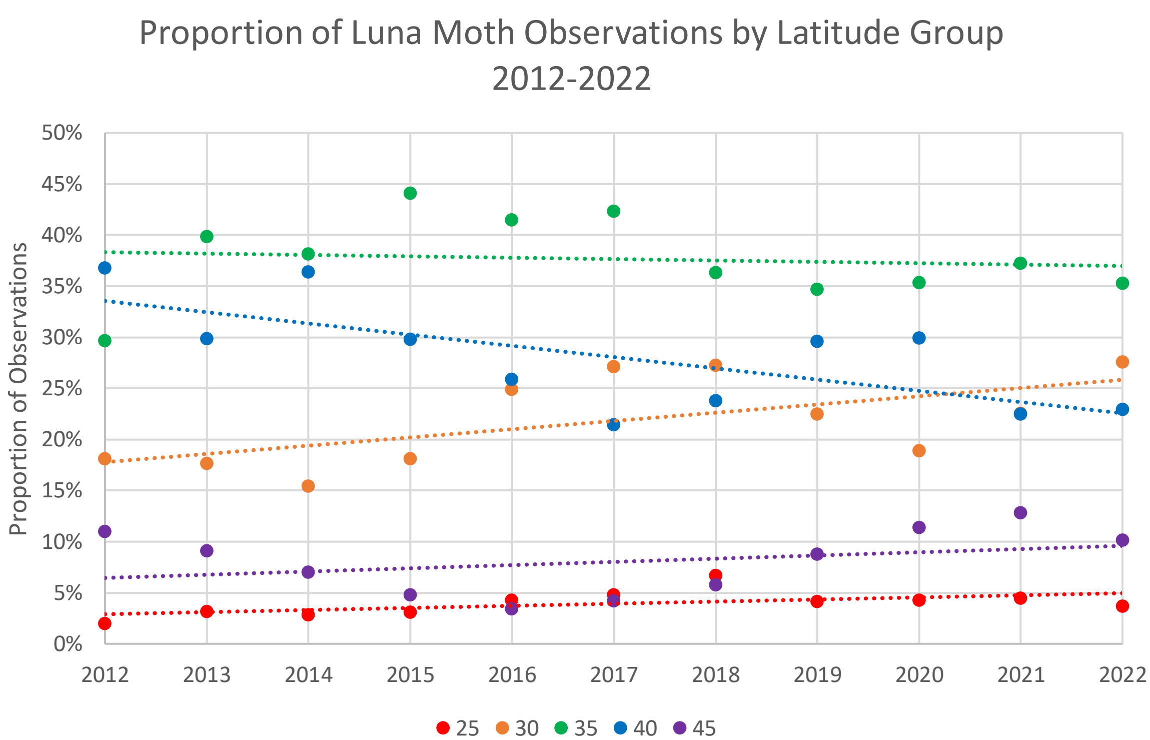
Proportion of Cecropia Moth Observations by Latitude Group 2012-2022

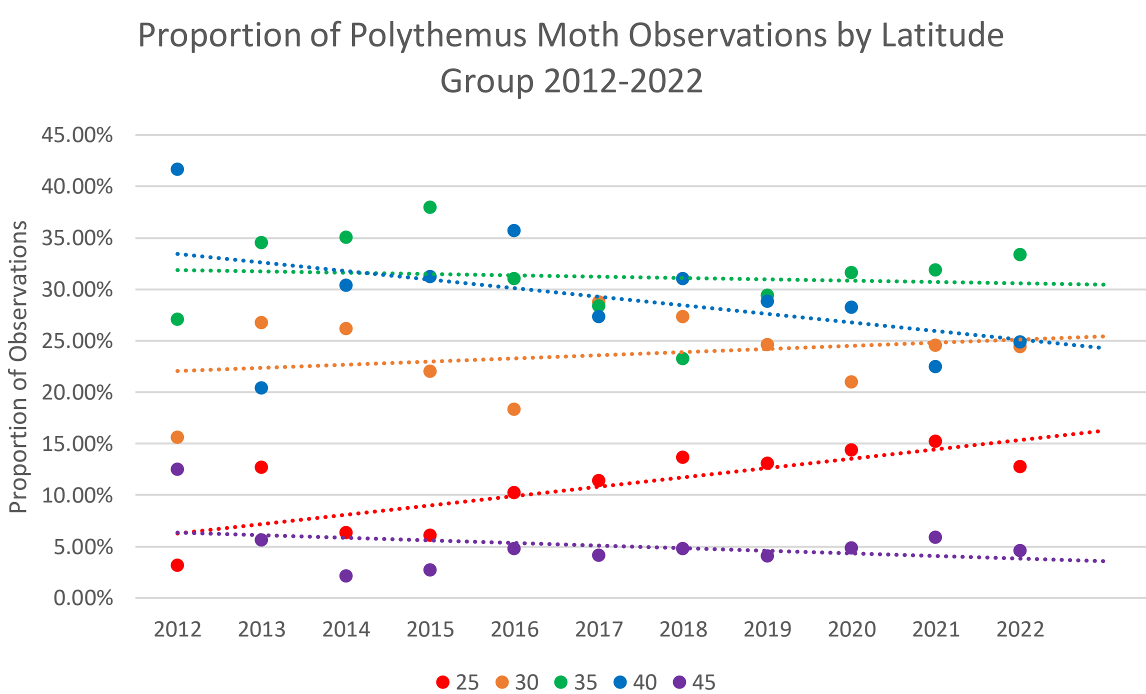


The image above contains a graph depicting the proportion of Cecropia moth observations recorded within the different latitude groups across the contiguous United States for the years 2012-2022. Latitude groups are defined as 25 (25'N to 29'N, shown in red), 30 (30'N to 34'N, shown in orange), 35 (35'N to 39'N, shown in green), 40 (40'N to 44'N, shown in blue), and 45 (45'N to 49'N, shown in purple). Latitude groups and colors depicting them as shown above are kept continuous for all moths.

Appendix A: Proportion of Observations by Latitude Group 2012-2022

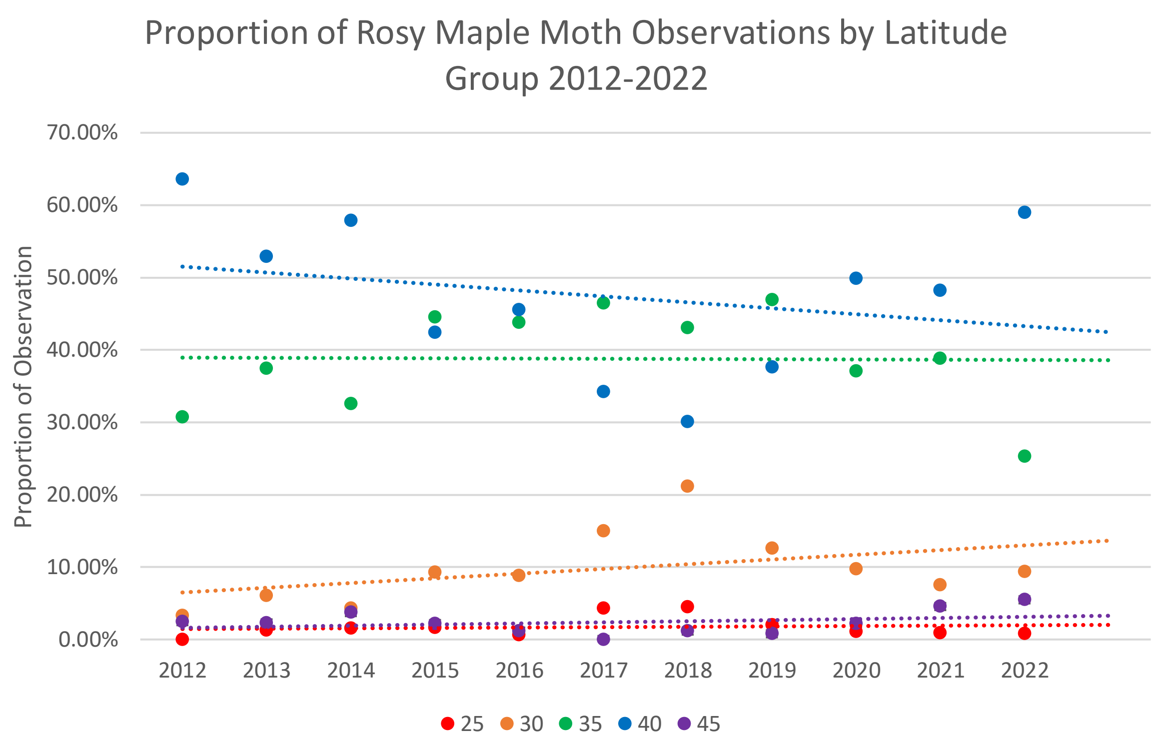
Proportion of Luna & Polyphemus Moth Observations by Latitude Group 2012-2022





Appendix A: Proportion of Observations by Latitude Group 2012-2022

Proportion of Rosy Maple Moth Observations by Latitude Group 2012-2022

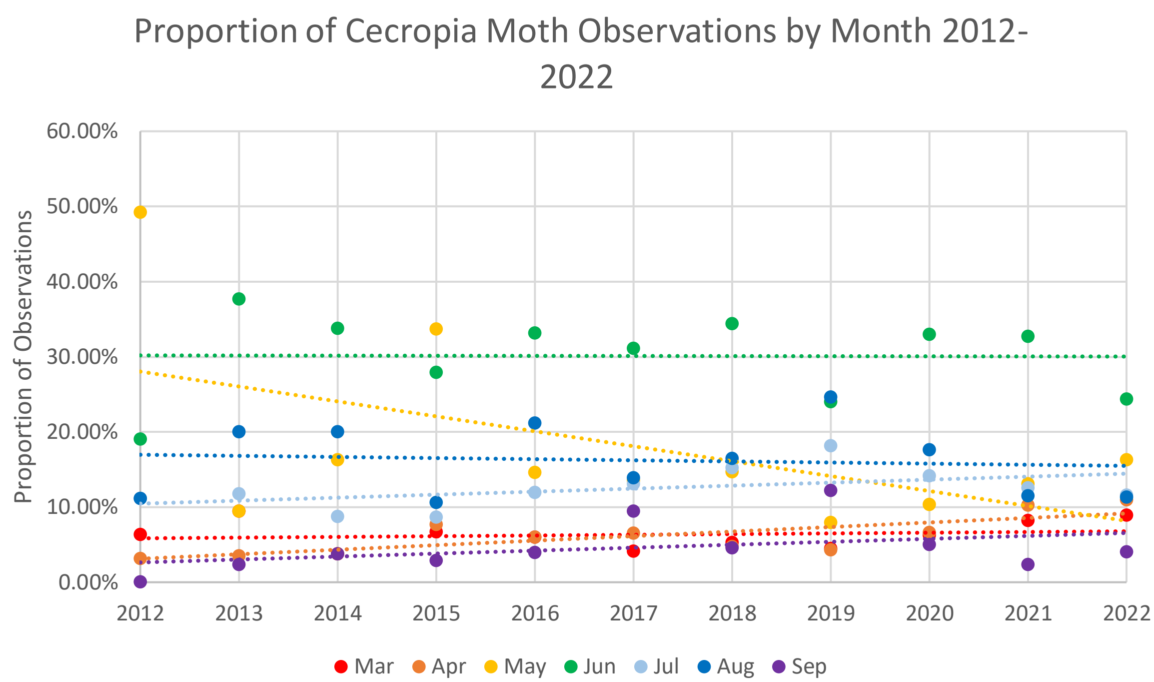


Appendix B: Slope and R^2 Values for Observations by Latitude

Latitude Group	Cecropia	Luna	Polyphemus	Rosy Maple
25	$y = 0.0014x + 0.015$ $R^2 = 0.2131$	$y = 0.0021x - 4.1155$ $R^2 = 0.3031$	$y = 0.0091x + 0.0536$ $R^2 = 0.5868$	$y = 0.0005x + 0.0139$ $R^2 = 0.014$
30	$y = 0.0005x + 0.063$ $R^2 = 0.0048$	$y = 0.0081x - 16.044$ $R^2 = 0.365$	$y = 0.0031x + 0.2175$ $R^2 = 0.0642$	$y = 0.0065x + 0.0584$ $R^2 = 0.1825$
35	$y = 0.008x + 0.1163$ $R^2 = 0.2251$	$y = -0.0013x + 3.0914$ $R^2 = 0.0119$	$y = -0.0013x + 0.32$ $R^2 = 0.0109$	$y= -0.0003x + 0.3897$ $R^2 = 0.0002$
40	$y = -0.0023x + 0.5882$ $R^2 = 0.0493$	$y = -0.011x + 22.447$ $R^2 = 0.4715$	$y = -0.0083x + 0.3428$ $R^2 = 0.217$	$y = -0.0082x + 0.5234$ $R^2 = 0.0654$
45	$y = -0.0078x + 0.2167$ $R^2 = 0.1382$	$y = 0.0031x - 6.2502$ $R^2 = 0.1061$	$y = -0.0025x +0.0661$ $R^2 = 0.0962$	$y = 0.0015x + 0.0145$ $R^2 = 0.0932$

Appendix C: Proportion of Observations by Month 2012-2022

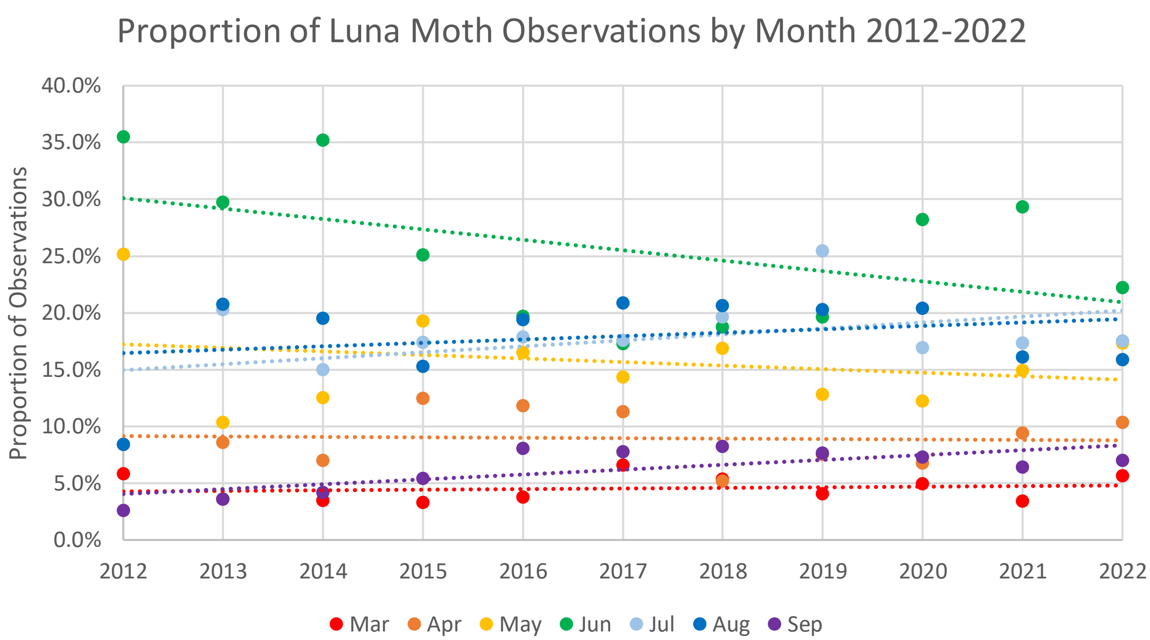
Proportion of Cecropia Moth Observations by Month 2012-2022

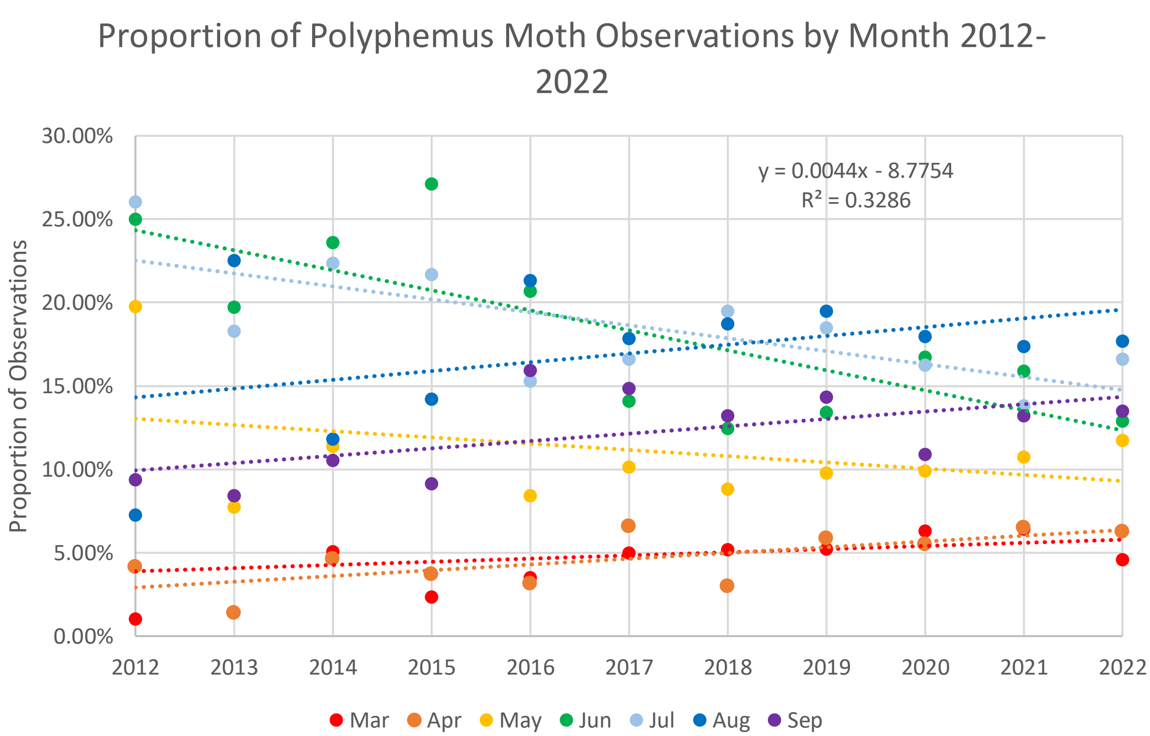


The graph above depicts the proportion of cecropia moth observations recorded within each month for the years 2012-2022 across the contiguous United States. Months were narrowed to March (red), April (orange), May (yellow), July (light blue), August (dark blue), and September purple) as they contained the most data recordings. Months and colors depicting them are kept continuous for all moths.

Appendix C: Proportion of Observations by Month 2012-2022

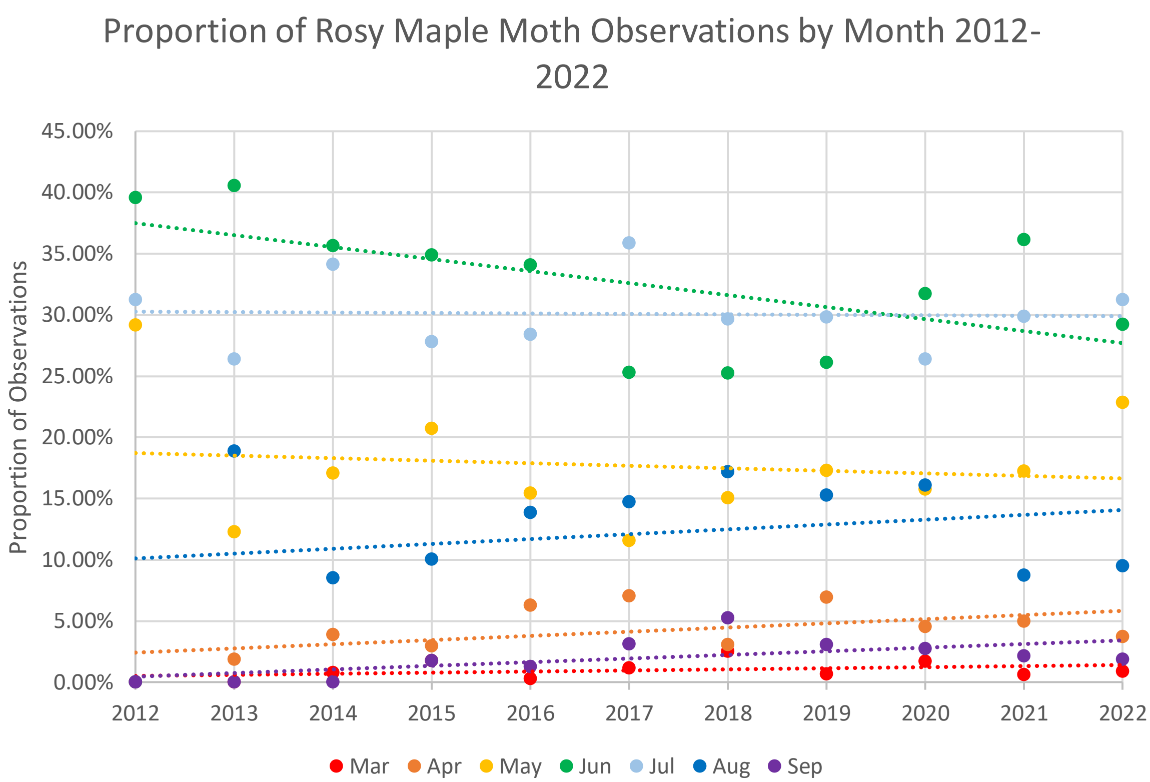
Proportion of Luna & Polyphemus Moth Observations by Month 2012-2022





Appendix C: Proportion of Observations by Month 2012-2022

Proportion of Rosy Maple Moth Observations by Month 2012-2022

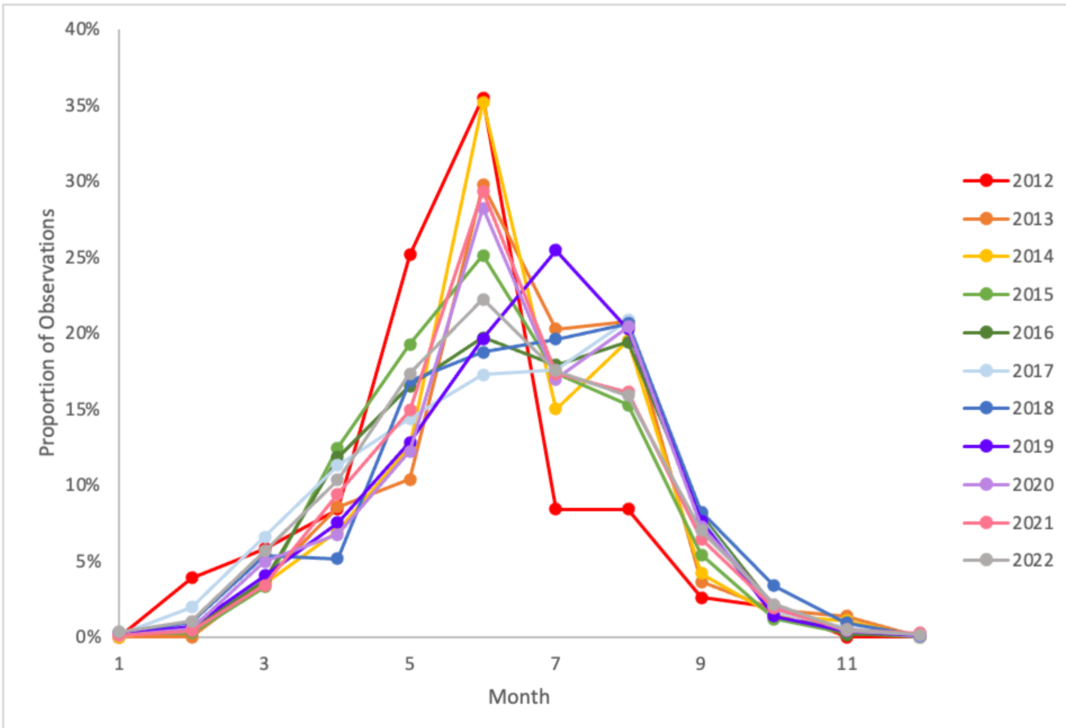


Appendix D: Slope and R^2 Values for Observations by Month

Month	Cecropia	Luna	Polyphemus	Rosy Maple
MAR	y = 0.0009x - 1.822 R^2 = 0.0266	y = 0.0009x - 1.7937 R^2 = 0.1409	y = 0.0019x - 3.7779 R^2 = 0.0978	y = 0.0009x - 1.7937 R^2 = 0.1409
APR	y = 0.006x - 12.111 R^2 = 0.5762	y = 0.0034x - 6.8414 R^2 = 0.2732	y = 0.0035x - 6.9166 R^2 = 0.4535	y = 0.0034x - 6.8414 R^2 = 0.2732
MAY	y = -0.0199x + 40.254 R^2 = 0.2848	y = -0.0021x + 4.3532 R^2 = 0.0188	y = -0.0037x + 7.6458 R^2 = 0.1354	y = -0.0021x + 4.3532 R^2 = 0.0188
JUN	y = -0.0001x + 0.5988 R^2 = 8E-05	y = -0.0098x + 20.075 R^2 = 0.3474	y = -0.012x + 24.381 R^2 = 0.5829	y = -0.0098x + 20.075 R^2 = 0.3474
JUL	y = 0.004x - 7.9238 R^2 = 0.233	y = -0.0004x + 1.0544 R^2 = 0.0017	y = -0.0078x + 15.85 R^2 = 0.5234	y = -0.0004x + 1.0544 R^2 = 0.0017
AUG	y = -0.0015x + 3.1532 R^2 = 0.0103	y = 0.004x - 7.8664 R^2 = 0.0596	y = 0.0053x - 10.444 R^2 = 0.1604	y = 0.004x - 7.8664 R^2 = 0.0596
SEP	y = 0.0039x - 7.873 R^2 = 0.1456	y = 0.003x- 5.9636 R^2 = 0.3731	y = 0.0044x - 8.7754 R^2 = 0.3286	y = 0.003x - 5.9636 R^2 = 0.3731

Appendix E: Silk Moth Seasonality Graphs for 2012-2022

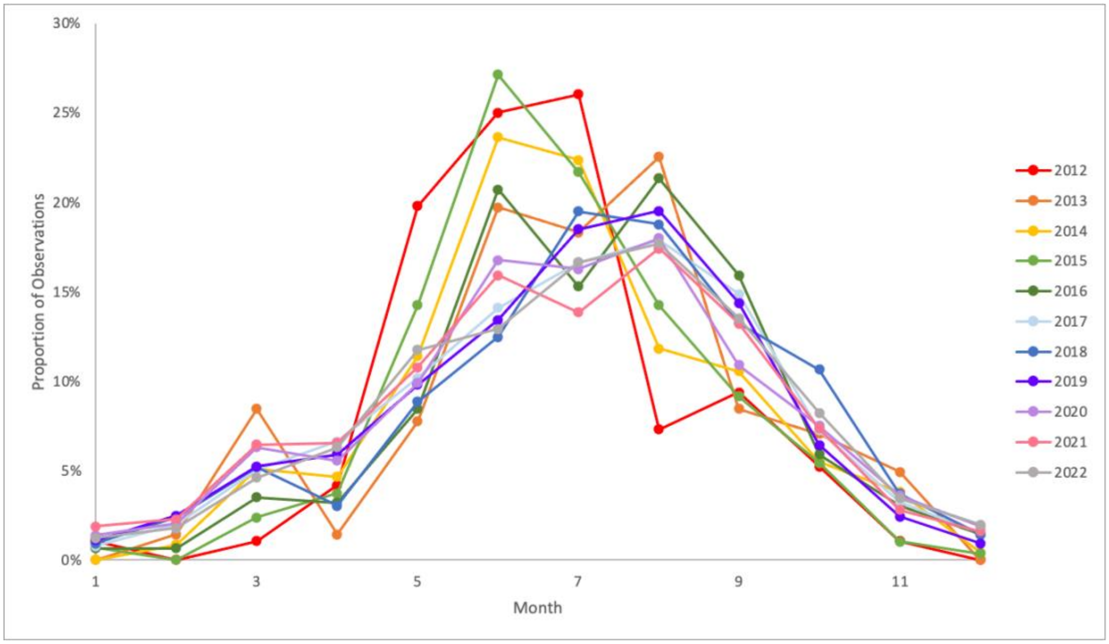
Luna Moth Seasonality for the Years 2012-2022

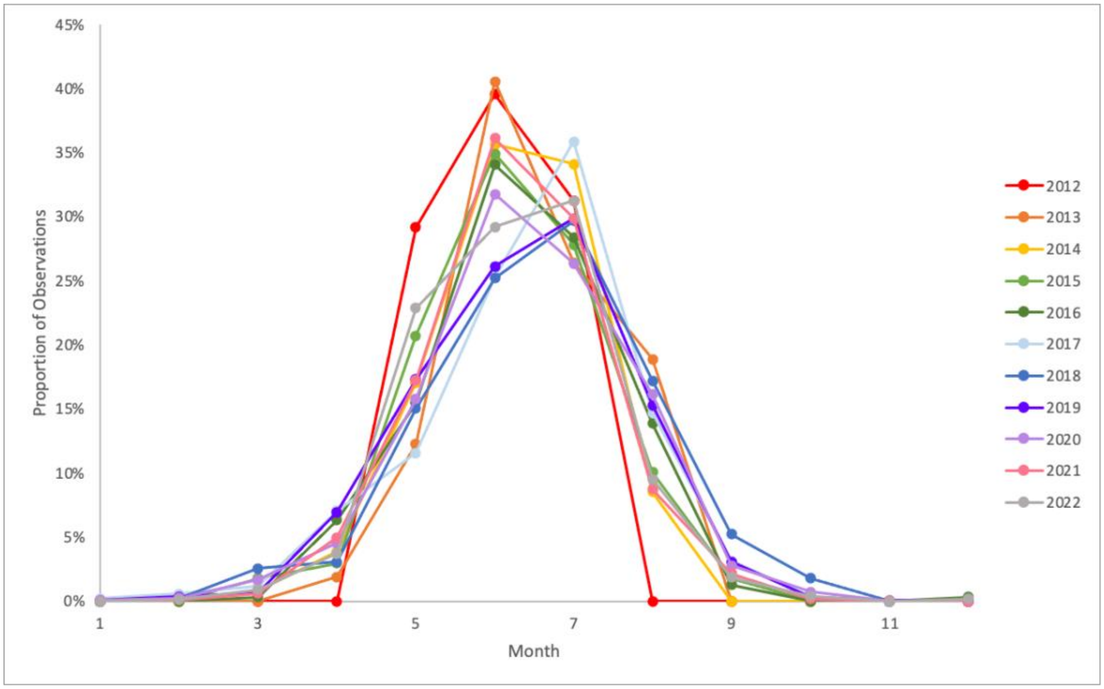


The above graph depicts the proportion of luna moth observations in each month for the years 2012-2022 across the contiguous United States. This helps illustrate the shifts in peak months for moths over time and enables us to make predictions about shifting population dynamics in response to changing climate.

Appendix E: Silk Moth Seasonality Graphs for 2012-2022

Seasonality Graphs of Polyphemus & Rosy Maple Moth Observations from 2012-2022

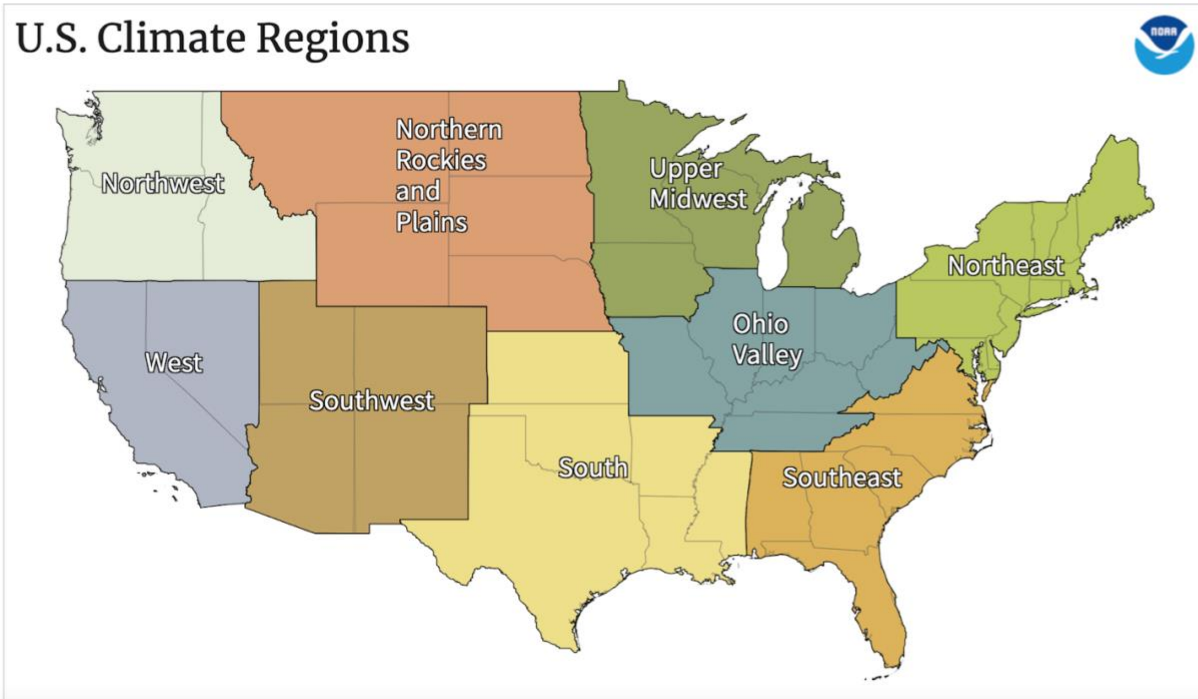




The uppermost graph depicts the proportion of polyphemus moth observations per month for the years 2012-2022 and the bottom graph represents the same relationship but for rosy maple. These particular graphs help illustrate the shifts in peak months for moths over time.

Appendix F: Map of U.S. Climate Regions as Defined by NOAA

Climate Regions of the U.S. Defined by NOAA



The image above is a map of the United States broken into nine climate regions, as defined by the National Oceanic and Atmospheric Association. For our study, we used climate data for the "Northeast" to compare our moth data with.

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