REGIONAL AND NATIONAL TRENDS IN LEPIDOPTERA COLLECTING IN THE UNITED STATES SINCE 1800

By

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ABSTRACT

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Though natural history collections began as private demonstrations of wealth and knowledge, they are now places of public learning and depositories of biodiversity. Insects have been collected for their beauty and small size since the beginnings of natural history collections, making them ideal for studies of long-term collecting patterns.

This thesis project characterizes collecting efforts focused on butterflies and moths within the United States, both at the institutional and national level. The A. J. Cook Arthropod Research Collection (ARC) at Michigan State University contains 96,618 databased Lepidoptera specimens, predominantly collected in the state of Michigan. The ARC has a long history of involvement by avocational collectors, both in terms of specimen donation and curation. Their contributions grew significantly in the 1950s. However, the number of specimens added annually by both professionals and non-professionals has decreased greatly since 1970. More than 1 million Lepidoptera specimens held in various US collections were also used to examine trends in Lepidoptera collecting nationally. Collecting has been inconsistent over time and markedly on the decline since the 1990s. States are not evenly represented in this dataset, mirroring the inconsistency seen in county representation among Michigan specimens in the ARC. This uneven distribution is at least partially associated with a lack of funding for databasing and other areas of curatorial effort for insect collections, in addition to a decrease in natural history education in K-12 and undergraduate curriculums.

For my best friend, Evan, for putting up with far too many
panic texts at 3am and for always insisting that I could (and would!) do this.

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insect display case builder, and parent a person could ask for.

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1500-1600

Though they have undergone many extensive changes since their beginnings in the sixteenth century, natural history collections continue to fascinate the professional and the amateur alike. In their influence on the professional scientist, collections of specimens from the natural world have informed and supported many major discoveries and theories in the biological sciences, from works in the field of anatomy to the development of Darwin's theory of evolution (Darwin 2003, Lubar 2017). Though early collections are a far cry from the professional institutions of today, these proto-collections would become one of the most important sources of scientific knowledge.

In Medici-era Italy and in Prague, early groupings of objects—not yet called collections—were encyclopedic in nature and privately owned. These collections were arranged according to some organizational scheme, largely based around ideas of differences between the items in the collection (Pearce 1995). Collectors were not using their specimens and objects to answer questions about the natural world and its biological functioning; this development would come with the advent of the seventeenth century (Pearce 1995).

The words "collection" and "collector" came to be associated with groupings of physical objects in the seventeenth century; up until this point these terms were only associated with written materials (Swann 2001). The objects in these collections, like their

[1] "A view of the whole" is the title given to the table of contents of the Catalogue of the Tradescant Collection, as published in 1656 by John Tradescant the Younger.

predecessors in Italy and elsewhere, had been set aside by a single person, away from regular use but would come to hold a place in investigating the world (Swann 2001). From early collections came the establishment of a new culture or form of culture. Specimens that were kept and recorded by collectors represented a way to verify stories and previous writings, in addition to being a way for a collector to reevaluate works conducted in the past (Pearce 1995, Parrish 2006). In this way, collections of natural history specimens in particular were involved in the reinvention of scientific endeavors by allowing for better description of details. This, in turn, shaped writings on the exact appearance and other characters of objects in the natural world, though many such publications—like the catalog of the Tradescant collection—read like grocery lists (Tradescant 1656, Pearce 1995, Swann 2001).

1600-1900

By the seventeenth century, natural history was an extension of the efforts of Classical era philosophers; it consisted of information about and explorations of the natural world. However, Classical natural history also included a variety of fields of interest that would no longer be considered a part of natural history, such as astrology (Swann 2001). Collections revolutionized the study of natural history as a science because they allowed for the reevaluation of past efforts that looked into the nature of the world. Observations of collected specimens, as made by discerning individuals, were to become the new way of discovering truths about the world. This was a move away from prior efforts, which consisted of trying to boil knowledge gleaned from earlier writers down to some universal truth purely through philosophical thought. By moving toward observation as a standard, collectors became able to question and revise the writings of the Classical world, though a deep understanding of classical writings was still greatly valued in determining the academic standing of an author (Pearce 1995, Swann 2001).

Natural history was then a movement in search of truths that would ideally allow the observer to sort specimens and other objects according to a universal language (Pearce 1995). This effort to sort and classify was a manifestation of a desire to understand Creation through observation and collecting (Lubar 2017). However, collections were not intended, at this time, to document all of life on Earth (Asma 2001, Parrish 2006)—instead, collections amassed things that were either from exotic locales or that were odd or rare for some other reason (Swann 2001, Parrish 2006). These masses of oddities were the origins of 'cabinets of curiosities' or '*wunderkammer*', which would eventually develop into more formal natural history museums and collections.

Because of this European interest in things taken from exotic or foreign lands, America and other distant lands represented a veritable treasure-trove of specimens and stories. For the American colonies in particular, this was due to the wild differences between the flora and fauna of the American and European continents. The existence of networks of correspondence between European countries and the New World aided in relating specimens and observations across the vast ocean (Parrish 2006). By collecting specimens of living things, in addition to objects from the native peoples, European explorers and collectors subjugated both the natural world and the peoples in it. In this way, collections of exotic objects became a symbolic representation of domination over newly discovered lands and a demonstration of prestige won overseas (Swann 2001, Lubar 2017). In a number of cases, living individuals from cultures perceived as 'primitive' were also collected and often displayed by people of European origin, both by early institutional efforts—such as the 1893 Columbian Exposition in Chicago, Ill. or the display of Ota Benga by the Bronx Zoo in 1906—and by private individuals like Carl Hagenbeck, a German man who dealt in animals (Domosh 2002, Purtschert 2015, Newkirk 2016). Some of the shows put on by individuals were associated with educational institutions and a growing professional scientific community (Purtschert 2015).

The prestige and social status won through collecting in foreign lands contributed to an individual's status as an authority on a subject—though this status was not extended to those, such as colonists, with easy access to foreign materials (Parrish 2006). For those in the British Empire, the expertise of a colonist—due to their geographic closeness to organisms and objects for observation—was sought after by higher-status naturalists in cities like London (Parrish 2006). However, colonists were seen as becoming less and less English the longer they spent in the American colonies, and their position in the networks of communication between naturalists was variable (Parrish 2006). A person's social and economic status, assuming they were not a colonist, determined what they could collect; these seventeenth century collections were used to advance socially and to demonstrate social status (Pearce 1995, Swann 2001, Lubar 2017). Only the fabulously wealthy could collect objects of fine art; middle class people collected natural specimens and cultural objects from around the world, both through their own travels and through correspondence with other collectors (Swann 2001, Mayhew 2005, Parrish 2006). Those trying to be perceived as having a higher economic status also endeavored to collect such objects (Swann 2001).

From this goal of being seen as high-status, private collections developed from emphasizing the odd and exotic to being a representative sampling of the objects a collector could acquire. During the seventeenth and eighteenth centuries, the meaning of curiosity began to change from denoting 'something that is out of the ordinary—be it exotic, disfigured, incomprehensible, or any number of other things' to a word that signaled a grouping of objects taken from the natural world (Pearce 1995, Parrish 2006). These groupings of objects were becoming more representative of the general state of things in nature due to a growing understanding that basic truths of the world could not be discerned by looking only at the rare and strange. Unusual or irregular specimens could not be classified according to a logical scheme due to their differences from the nature of a typical representative (Pearce 1995). When specimens that represented the population were chosen, there was a greater potential for the object to provide some understanding as to its nature and the nature of the place it came from. In this way, biological classifications grew out of collecting efforts (Pearce 1995, Asma 2001).

Unlike the private collecting that had been so concerned with proving wealth and status, collecting for some in the eighteenth century became an effort for the public good, for science and natural history. However, the shift from specimens as curiosities of old to things of scientific value and merit was not without tension and resulted in the formation of a few different streams of collecting philosophy (Pearce 1995). On the one hand were those who continued to collect exotic objects and aimed, often, for commercial success; the other main collecting philosophy was focused on formal scientific collecting with the desire to understand and explain (Pearce 1995). Despite this divide between collectors and a middle-ground group existing with them, the growing trend toward organization and more thorough understandings of the world were reflected in the collections of the time and their increasing levels of order (Pearce 1995).

Further organization of collections would come with the invention of a formal system of classification of living things. Carolus Linnaeus assembled his first plant collection in the first half of the eighteenth century and from this would develop a systematic way to classify living things. This system would be published in *Systema Naturae, Genera Plantarum, Species Plantarum,* and *Philosophia Botanica* (Linné and Turton 1806, Pearce 1995, Linnaeus 2003, Clark 2009, Reid 2009, Grande 2017). Prior to Linnaeus' system, there was not a universally accepted method of classifying living organisms in a scientific manner; though many had made attempts in one form or another none was implemented or accepted by all natural historians (Asma 2001, Clark 2009). There had also been a long-standing tendency among natural historians to keep their efforts in scientific thought close to their chest, without communicating their findings to their peers (Reid 2009), which likely limited the ability of natural historians to come to a consensus with regards to a system of naming and classification. In his efforts, Linnaeus made use of contemporary methods of scientific thought, i.e. Linnaeus went back to the idea of description and trying to extract some fundamental truth about the thing he was describing through the action (Reid 2009, Grande 2017), while developing an 'artificial system' of boiling things down to essential characters, not using details to represent nature's full complexity (Asma 2001, Clark 2009). This was in keeping with the philosophies of the ancient world, especially Plato and Aristotle (Lloyd 1961, Morge 1973, Asma 2001). However, Linnaeus' system—importantly—required empirical evidence in the form of detailed observation or specimens in order for description and naming to be viable where many previous efforts at classification had been implicitly aimed at combining natural history with religious beliefs (Clark 2009, Reid 2009). Linnaeus was also dedicated to communicating his ideas; by actively sharing his system with other natural historians, Linnaeus popularized his ideas in the community in a way others had not managed.

In addition to Linnaeus' scientific collecting endeavors, many others were engaged in the fervor of specimen collecting. Natural history societies, social clubs, and field groups were formed in order to support collecting efforts; such collaborations enhanced the ability of the middle classes to contribute to scientific thought and developments to a degree (Pearce 1995). These collecting groups arguably represented precursors for later professional groups and societies, and they mirror later occurrences to the amateur following the professionalization of the biological sciences in their relative exclusivity.

For much of the late eighteenth and early nineteenth centuries, the focus in natural history studies was on collecting specimens, observing their morphologies, and developing an encyclopedic understanding of living things (Gates 2007). The importance of singular characteristics in description and classification continued to define this period in the history of systematics. Over the course of this period of time, many were fascinated by the natural world and wrote extensively on their observations (Gates 2007). By the end of the nineteenth century, collecting of natural history specimens was focused towards the further development of a system of hierarchies for natural things. Such a system of classification, building from Linnaeus but taking into account more than a single characteristic, would allow naturalists to better understand the biological world and the place of humans in this scheme (Pearce 1995, Asma 2001, Grand 2017, Lubar 2017). The development of a biological hierarchy hinged on the perspective of objects and specimens in such a way that the observer could understand some part of a larger overall picture.

Despite this larger trend of collecting for systematization, specimen collecting was never homogenous—there were always a small number of collectors who sought out the rarities and oddities, including things with supposed historical significance (Pearce 1995, Lubar 2017). Within curiosities collecting, the idiosyncrasies of each individual collection were dependent on the collector, their interests, and their means (Guralnick and Van Cleve 2005, Beck and Kitching 2007, Lubar 2017).

This aspect of private collecting was not necessarily excluded completely from the encyclopedic and organized formal institutions, however, as curators and other professionals often built collections by engaging in expeditions. Often these expeditions were intended for specimen collection; it was the purview of museum curators to acquire specimens themselves and then prepare them for addition to the museum collection. In this way, the interests of the curator could be seen in the objects brought back and incorporated into the institutional collection, though curators were often required to be somewhat of a generalist in their collecting (Rader and Cain 2014, Lubar 2017). What contributed to the separation of professional curators and the self-taught collectors was the level of collection information and description saved with natural history specimens; within institutions there was often a protocol for curators to document specimens, including a minimum requirement for the information to be saved (Lubar 2017). Though museum professionals were often required to go on collecting trips, the public was also able to contribute specimens to the museum; museums would put out calls for well-documented specimens and amateur collectors would answer (Lubar 2017). Such donors saw their donation of specimens to museums as both a way to contribute to others' learning and as a way to preserve their collections securely, among various other motivations in donating (Lubar 2017). This system of call-and-respond would continue on in the twentieth century, extending the time that the amateur naturalist was able to contribute to professional science (Rader and Cain 2014). In addition, the donation of large, private collections to public museums served both professional scientists and a visiting public (Lubar 2017).

Calls to the public for specimen donations solved one of the more important issues facing professional natural history museums: the need for large numbers of specimens. Without a collection consisting of many specimens, both similar and dissimilar, professional scientists could not investigate areas of natural history such as geographic range and variations in species across regions and seasons. Additionally, multiple specimens were necessary for comparison and description (Lubar 2017). Detailed descriptions and the ability to compare one specimen to another were needed for the positive identification of newly-collected specimens and served a major role in the scientific community, making natural history museums important to scientists beyond their walls (Lubar 2017).

The nineteenth century also saw the further development of the concept of a natural history museum as a public institution, rather than a private collection. Through visits to an institution of natural history, a person could better both themselves and society at large, though museum professionals had mixed opinions on whether the public was an important audience to the museum (Rader and Cain 2014, Grande 2017, Lubar 2017). Due to economic growth from both the First and the Second Industrial Revolutions and rapid, lucrative technological change in the United States and Western Europe, it was possible to more firmly establish formal institutions that served to educate the public (Pearce 1995, Levin et al. 2010, Rader and Cain 2014, Lubar 2017). Once a handful of natural history museums had been formed, it became possible for staff to exchange or distribute specimens from one institution to another for the betterment of each collection (Lubar 2017).

1900-Present

Over the course of the twentieth century, collections of natural history specimens in museums served a larger societal purpose with increasing frequency by serving an educational mission and by documenting biodiversity (Lubar 2017). Though the public was welcome to the public portion of the museum, they were barred from the professional research division of museums' scientific efforts, sometimes not even aware that biological research was happening behind-the-scenes (Lubar 2017). In conducting these two separate functions, museums were often arranged with some specimens out for public viewing with many others saved just for professional researchers (Rader and Cain 2014). Public displays of collections were aimed toward presenting a complete picture of biodiversity with a goal of attaining an understanding in the public audience of biological concepts as they were portrayed in displays (Rader and Cain 2014).

The effort to document all of life on earth was not just a goal for the public half of the museum. Natural history museums attempted to be ever-growing collections of specimens that would serve as documentation of all forms of life on earth in preparations ranging from full specimens to frozen tissue samples (Rader and Cain 2014, Lubar 2017).

The professional scientists in a museum put their effort toward preserving type specimens, in addition to those that served to delineate geographic ranges. In their documentation of geographic information, curators continued to rely on the well-documented donations of the amateur naturalist in addition to specimens coming out of the fieldwork of researchers (Rader and Cain 2014, Lubar 2017). However, the professional researcher was the one to determine the worth of a collection or object, thus reinforcing a growing divide between the professional and the amateur in terms of having authority over such decisions (Lubar 2017). More and more, however, justification for the addition of an object to a collection would be needed; some perceived authority would no longer be adequate (Lubar 2017). In addition, a movement to return unethically collected and held cultural objects has been started—particularly in the United States with the passage of the Native American Graves Protection and Repatriation Act (NAGPRA) in 1990 (Colwell 2014, Lubar 2017). In doing so, authority over cultural heritage objects and human remains is returned to the peoples of origin (Colwell 2014). However, returning authority over objects and stories is an ongoing process and source of debate.

By the twenty-first century, museums in the United States would contain over 1 billion objects, and 820 million of these would be natural history specimens. Internationally, institutions hold over 3 billion natural history specimens (Lubar 2017). Today, biological collections continue to be systematically arranged, now according to taxonomic relationships (Lubar 2017), though this sometimes poses a challenge due to the frequency of changes made to the classification of some organisms. Digitization of collections and data is an ongoing struggle for museums, though biological collections lead this endeavor (Hill et al. 2014, Grande 2017, Lubar 2017, Short et al. 2018). Increasingly, digitization efforts are undertaken as collaborations among institutions (Grande 2017). For many institutions, the digitization of their collections serves not only a research purpose but an educational purpose as well. Museums continue to acknowledge the educational value of their collections to the greater public (Winston 2007, Grande 2017, Lubar 2017).

Museums also face the task of making their collections appear meaningful to the public and remaining useful to science; attitudes toward collecting have changed since the sixteenth century. Collecting is no longer done willy-nilly (Rocha et al. 2014, Lubar 2017). These and other shifts in popular opinion toward collecting have contributed to an inability to ever potentially replace currently held specimens in institutional collections (Short et al. 2018). Specimens saved during the heyday of collecting a century or more in the past continue to play a role in biological research as they document changes over time and thus provide modern scientists with larger datasets for studies determining biological needs today (Brooks et al. 2014, Lubar 2017, Short et al. 2018). Specimens collected over a large timeframe allow researchers to understand relationships between organisms and between organisms and their environment, including the influence of climate change (Suarez et al. 2004, Winston 2007, Hill et al. 2012, Brooks et al. 2014, Grande 2017, Lubar 2017). By allowing for a greater understanding of such influences, natural history museums assist in efforts to conserve biodiversity into the future (Grande 2017).

"Can learned skill on little specks display…"[2]: Collecting and classifying insects, 1800-2019

From the first cabinets of curiosity and beginning of natural history collecting, insects were sought after for the beauty they manage to exhibit even at their small size. This early inclusion of insects in collections made them of great interest to those developing systems of biological classification, and insect specimens were the subjects of many attempts at a system of classification (Swann 2001, Clark 2009, Roos 2012). By examining the morphologies and natural histories of insects, eighteenth century insect collectors developed a number of different methods of classification that would inform later systems, though a single, accepted system took longer to develop for insects than it did for plants (Clark 2009). All of the classification schemes that were developed centered on external morphologies, not internal. The determination of which classification schemes would last the longest or be thrown out the fastest was linked to the idea of the status quo and authority (Clark 2009).

This idea of the status quo in natural hierarchies was linked in many ways to attempts to justify a social hierarchy. Through investigations into anatomy and physiology, naturalists assigned levels in the hierarchy, moving from things belonging to the 'mineral kingdom' that lacked many traits of living things up to mammals and other vertebrates that had some form of consciousness (Clark 2009).

Insect classification—and the classification of other living things—in the nineteenth century was a reflection of a desire to better understand the theological concept of Creation through the collection of natural objects. In a way, collecting and naming species was an

[2] From "The Natural Philosopher" in "The Age of Frivolity" by Thomas Beck ("Timothy Touch'em"), 1806.

effort to not only own the specimen but also to exercise domination over nature, in addition to appreciating the diversity of divine Creation (Harris 2005, Clark 2009). This idea of domination and ownership was a reflection of larger trends in the field of natural history collecting and more general social values.

During the nineteenth century, the culture of collecting and naming insect specimens was not particularly disturbed by the publication of Charles Darwin's theory of evolution, and entomologists were divided in their opinions on his ideas (Clark 2009). However, insects and their collection played a major role in the development of the theory of evolution, as both Darwin and Alfred Russel Wallace were coleopterists. Wallace would come to attribute the agreement of these two men on the process of evolution to their shared interest in beetles. In addition to contributing to Darwin's work on the development of evolutionary theory, insects provided him with data reinforcing such concepts in further writings outside of *Origin of Species*, including investigations into pollination and other behaviors (Darwin 2003, Clark 2009). Other naturalists found evidence supporting Darwin's theory of evolution in the insect world. Henry Walter Bates, for example, observed butterflies in the South American rainforest and described a form of mimicry. Bates' trip abroad was intended as a collecting trip to find specimens to put up for sale and justify the entire trip financially. While collecting specimens, Bates discovered a form of mimicry in Heliconian butterflies that protected non-poisonous species from being eaten by appearing similar to species that were poisonous (Bates 1862). The development of this pattern of similar coloration was easily explained using the idea of natural selection, thus supporting Darwin's ideas (Clark 2009).

However, many members of the public entering museums were not fond of insect specimens. Insects seemed to serve no purpose on their display shelves. This opinion, for some, extended to the idea of the entire museum. A general sense of the attitude museumgoers may have had is exemplified in the poem "The Age of Frivolity" written by Thomas Beck (under the pseudonym "Timothy Touch'em") before the turn of the twentieth century (Touch'em 1806, Carty 2015, poem quoted in Lubar 2017):

> "Some spend a life in classing grubs, and try,
> New methods to impale a butterfly;
> ….
> This precious lumber, labell'd, shelv'd, and cas'd,
> And with a title of Museum grac'd
> Shews how a man may time and fortune waste,
> And die a mummy'd connoisseur of taste."

By the end of the nineteenth century, entomology—and biological science as a whole—had undergone and was continuing to undergo a process of professionalization. Entomology more than other fields of study had been accessible to the amateur naturalist or lay-collector due to the relative ease of acquiring and using the materials used to build an insect collection (Clark 2009). This made insect collecting a potential hobby for many, assuming they had the economic means to purchase the tools necessary. Some naturalists made an effort to interact with others who shared their interest in collecting insects. To create a community of collectors, entomological societies and clubs were formed, often specific to a particular state or region (Essig 1931). Such groups began to arise in the mid-nineteenth century and continued forming from there (Clark 2009, Kaplan 2009). Many of the entomological societies formed from groups of amateurs would eventually become societies for the professional scientist and inaccessible to the amateur collector (Clark 2009).

The private insect collections of these individuals in the late nineteenth and early twentieth centuries were commonly donated to institutions, though they were occasionally sold to other private collectors (Essig 1931). Donation of collections was not a common practice in natural history collecting in previous centuries. In the twentieth century, these institutional collections would often come to hold specimens that had been named and designated as type specimens in the description of species (Essig 1931, Lubar 2017), often by amateur entomologists (Waters and MacKenzie 2018). Though these specimens are extremely important, limitations of space would be a growing concern for natural history museums. While insects often take up relatively little space, the single largest collection in all the museums in the world is Alfred Kinsey's gall wasp collection in the American Museum of Natural History, New York and consists of over 7.5 million gall wasp specimens. This manages to outdo even Harvard's collection of 1 million ants (Lubar 2017).

Museums, by the end of the twentieth century, would involve insects in their mission of public education in a variety of ways. Some used insects, along with specimens of other living things, in dioramas with the intention of teaching the public about various ecological concepts (Rader and Cain 2014). However, many insect collections were saved for the purpose of professional scientific research—arguments in favor of maintaining insect collections harken back centuries to the motivations involved in founding public museum collections in the first place. For example, preserved specimens of insects which vector diseases were used to teach field medics and hospital workers in both World Wars (Winston 2007, Lubar 2017). Specimens were lent out to these non-entomologist professionals in an effort to allow for the identification of such medically important species in the field (Lubar 2017). Collections in natural history museums also supported agricultural aims and helped to spread Western-style science to other regions of the world (Suarez et al. 2004, Lubar 2017).

Though amateur entomologists in some ways have been pushed from the entomological scene, they continue to make lasting contributions, particularly in the way of specimens. For example, two amateur collectors recently donated their pooled Lepidoptera collection—representing over 70,000 specimens from a wide variety of taxa—to the McGuire Center for Lepidoptera and Biodiversity (Watkinson 2018). The sum of historical collections from a variety of amateur collectors that have been donated to institutions over time also represent a valuable resource to modern professional entomologists, e.g. the Lyman collection (Waters and MacKenzie 2018). Groups specifically founded to support amateur entomologists and their contributions continue to exist despite growth in professional societies that cater to the vocational entomologist; the Amateur Entomologists' Society in the United Kingdom continues to function both as a conservation-concerned Society and works to encourage potential future entomologists (Lonsdale 2012). Groups of amateur entomologists have both noticed and investigated—among other things—global insect decline, some likely being among the first to voice concern in the 1930s (Lonsdale 2012, Hallmann et al. 2017).

The debate over the value of keeping and adding to insect collections continues, and the pro-collecting side stresses the usefulness of collections to science today and in the future as a justification for continued collecting efforts. Historical insect collections are almost entirely irreplaceable for many reasons—including habitat change, climate change, funding for collections staff and collecting trips, and decreases in global biodiversity—making old collections invaluable to research (Suarez et al. 2004, Winston 2007, Brooks et al. 2014, Short et al. 2018). The efforts of groups like iDigBio to digitize collections of insects and other natural history specimens make the information contained in these old collections available to researchers, in addition to preserving specimen data should the specimens ever be destroyed. Researchers involved in such projects ask many diverse questions about the biological world that would otherwise be impossible to address. However, databasing and digitization is extremely time-consuming and often not well-funded; less than 2% of the total number of institutionally-held insect specimens have been databased (Short et al. 2018). For some digitization projects, the field of entomology has come full circle; volunteers and citizen science initiatives have been used to database specimens, once again involving the amateur in scientific pursuits (Hill et al. 2012). Given that a relatively small percentage of the total number of museum specimens has been databased, there has historically been a limit on the variety and depth of studies using whole-collection data for various purposes. The dearth of digitized specimens is not the only limitation to entomological research; though insect collections are irreplaceable, they will also never be complete due to various limitations on collectors over the past four centuries (i.e. there has not been consistent collecting everywhere in the world every single year since collecting began) (Beck and Kitching 2007, Winston 2007). Efforts to pool data from many institutions aim to minimize the effect of this limitation to future research.

LepNet consists of 27 United States insect collections, which aim to collectively database and georeference the label information of 1.7 million Lepidoptera specimens (Seltmann et al. 2017). Using the existing efforts of LepNet to database and pool data from Lepidoptera specimens housed in US institutional collections, this thesis project aims to characterize American efforts to collect butterflies and moths since 1800. First, we examined the influence of avocational, or non-professional, collectors based in the state of Michigan on the A.J. Cook Arthropod Research Collection located at Michigan State University across time. Using country-wide data generated through LepNet, changes across both time and space were characterized as trends associated with the growth and decline of natural history as a scientific study, in addition to examining the influence of non-professional collectors at the national level. This research was conducted with the intention of determining (a) the scope of the role of non-professional collectors in terms of specimens collected, (b) how the influence of non-professional collectors affects scientific research making use of institutionally-held Lepidoptera collections, (c) how evenly—or unevenly—distributed collection locations have been historically for Lepidoptera specimens collected in the United States, and (d) how collection efforts have changed over time, affecting research questions regarding time series, including studies around climate change.

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CHAPTER 2: THE LEPIDOPTERA OF THE A.J. COOK ARTHROPOD RESEARCH COLLECTION AND THE IMPACT OF AVOCATIONAL COLLECTING

Introduction

There has long been a history of the amateur naturalist or lay-person being engaged in scientific study to varying degrees—in the areas of collecting, observing, and communications with 'professionals', among other things (Vetter 2011). However, in many cases, the line between the amateur and the professional, or lay-person and expert, has been blurred. Despite a lack of consistent differentiation between the amateur naturalist and the professional scientist, there has also been a history of excluding the 'stamp-collecting naturalists' from the realm of science as biology became more and more concerned with experimentalism (Johnson 2007, Vetter 2011). In some cases, it has been said that amateur collecting efforts were simply a steppingstone to 'proper' science (Kohler 2007). However, the efforts of non-professional scientists continue to be valuable sources of data in many fields of biological science, including entomology. For example, skilled amateurs working in Germany were the first to quantify a continuing decline in insect biomass based on decades of saved mixed-species alcohol samples from traps (Hallmann et al. 2017). However, the number of non-professionals working and publishing in natural history and insect taxonomy is on the decline, in spite of their importance in identifying and recording sightings of specific insect species (Hopkins and Freckleton 2002). For this reason, it is important to evaluate the overall impact of amateur collectors on existing specimen collections.

The A.J. Cook Arthropod Research Collection (ARC) was founded by its namesake in 1867 at Michigan State University (MSU, then the Agricultural College of the State of

Michigan). The collection currently houses 1.1 million pinned insect specimens, in addition to others preserved on slides or in alcohol. The collection holds specimens documenting Michigan insect biodiversity with areas outside of the state addressed to varying degrees dependent on the individual collecting efforts of its many donors. The Lepidoptera in particular are well-represented, consisting of approximately 185,000 specimens. The ARC owes much to amateurs and volunteers in terms of both building the collection and its curation during the ARC's 152-year history.

Databasing of the ARC's lepidopteran specimens is ongoing as part of a national collaborative databasing effort known as LepNet (lep-net.org, Seltmann et al. 2017). LepNet allows for a greater understanding of collecting patterns over time both nationally and locally. Information about the specimens, as well as images, are available via the LepNet public website, providing information to both researchers and laypersons across the world (SCAN-bugs.org). As such, this database represents an unparalleled opportunity to analyze the development of Lepidoptera collections, including the collection of North American Lepidoptera found in the ARC. We focus on specimens in the ARC as a case study because there is a long history of extensive work done by non-professional entomologists building and curating this collection. Examination of the influence non-professional and professional collectors have had on institutional collections is important due to the implications changes in collecting effort might have on the collections as a whole and thus their potential for supporting future research using historical specimens, particularly time series analyses.

This study describes the pattern of collecting North American Lepidoptera found in the ARC. Specifically, we quantify represented taxa; specimens collected per year; and specimens collected by professional and non-professional (or avocational) collectors. In particular, we examine the relative impact of avocational collecting on the ARC.

Methods

Data associated with the 96,618 currently digitized specimens of the approximately 185,000 total Lepidoptera specimens housed in the A.J. Cook Arthropod Research Collection at Michigan State University (ARC) were downloaded from the Symbiota Collections of Arthropods Network database (SCAN-bugs.org), accessed 23/03/2019. Using the 'tidyverse' R package (Wickham 2017), the collection data were revised to only include specimens that were collected in the United States between 1800 and 2018. The remaining 83,682 specimens were assessed with respect to the number of collection events per year and the collection locality at state level. A rolling decadal average and standard deviations for collecting events were calculated using the 'TTR' package (Ulrich 2018). Rolling decadal averages and standard deviations are the unweighted means and standard deviations of the values—specimen counts—for the previous ten years. The package 'ggplot2' from the 'tidyverse' suite of R packages was used to generate all graphs. The number of specimens per square kilometer collected per state was generated using the 'usmap' R package. A map of specimens collected per square kilometer in Michigan counties was also generated using the R packages: 'ggmap', 'maps', and 'mapdata'. Specimen records were also used to determine the composition of Lepidoptera families represented in the collection and whether collectors were professionals or non-professionals. For the latter, the records were sorted by collector name and year, and tallied to generate a specimen count per year for each collector. Collectors were identified as professional or non-professional by reviewing ARC records (Houk 1954) and 1964 - 2018 newsletters of the Michigan Entomological Society (michentsoc.org) written by and about people associated with the ARC and using Google Internet searches of names on the Internet. Collectors were considered professional if they held positions as university professors or as collections staff in an institutionally-held natural history collection. The collection efforts of professionals and non-professionals were then compared using repeated Mann-Whitney-Wilcoxon tests in the base R statistical package for each decade between 1950 and 1994 on a sliding window basis. This window of time was used to analyze the collecting effort of different types of collector because it includes the top ten years in terms of total specimens collected. During the period from 1950 to 1994, 68.7% of the specimens in the A. J. Arthropod Research Collection were collected, so the majority of the data was included in analyzing the differences between avocational and vocational collectors.

Results

Our initial review of the LepNet data removed 13.39% of the specimen records because of missing or erroneous collection year or country of origin, resulting in a dataset consisting of 83,682 records. The maximum of the data, in terms of collection events per year, occurred in 1960 with a total of 3,753 specimens collected (Figure 2.1). The second highest peak in collection events occurred in 1965 (3,224 specimens). For almost 60 years, there has been, on average, a steady decline in annual collection events in Michigan. This decline has become steeper in recent years, decreasing from 1,693 specimens in 1987 to fewer than 100 specimens collected annually since 2011. The most frequently collected family was the Erebidae (25.64% of total), the favorite taxon of a handful of Michigan collectors, while other commonly collected families included Geometridae (13.76%), Noctuidae (11.43%), and Tortricidae (8.23%) (Table 2.1).

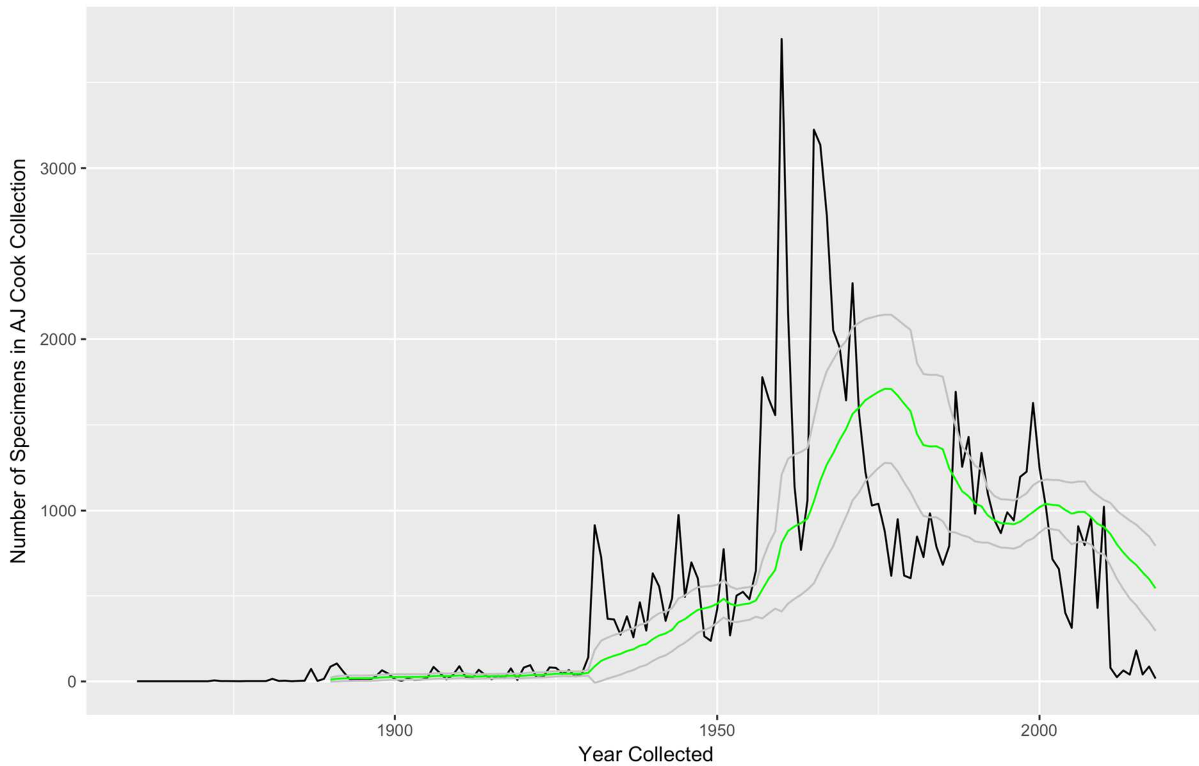

Figure 2.1: *Specimen collection events per year since 1800 in A. J. Cook Arthropod Research Collection. The green line is a rolling decadal average, and the grey lines represent a single standard deviation from this average on a rolling decadal basis.*

Table 2.1: *Counts and percentages of specimens from represented Lepidoptera families.*

Family	Count	Percent
Acanthopteroctetidae	2	0.002
Acrolepiidae	1	0.001
Acrolophidae	2	0.002
Adelidae	39	0.047
Alucitidae	11	0.013
Apatelodidae	201	0.240
Arctiidae	2	0.002
Argyresthiidae	36	0.043

Table 2.1 (cont'd)

Attevidae	126	0.151
Autostichidae	33	0.039
Batrachedridae	2	0.002
Bedelliidae	18	0.022
Blastobasidae	76	0.091
Bombycidae	11	0.013
Bucculatricidae	49	0.059
Carposinidae	5	0.006
Choreutidae	55	0.066
Coleophoridae	189	0.226
Copromorphidae	1	0.001
Cosmopterigidae	108	0.129
Cossidae	178	0.213
Crambidae	5,930	7.086
Dalceridae	3	0.004
Depressariidae	857	1.024
Doidae	2	0.002
Drepanidae	57	0.068
Dudgeoneidae	3	0.004
Elachistidae	16	0.019
Epermeniidae	125	0.149
Epiplemidae	1	0.001
Erebidae	21,460	25.645
Eriocraniidae	14	0.017
Euteliidae	34	0.041
Galacticidae	7	0.008
Gelechiidae	951	1.136
Geometridae	11,511	13.756
Glyphipterigidae	8	0.010
Gracillariidae	614	0.734
Heliodinidae	19	0.023
Heliozelidae	31	0.037
Hepialidae	54	0.065
Hesperiidae	2,870	3.430
Incurvariidae	7	0.008
Lacturidae	4	0.005
Lasiocampidae	1,814	2.168
Lecithoceridae	6	0.007
Limacodidae	612	0.731
Lycaenidae	1,710	2.043
Lymantriidae	32	0.038
Lyonetiidae	9	0.011
Megalopygidae	139	0.166

Table 2.1 (cont'd)

Micropterigidae	1	0.001
Mimallonidae	69	0.082
Momphidae	19	0.023
Nepticulidae	62	0.074
Noctuidae	9,569	11.435
Nolidae	61	0.073
Notodontidae	755	0.902
Nymphalidae	2,569	3.070
Oecophoridae	68	0.081
Opostegidae	2	0.002
Papilionidae	1,392	1.663
Pieridae	616	0.736
Plutellidae	44	0.053
Prodoxidae	86	0.103
Psychidae	131	0.157
Pterolonchidae	1	0.001
Pterophoridae	316	0.378
Pyralidae	1,689	2.018
Riodinidae	43	0.051
Saturniidae	1,703	2.035
Scythrididae	31	0.037
Sesiidae	2,499	2.986
Sphingidae	3,935	4.702
Stathmopodidae	2	0.002
Thyrididae	37	0.044
Tineidae	585	0.699
Tischeriidae	124	0.148
Tortricidae	6,883	8.225
Uraniidae	7	0.008
Yponomeutidae	206	0.246
Ypsolophidae	57	0.068
Zygaenidae	73	0.087
N/A	2	0.002

Given that the A. J. Cook Collection is a collection housed in Michigan and largely supported by collectors based in Michigan, it is unsurprising that the geographical spread of collection locales is heavily biased toward the state of Michigan (63,907 specimens). This is followed by New Mexico (2,393 specimens), Arizona (2,046 specimens), and Ohio

(1,775 specimens) (Figure 2.2). Other states are represented to a lesser degree. Specimens collected within the state of Michigan are not evenly distributed across counties (Figure 2.3). The counties with the most specimens collected are Otsego (4,810 specimens), Kalamazoo (4,287 specimens), Oakland (3,503 specimens), and Clinton (3,332 specimens).

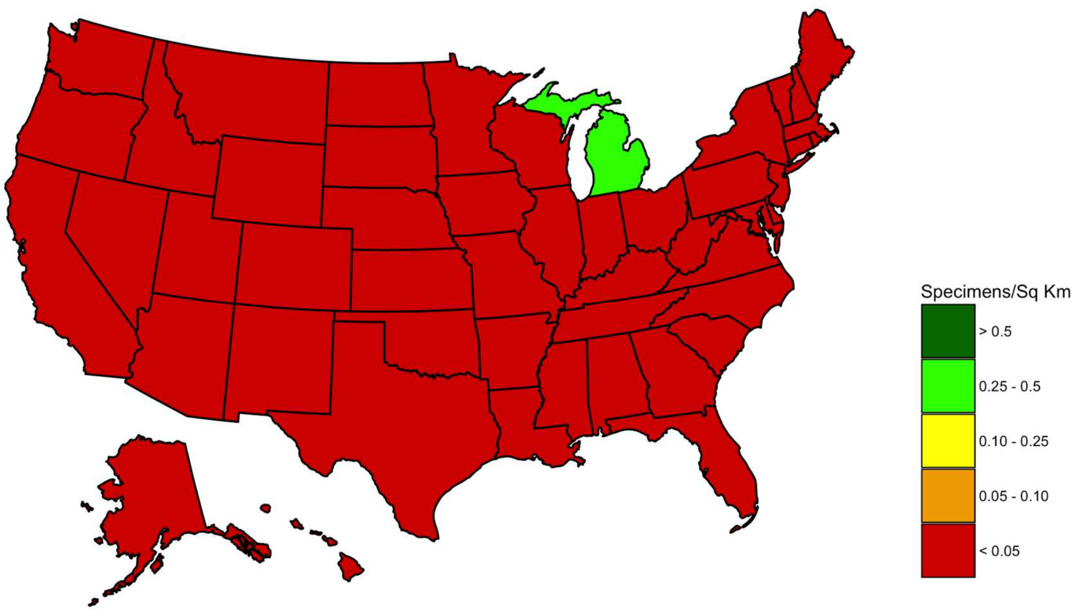

Figure 2.2: *National distribution of Lepidoptera specimens in the A. J. Cook Arthropod Research Collection.*

Using collection data sorted by collector name, we compared the collection contributions of vocational and avocational collectors to the Cook Collection over time (Figure 2.4). Avocational collectors contributed 56,323 Lepidoptera specimens while vocational collectors contributed 21,127 specimens. Temporal patterns in collection event numbers are also inconsistent between avocational and vocational collectors; while vocational collectors were at their most active in the 1950s through the early 1970s, avocational collectors were in the midst of a gradual increase in collecting activity. During a 20-year period of peak collecting (1950-1970), the collecting efforts of these two groups were significantly different (Table 2.2). However, after that time, neither group of collectors collected significantly more specimens than did the other, statistically (Table 2.2). If the role of time is ignored completely, there is not a significant difference between the specimen numbers contributed by the two groups (W = 2243786, p = 0.7014).

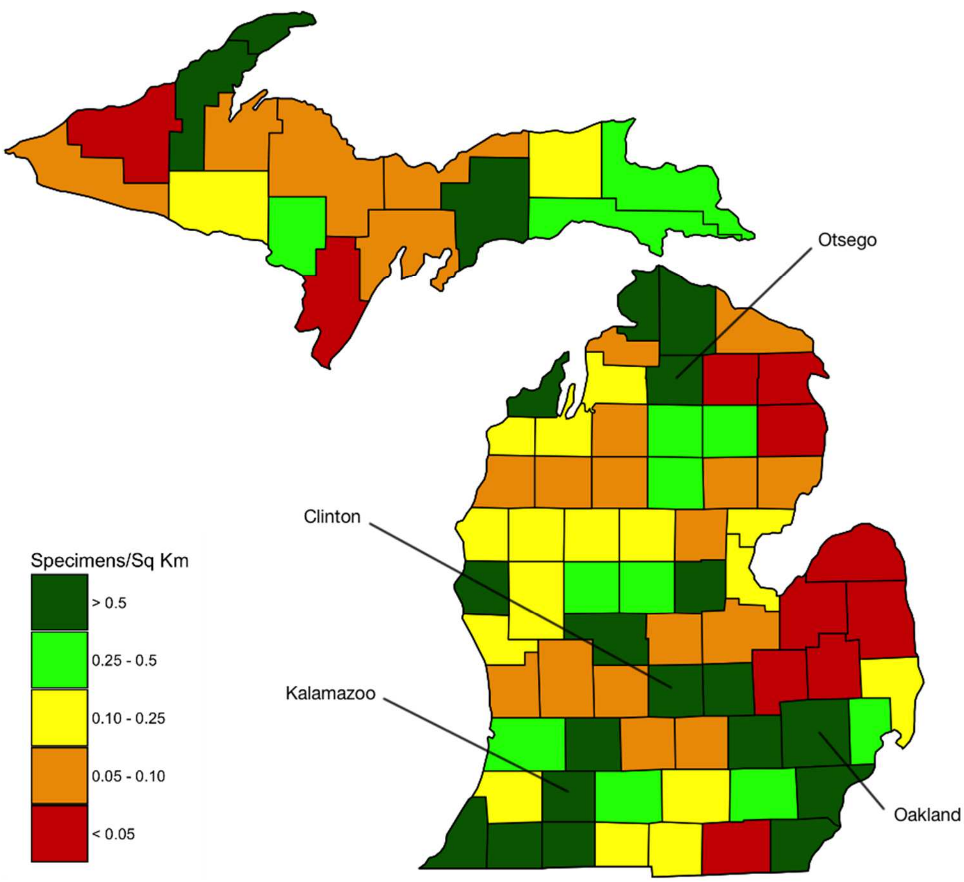

Figure 2.3: *Michigan distribution of Lepidoptera specimens in the A. J. Cook Arthropod Research Collection at the county level.*

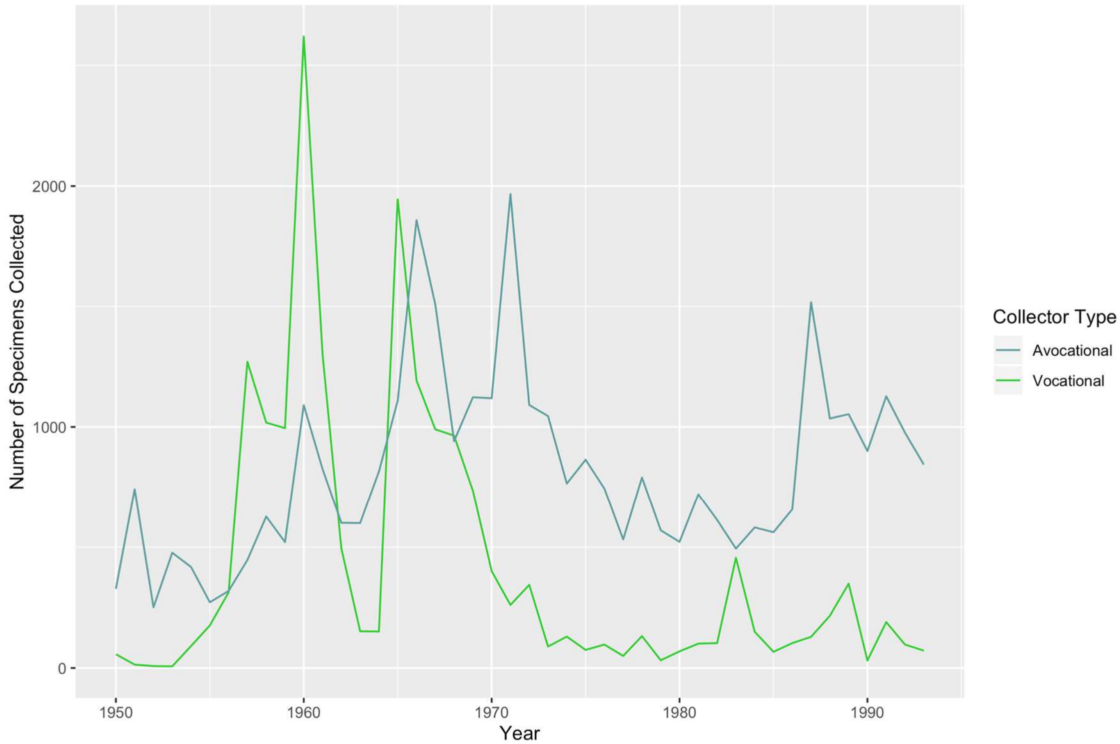

Figure 2.4: *Avocational and vocational specimen collection events, 1950-1993.*

Table 2.2*: Vocational vs. avocational collectors: comparison of specimen numbers by decade.*

Year Range	P-value	Interpretation
1950-1959	0.0137	Significant difference
1951-1960	0.0002981	Significant difference
1952-1961	1.381 e-5	Significant difference
1953-1962	5.29 e-6	Significant difference
1954-1963	5.381 e-6	Significant difference
1955-1964	3.648 e-6	Significant difference
1956-1965	2.107 e-6	Significant difference
1957-1966	0.000115	Significant difference
1958-1967	0.001311	Significant difference
1959-1968	0.008534	Significant difference
1960-1969	0.07216	No difference
1961-1970	0.2681	No difference
1962-1971	0.6377	No difference
1963-1972	0.5317	No difference
1964-1973	0.8308	No difference
1965-1974	0.5104	No difference
1966-1975	0.3096	No difference
1967-1976	0.4148	No difference

Table 2.2 (cont'd)

1968-1977	0.2713	No difference
1969-1978	0.2717	No difference
1970-1979	0.07194	No difference
1971-1980	0.1682	No difference
1972-1981	0.1528	No difference
1973-1982	0.1766	No difference
1974-1983	0.1078	No difference
1975-1984	0.4201	No difference
1976-1985	0.2665	No difference
1977-1986	0.3383	No difference
1978-1987	0.1664	No difference
1979-1988	0.5256	No difference
1980-1989	0.7449	No difference
1981-1990	0.4907	No difference
1982-1991	0.4828	No difference
1983-1992	0.8075	No difference
1984-1993	0.6029	No difference

The most prolific collector who contributed to the ARC is Mogens "Mo" Nielsen, an avocational collector active for 53 years (Table 2.3). Mr. Nielsen contributed more than three times the number of Lepidoptera specimens that were donated by the top vocational collector and second most prolific collector (Julian Donahue).

Table 2.3: *The top 10 avocational and vocational collectors represented in the ARC*

Collector	Association	Specimens	Years Active
M. C. Nielsen	Avocational	19,326	1957-2010
J. P. Donahue	Vocational	5,201	1960-1993
E. H. Metzler	Avocational	5,188	1962-2013
R. L. Fischer	Vocational	5,011	1937-1991
W. C. Stinson	Avocational	2,902	1930-1983
J. H. Newman	Avocational	2,758	1941-1986
G. J. Balogh	Avocational	2,040	1944-1999
R. R. Dreisbach	Vocational	2,003	1915-1963
G. C. Eickwort	Vocational	988	1959-1966
G. L. Parsons	Vocational	892	1970-2018

Discussion

The A. J. Cook Arthropod Research Collection logically consists largely of specimens from Michigan (Figure 2.2), as this is the state the collection is located in, with Erebidae representing the majority of lepidopteran specimens (Table 2.1). However, Michigan counties are not evenly represented in terms of Lepidoptera specimens collected per square kilometer. Most activity was near urban areas or vacation localities, and the Michigan "thumb" is the most under collected region (Figure 2.3). The highest peak in annual collecting events occurred in 1960; since then there has been a general decline in annual collection events (Figure 2.1). In total, avocational collectors have contributed more than twice the specimens of vocational collectors, and this contribution was significantly greater between 1950 and 1968 (Table 2.2).

Clearly, avocational collectors are important to the growth of entomology collections; in the case of the A. J. Cook Arthropod Research Collection, they contributed the majority of specimens. Historically, the vast majority of entomologists have been amateurs, working with insects out of enjoyment separate from their paying vocations (Wolfenbarger 1954). Many organized groups of avocational collectors arose from their shared enthusiasm for insects, especially in the nineteenth and twentieth centuries, even amidst a growing emphasis on professionals in the biological sciences (Essig 1931, Hunter and Jaros-Su 1997, Clark 2009, Kaplan 2009, Lonsdale 2012, Michigan Entomological Society 2018). These non-professional entomological groups include the Amateur Entomologists' Society in the UK, the Florida Entomological Society, and the Michigan Entomological Society (MES), which are all still active (Florida Entomological Society 1917, Lonsdale 2012, Michigan Entomological Society 2018). These societies act as catalysts for citizen participation in biodiversity science and support amateur collecting, along with helping to engage the next generation in entomological study. For example, the members of the Michigan Entomological Society have organized group collecting trips in the past—including the foundation of a formal annual spring collecting trip in 1965 (Michigan Entomological Society 1965)—which likely contributed to spikes in collecting activity following the founding of the Society in 1954. The accumulated collections of insects and data from non-professional entomological societies continue to contribute, and likely enable, professional entomological research (Winston 2007, Brooks et al. 2014).

In the case of the Michigan Entomological Society, there have been a number of highly dedicated Lepidopterists collecting both in Michigan and out of state. Of the many avocational collectors who contributed to the collection over the last century, Mr. Mo Nielsen was a particularly dedicated benefactor to Michigan Lepidopterology and to the development of the ARC. Mr. Nielsen enrolled in Forest Management at Michigan State University after his service in World War II and was mentored by John H. Newman, who also contributed to the ARC through specimen identification, curation, and donation. After graduating from MSU, Mr. Nielsen worked for the Michigan Department of Natural Resources and continued to develop a lifelong interest in butterflies and moths (Michigan Entomological Society 2014). He was a founding member of the Michigan Entomological Society (est. 1954) and a mentor to young Lepidopterists. He amassed a collection of over 13,000 Lepidoptera specimens, and he concentrated on Erebidae and Noctuidae. This collection was the basis for a field guide to the butterflies of Michigan (Nielsen 1999). Mr. Nielsen assisted in the curation of the ARC's butterfly and moth collection and donated specimens throughout his adult life. He left the total of his personal collection to the ARC, which was incorporated into the research collection following his passing in 2014.

As many of the collectors who have contributed to the ARC were living and working in the state of Michigan at or before the time they started donating specimens, it is unsurprising that the Lepidoptera collection is heavily skewed in favor of Michigan localities. In particular, Mo Nielsen had what he referred to as his “hut” located in Otsego County. Mo often did extensive collecting of Lepidoptera specimens while there, and he also hosted friends—many of them from MES— to collect as well (Michigan Entomological Society 2014). In addition, Clinton County is home to portions of East Lansing, where MSU is located; it is likely that many collectors associated with the Michigan Entomological Society and Michigan State University collected frequently in the area. Mo and others focused heavily on the Erebidae, making the family the most numerous in the ARC. Other commonly collected families of moth—Geometridae, Noctudiae, and Tortricidae—are economically important crop pests; they were likely collected in large numbers as part of agricultural research. Given the contributions to the ARC by Mo and his contemporaries, including nearly 5,000 specimens from Otsego county, it becomes clear that collecting efforts by non-professionals have been very important to the growth of the A. J. Cook Arthropod Research Collection, and likely other collections around the country.

The difference in the magnitude of contributions made by avocational collectors as compared to their professional counterparts may be due to differences in the nature of their interest in entomology; avocational collectors tend to have greater enthusiasm for active collection of specimens relative to professional biologists (Strasser 2012). Changes in the focus of biology, such as the rise of molecular studies and other laboratory-based science in defining professional biology, have brought with them—in many ways—an exclusion of avocational collectors (Clark 2009, Strasser 2012), which likely contributed to the decline in specimen acquisition. The availability of funding for particular biological sub-disciplines has greatly influenced the pursuits of professional scientists (Asma 2001, Tewksbury et al. 2014). The decline of funding for natural history research has stymied dedicated professional collecting efforts (Tewksbury 2014). Only the collections manager of the A. J. Cook Arthropod Collection (Gary Parsons) consistently contributes lepidopteran specimens (Table 2.3).

However, the decline in Lepidoptera specimen collecting may not be as dire as the data suggests. Institutional insect collections have an approximate 10-year lag between when donated specimens are physically added to public collections and when these specimens are catalogued in databases (ECN annual meeting attendees, personal communication, November 10, 2018). In addition, collectors likely keep specimens in their private collection for years before donation, so specimens collected in 2015 may not become publicly available for 20-30 years (e.g. the Kenelm Philip collection at USNM/University of Alaska, the Finkelstein and Knudson/Bordelon collections at the McGuire Center at the University of Florida). These two aspects of vocational and avocational specimen acquisition probably contribute to the observed steep decline in the last decade (Figure 2.1), making the number of recently collected specimens artificially low. In case of the A. J. Cook Arthropod Collection, there are only 4 or 5 substantial pending donations, which would increase the representation of specimens collected in the 21st century. However, these collections and unknown future donations likely will not approach the numbers of specimens added to the ARC in the height of collecting activity (Figure 2.1).

Engaging new collectors is necessary for institutional entomological collections to continue to grow and represent insect diversity. The existing networks of amateur collectors have encouraged new participation often through reduced membership dues for students (e.g. MES). In addition, the Amateur Entomologists' Society conducts public outreach and has established a group for new, young collectors (Lonsdale 2012). Other opportunities for creating a future core of avocational collectors exist in K-12 schools and at undergraduate and graduate institutions. Extracurricular K-12 activities often include science clubs and summer camps, some with a focus on natural history (e.g., Science Olympiad, 4-H, Girl Scouts). General entomology and insect taxonomy courses are available at nearly all US state universities—often with associated insect-focused student clubs. Thus, the "infrastructure" is in place to grow and nurture amateur entomologist collectors, but the "metamorphosis" of these amateurs into lifelong avocational collectors is the challenge. It is unknown how effective the "infrastructure" may prove to be into the future as far as inspiring lifelong collecting. At the A. J. Cook Arthropod Research Collection, we know of only a few amateur and avocational Lepidoptera collectors that may donate specimens collected in the 21st century. We fear that the heyday of the avocational collector has passed.

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CHAPTER 3: THE RISE AND FALL OF LEPIDOPTERA COLLECTING IN THE UNITED STATES SINCE 1800

Introduction

Insects have been kept in natural history collections from their earliest days as Renaissance cabinets of curiosity (Alberti 2002, Harkness 2007). Historical natural history collections, now often held by institutions, are unmatched in their ability to document information about species across time and space (Bartomeus et al. 2011, Polgar et al. 2013). These historical collections—combined with more recent collecting activity—record changes in species range, seasonality, plasticity of characters, and allow for the identification of specimens in all fields of natural history (Prather et al. 2004b, Winston 2007). Museum collections of insects have been used in several studies regarding temperature shifts that have come with global climate change (Bartomeus et al. 2011, Polgar et al. 2013, Brooks et al. 2014). For example, using the specimens in the Natural History Museum, London, Brooks et al. (2014) found a correlation between the collection date of early spring Lepidoptera and temperature over time. Studies that use collections to test hypotheses or describe natural patterns tend to use specimens of a certain taxon, particularly those within one or a few collections. The enormity of gathering specimen-level data limits large-scale inferences. Only the databasing of specimen-level data across many institutes enables testing of grand hypotheses, such as the effects of global climate change on the range of Lepidoptera native to southern states. For example, a database of over 1-2 million historical and contemporary mammal specimens from multiple US institutes is available for such large-scale studies (Malaney and Cook 2018).

Specimens of butterflies and moths and their associated data offer detailed insight to environmental and species change over time and space. Given their aesthetic appeal, they have been collected in earnest over time and are well-represented in collections throughout the United States and worldwide. Approximately 17 million lepidopteran specimens exist in collections worldwide (Kawahara and Pyle 2012), which if databased, could provide the data needed to address large-scale hypotheses. An effort to connect Lepidoptera collections in the US began in 2016 with LepNet: a group of 27 US collections, which aims, in part, to database and georeference label information for 1.7 million specimens, a third of the collections' total holdings (Seltmann et al. 2017). This sample represents most US states and the 86 lepidopteran families occurring in North America. However, details of the distribution and numbers of specimens collected in specific time periods and areas of the US are unknown, both because of inadequate sampling effort and incomplete label data associated with specimens. As observed in other specimen-level datasets, the spatial and temporal distribution is likely uneven (Malaney and Cook 2018). This uneven spatial and temporal distribution has been noted in global inventories and observation records of Lepidoptera species (Girardello et al. 2019). Declines in collecting efforts observed across many taxa in part explain contemporary gaps in collection records and specimen distributions (Gardner et al. 2014). Also not widely documented is the profession of the collector; naturalists and non-professional systematists have made great contributions to science and collections (e.g., Alfred Russell Wallace) (Vetter 2011). However, their impact and significance as compared to professionals have not been quantified up until this point. Anecdotal evidence, combined with analysis of the A.J. Cook Arthropod Research Collection in Chapter Two, suggests that their impact is significant (e.g., Hallmann et al. 2017), so understanding their role in documenting lepidopteran diversity is pertinent. This is especially true in the midst of an observed decline in amateur interest in the natural sciences (Hopkins and Freckleton 2002). Because of the overall declining trend in specimen collecting, documented in numerous other studies, including Chapter Two of this thesis, we predict that Lepidoptera collecting as a whole has not been consistent over time, space, and collector profession. Thus, the collections held in many institutions may not be truly representative of the natural world. As such, this study describes the patterns of lepidopteran collecting in the US since the mid 1800s as reflected in one million LepNet databased specimens. It also tests for correlations between patterns of collecting and collector profession and trends of lepidopteran interest in an effort to explain the observed patterns.

Methods

Data associated with 1,405,997 databased Lepidoptera specimens housed in 75 US insect collections were downloaded from the Symbiota Collections of Arthropods Network database (SCAN-bugs.org), accessed 16/05/2019. Using the 'tidyverse' R package (Wickham 2018), the collection data were revised to include only specimens that were collected in the United States between 1800 and 2018. These 1,031,401 specimens were used to determine the number of collection events per year and the collection locality at state level. The package 'ggplot2' from the 'tidyverse' suite of R packages was used to generate all graphs. A rolling decadal average and standard deviations (also on a rolling decadal basis) for annual collecting events were calculated using the 'TTR' package (Ulrich 2018).

The base R statistics package and ggplot2 (Wickham 2018, R Core Team 2019) were also used to test for a statistical difference between the data from states with LepNet participants and states without institutions funded through LepNet. We used a single data.frame of state names, specimens collected per square kilometer, a categorical variable to indicate if the state has a LepNet institution and the log10 of the specimens/km^2 value for each state. A one-sample Kolmogorov-Smirnov test was used to determine if the specimens/ km^2 data represent a normal distribution (ks.test where x is specimens/km^2 and y is pnorm). This was not the case and the data are heavily skewed, so the Central Limit Theorem does not apply. The data for states with and without a LepNet institution were compared using a Kruskal-Wallis one-way analysis of variance.

To understand potential reasons for the observed collecting activity, we compared membership information from the Lepidopterists Society with the Lepidoptera collection data using the base R statistics package and ggplot2. This was conducted using two data.frames, one for LepSoc membership data (year joined, year paid through) and one for Lepidoptera collection events per year. The Lepidoptera collection data were trimmed to fit the membership data from the Lepidopterists' Society (LepSoc), which was founded 1974 and whose data terminate at 2016 for new memberships. LepSoc membership and Lepidoptera collection datasets were compared using a two-sample Kolmogorov-Smirnov test to determine if the number of members added per year was drawn from the same distribution as the number of collection events per year. This would indicate a strong relationship between a major entomologists' society and collecting activity.

In addition, valid specimen records were sorted by collector name and year, and were tallied to generate a specimen count per year for each collector. Collectors were identified as professional or non-professional by reviewing institutional records of associated collectors and using Google searches of names on the Internet. Collectors were considered professional if they held positions as university professors or as collections staff in an institutionally-held natural history collection. The top 10% of collectors—both professionals and non-professionals—in terms of specimens collected were then compared using repeated Mann-Whitney-Wilcoxon tests for each decade in the between 1963 and 2009 on a sliding window basis of highest total collection effort using the base statistical package in R. This top 10% of collectors represented 80.89% of the total number of specimen records.

We limit our inferences and conclusions of the analyses for collector data to the years prior to 2009 because of a potential 10-year lag for the curation of recently collected specimens (discussion with participants of Entomological Collections Network 2018). That is, specimens collected in 2009 are mostly likely to be curated, identified, and available for databasing by 2019. Percent lepidopteran family composition was also calculated for the data.

Results

Our initial review of the national LepNet data removed 26.64% of the specimen records because of erroneous collection years, non-US countries of origin, collections not in US states, or non-lepidopteran families. The single year with most collected specimens (23,319) was 1996. For the last couple decades, there has been a general decline in annual collection events of Lepidoptera in the United States. This decline has become more prominent in recent years, decreasing from nearly 20,000 specimens in 2010 to less than

10,000 specimens collected annually since (Figure 3.1). Nationally, the most collected family of Lepidoptera was the Noctuidae (16.29% of total) followed by Geometridae (13.47%), Erebidae (12.98%), and Nymphalidae (9.42%) (Table 3.1).

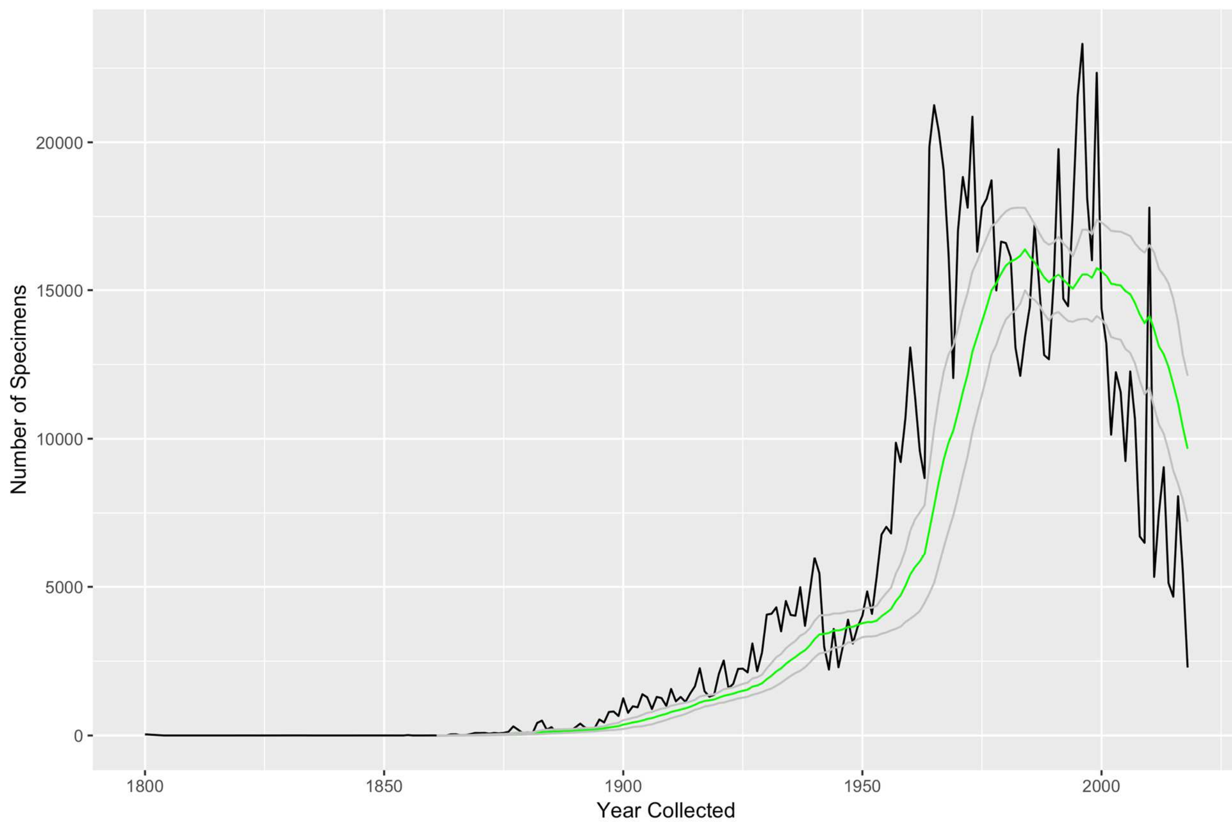

Figure 3.1: *Specimen collection events per year since 1800 in institutional collections across the United States. The green line is a rolling decadal average, and the grey lines represent a single standard deviation from this average on a rolling decadal basis.*

Table 3.1: *Counts and percentages of specimens from represented Lepidoptera families*

Family	Count	Percentage
Acanthopteroctetidae	25	0.002
Acrolepiidae	3	2.909 e -4
Acrolophidae	104	0.010
Acrolophilidae	2	1.939 e -4
Adelidae	427	0.041
Agonoxenidae	13	0.001
Alucitidae	121	0.012

Table 3.1 (cont'd)

Apatelodidae	613	0.059
Arctiidae	235	0.023
Argyresthiidae	267	0.026
Attevidae	598	0.058
Autostichidae	745	0.072
Batrachedridae	98	0.010
Bedelliidae	73	0.007
Blastobasidae	1037	0.101
Bombycidae	14	0.001
Bucculatricidae	882	0.085
Carposinidae	102	0.010
Choreutidae	234	0.023
Coleophoridae	803	0.078
Copromorphidae	85	0.008
Cosmopterigidae	2009	0.195
Cossidae	874	0.085
Crambidae	36734	3.562
Ctenuchidae	3	2.909 e -4
Dalceridae	36	0.003
Depressariidae	4476	0.434
Doidae	62	0.006
Douglasiidae	7	6.787 e -4
Drepanidae	1507	0.146
Dryadaulidae	88	0.009
Dudgeoneidae	78	0.008
Elachistidae	188	0.018
Epermeniidae	264	0.024
Epicopeiidae	1	9.696 e -5
Epiplemidae	2	1.939 e -4
Epipyropidae	101	0.010
Erebidae	133831	12.976
Eriocraniidae	251	0.024
Euteliidae	1417	0.137
Galacticidae	124	0.012
Gelechiidae	19544	1.895
Geometridae	138908	13.468
Glyphipterigidae	255	0.025
Gracillariidae	2951	0.286
Heliodinidae	130	0.013
Heliozelidae	196	0.019
Hepialidae	376	0.036
Hesperiidae	95941	9.302
Hyblaeidae	1	9.696 e -5

Table 3.1 (cont'd)

Immidae	24	0.002
Incurvariidae	31	0.003
Lacturidae	229	0.022
Lasiocampidae	4587	0.445
Lecithoceridae	39	0.004
Libytheidae	82	0.008
Limacodidae	4768	0.462
Lycaenidae	59375	5.757
Lymantriidae	61	0.006
Lyonetiidae	52	0.005
Meesiidae	23	0.002
Megalopygidae	1231	0.119
Micropterigidae	6	5.817 e -4
Mimallonidae	220	0.021
Momphidae	392	0.038
Nepticulidae	356	0.035
Noctuidae	168016	16.290
Nolidae	2947	0.286
Notodontidae	12908	1.252
Nymphalidae	97016	9.415
Oecophoridae	1578	0.153
Opostegidae	74	0.007
Papilionidae	31562	3.060
Phyllocnistidae	1	9.696 e -5
Pieridae	67394	6.534
Plutellidae	533	0.052
Praydidae	26	0.003
Prodoxidae	475	0.046
Psychidae	706	0.068
Pterolonchidae	6	5.817 e -4
Pterophoridae	2357	0.229
Pyralidae	13065	1.267
Riodinidae	2585	0.251
Saturniidae	17640	1.710
Satyridae	30	0.003
Schreckensteiniidae	115	0.011
Scythrididae	335	0.032
Sesiidae	5885	0.571
Sphingidae	26468	2.566
Strathmopodidae	3	2.909 e -4
Symmocidae	2	1.939 e -4
Thyatiridae	40	0.004
Thyrididae	377	0.037

Table 3.1 (cont'd)

Tineidae	7510	0.728
Tischeriidae	313	0.030
Tortricidae	50546	4.901
Tridentaformidae	10	9.696 e -4
Uraniidae	192	0.019
Urodidae	252	0.024
Xyloryctidae	2	1.939 e -4
Yponomeutidae	943	0.091
Ypsolophidae	258	0.025
Zygaenidae	628	0.061
N/A	31	0.003

The number of specimens collected per square kilometer in states with a LepNet institution is drawn from a different distribution than the same metric in states without a LepNet institution (P = 0.005694). In other words, the LepNet and non-LepNet states are statistically different populations. Overall, there is a dearth of specimens collected throughout the middle of the United States, especially the states composing the Great Plains (Figure 3.2). For the vast majority of the fifty states, less than one half of a specimen has been collected and databased per square kilometer (Figure 3.3). Other states that are particularly lacking sampling of Lepidoptera include Alaska, Nevada, Kentucky, and Virginia. The states with such low numbers of specimens per square kilometer are mostly those without an institution participating in LepNet; specimens may exist in collections, but they have not been added to the SCAN database. If specimens from states that are underrepresented in the SCAN sample were in collections that are not databased, this would potentially change the pictured spatial distribution of US Lepidoptera in a significant way.

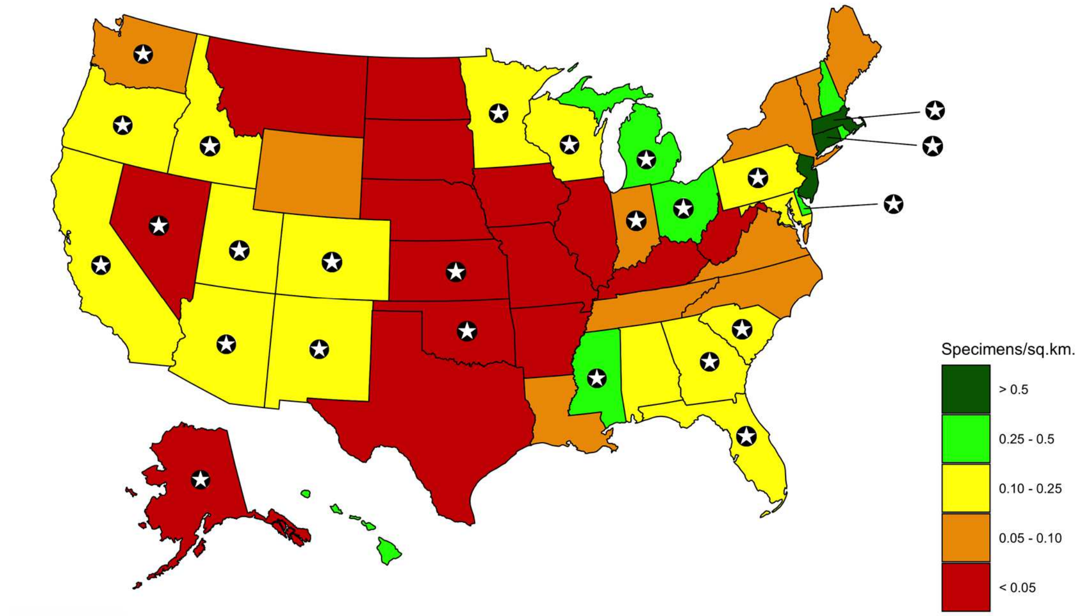

Figure 3.2: *National distribution of Lepidoptera specimens held in institutional collections across the country normalized by state area in square kilometers. States marked with a star have at least one institution participating in LepNet.*

The number of collectors who joined the Lepidopterists' Society between 1947 and 2016 is pulled from a different distribution than the number of specimens collected per year over the same time period ($P < 2.2$ e -16). There is not a significant association between Lepidoptera Society membership numbers and the number of specimens collected for each year. We also compared the collection efforts of avocational and vocational collectors over time. The total number of specimens collected by avocational collectors was 487,152 in the top 10% of collectors, which is more than the 346,740 collected by vocational collectors (Figure 3.4). The overall collection efforts of avocational collectors were significantly different from that of the vocational collectors ($W = 74549054$, $P = 0.01111$).

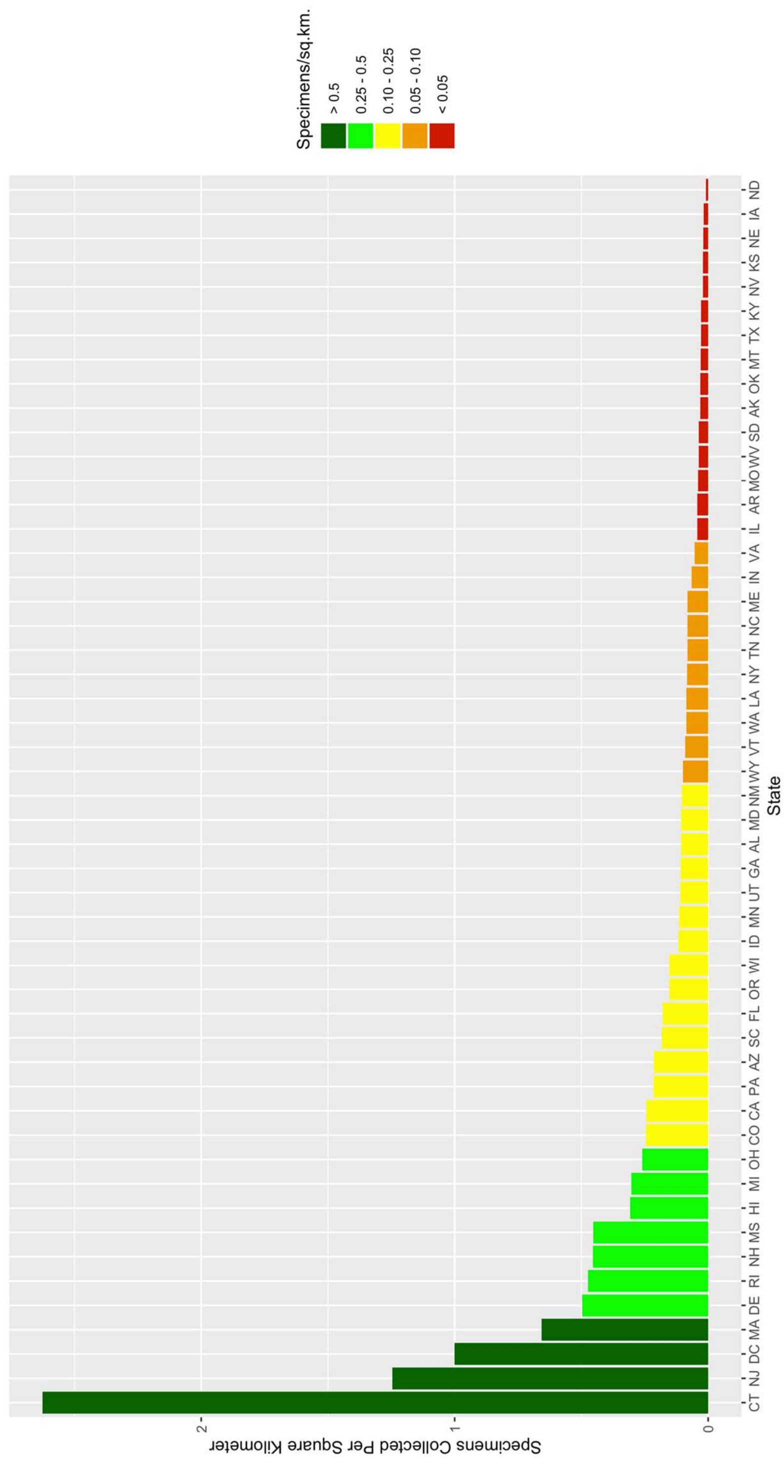

Figure 3.3: *Graph of Lepidoptera specimens held in institutional collections across the country normalized by state area in square kilometers.*

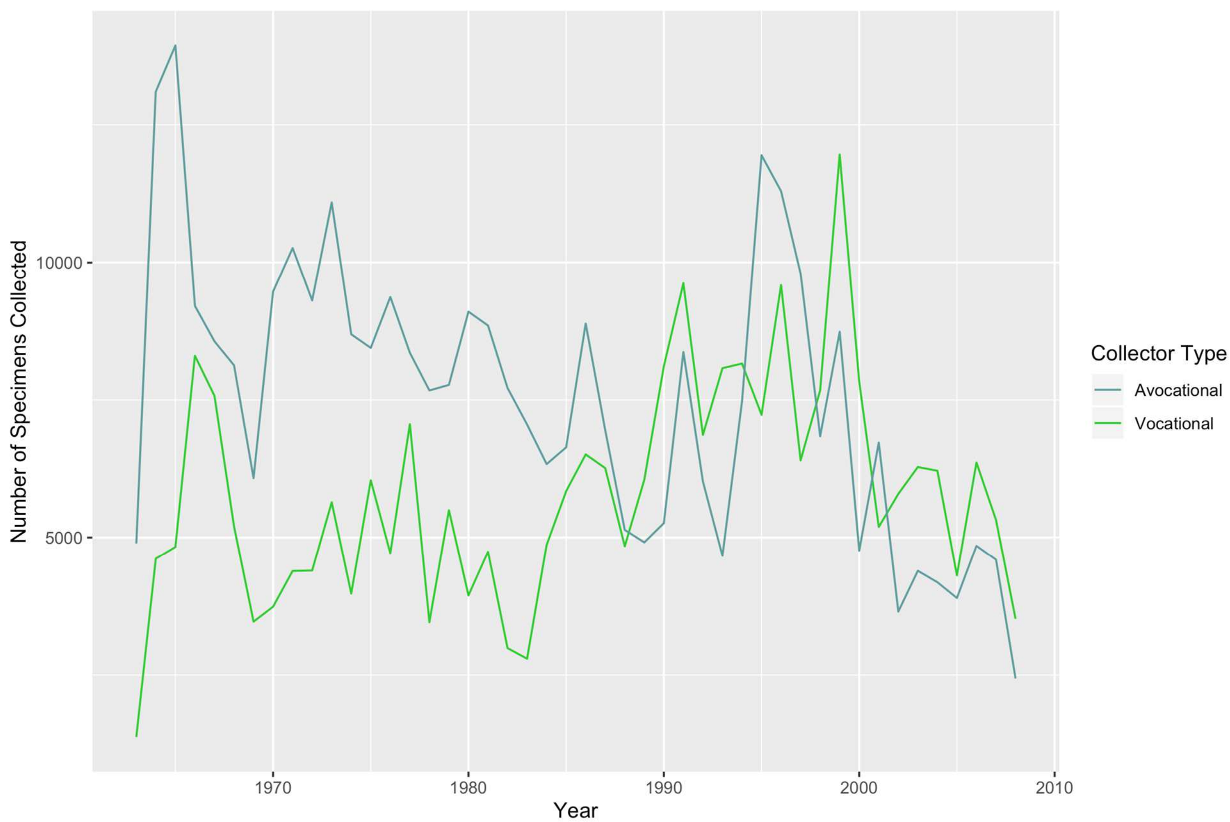

Figure 3.4: *Avocational and vocational specimen collection events, 1963-2008*

Between the years of 1963 and 1989, there was a significant difference between the numbers of specimens collected by avocational as compared to vocational collectors (Table 3.2). After 1989, there was not a statistical difference between the collecting effort of avocational and vocational collectors (Table 3.2).

Table 3.2: *Avocational vs. vocational collectors: comparison of specimen numbers by decade*

Year Range	P-value	Interpretation
1963-1972	0.0002879*	Significant difference
1964-1973	0.0002879*	Significant difference
1965-1974	0.0002879*	Significant difference
1966-1975	8.227 e-5*	Significant difference
1967-1976	4.114 e-5*	Significant difference
1968-1977	8.227e-5*	Significant difference
1969-1978	4.114 e-5*	Significant difference
1970-1979	4.114 e-5*	Significant difference

Table 3.2 (cont'd)

1971-1980	4.114 e-5*	Significant difference
1972-1981	4.114 e-5*	Significant difference
1973-1982	4.114 e-5*	Significant difference
1974-1983	8.227e-5*	Significant difference
1975-1984	0.0001645*	Significant difference
1976-1985	0.0002879*	Significant difference
1977-1986	8.227 e-5*	Significant difference
1978-1987	8.227 e-5*	Significant difference
1979-1988	0.0004936*	Significant difference
1980-1989	0.00399*	Significant difference
1981-1990	0.09391	No difference
1982-1991	0.3401	No difference
1983-1992	0.8633	No difference
1984-1993	0.4894	No difference
1985-1994	0.3865	No difference
1986-1995	0.3865	No difference
1987-1996	0.5457	No difference
1988-1997	0.8633	No difference
1989-1998	0.8633	No difference
1990-1999	1	No difference
1991-2000	0.6665	No difference
1992-2001	0.8633	No difference
1993-2002	1	No difference
1994-2003	0.9314	No difference
1995-2004	0.5457	No difference
1996-2005	0.3865	No difference
1997-2006	0.1359	No difference
1998-2007	0.06253	No difference
1999-2008	0.06253	No difference

Discussion

In the past 150 years, there has been a significant increase in specimen acquisition with a peak in 1996 followed by an apparent decline in collecting events across the United States (Figure 3.1). This decline in collection events is most prominent in the last 15 years. The more than 1 million specimens are not evenly distributed across the United States (Figure 3.2). There is a significant difference in the number of databased specimens between states that have at least one institution associated with LepNet and those that do not, suggesting that the database is geographically under-sampled. Avocational collectors have contributed more specimens to institutional collections than vocational collectors (Figure 3.4). However trends in their collecting are not significantly associated with membership in Lepidopterists' Society. Overall, there is a significant difference between the two groups but for some periods in the last 65 years, the efforts of avocational and vocational collectors varied.

Given their aesthetic appeal, Lepidoptera are potentially the most collected insect group throughout history. The appeal of Lepidoptera may inspire people to start collections, regardless of whether or not such collectors become professional entomologists or remain hobbyists. Overall, the collection of 17 million US specimens (Seltmann et al. 2017) relied in part on the efforts of amateurs and those in the process of acquiring scientific training. Collections of butterflies and moths may reflect the best dataset of ecologically important insects available to scientists, although their numbers in space and time are not evenly distributed.

The geographical gaps in collecting are striking (Figure 3.2). Most of the states are represented by < 0.5 specimens/km^2. In part, this maybe an artifact of state size—larger states require more specimens for a similar proportion of specimens as compared to smaller states. For example, though the Kenelm Philip collection of over 83,000 arctic Lepidoptera specimens (Bakker 2014) is included in SCAN, Alaska is still represented by less than 0.05 specimens/km^2 due to its sheer size. In other cases, a lack of funding for databasing correlates with fewer databased specimens. For example, no Texan institute was part of LepNet (Seltmann et al. 2017), and only 360 specimen records collected in

Texas from Texan institutes exist in SCAN database. In contrast, the Texas A&M Insect Collection houses the Roy Kendall Lepidoptera collection, which contains approximately 100,000 specimens from the southwestern United States (AgriLife Today 2004). Funding for databasing this collection alone would have a significant positive impact on documenting the geographic occurrence of southwest Lepidoptera, though it would likely not have a significant effect on overall trends in collecting activity.

The accumulation of US specimens greatly increased in the years following World War II. Following the establishment of the GI Bill, the number of years men spent in postsecondary educational levels increased by an estimated 15-20%. Nearly 70% of men who turned 21 between 1940 and 1955 attained a college education for little to no cost (Stanley 2003). Many veterans who made use of the GI Bill studied the sciences (Bennett 1996, Altschuler and Blumin 2009), and were likely inspired to continue collecting as a hobby and the addition of their student collections to institutional collections may have contributed to overall collection growth.

According to the US Department of Education, 11% of undergraduate students starting in academic year 2003-2004 declared a biology major at some point between 2003 and 2009 (Chen 2013). College attendance is, in general, on the rise; enrollment in the fall semester was 12% higher in 2016 than it was in 2006 (Snyder et al. 2019). The actual completion of bachelor's degrees is also on the rise, including in the fields of agriculture and natural resource fields, with a 29% growth from 2010-2011 to 2015-2016, through growth in health-related fields is more than double that of agriculture and natural resources (Snyder et al. 2019).

Despite this growth, undergraduate biology majors are overwhelmingly choosing further education outside of biology. In the academic year 2015-2016, 73,700 doctoral-level degrees in health profession-related fields were granted in the United States as compared to 7,900 doctoral degrees in biology and biomedical sciences (Snyder et al. 2019). Given that relatively few students are pursuing advanced studies in biology and natural science, these ongoing educational shifts have serious implications for the growth of institutional collections. Though college attendance is on the rise, comparatively few students are choosing fields where collections would be emphasized, decreasing potential levels of natural history training and eagerness to collect.

The accumulation of specimens shows significant recent declines (Figure 3.1). Though Lepidoptera collecting increased dramatically from the late nineteenth century through the 1970s, collection events have plummeted since the late 1990s and this trend has become more pronounced from 1999 to 2009 (Figure 3.1). Lepidoptera collecting is not alone in this decline; many herbaria have also hit a peak in annual specimen collection events (some of those peaks occurring in the 1990s) before declining dramatically (Prather et al. 2004a). This decline may be associated with the number of students studying the natural sciences at the undergraduate college level; by 1990, interest in a number of scientific majors had greatly declined (Green 1989). This trend in post-secondary educational choices, particularly in fields relating to natural history, continues today—both at the undergraduate and graduate level—and likely impacts the growth of natural history collections (Tewksbury et al. 2014).

The decrease in Lepidoptera specimen collecting has the potential to greatly impact future research studies by limiting temporal data and geographic locations represented for any given species of butterfly or moth. Historical collections document environmental conditions and species distributions at a particular place and time. Over time, such collections become more and more valuable sources of information to researchers, as the collections become increasingly irreplaceable and arguably more meaningful in studies dependent on a long timescale. Malaney and Cook (2018) used such historical collections of mammals to investigate collection and accession efforts for mammalian specimens over time and across the United States; they reported a decline in such efforts over the last couple of decades. Compared to mammals, insects are easier to collect, requiring relatively less preservation effort and few to no permits. Despite the ease and appeal of collecting lepidopterans, declines in insect collecting follow those observed in many areas of biology that have historically added many biological specimens to museum collections (Prather et al. 2004a, Gardner et al. 2014). The continued existence of specimens and collection records has many implications for the biological sciences; there are many areas of research that will depend on specimens into the future, including uses for these data that we cannot predict or foresee (Heberling et al., in press).

Continued collection of biological specimens is critical for a greater understanding of biodiversity and environmental change (Prather et al. 2004b). Through the efforts of avocational and professional entomologists, historical collections of biological specimens provide the data to track changes in patterns of biological diversity (Hill et al. 2014; Lubar 2017; Short et al. 2018; Heberling et al., in press). The availability of collection and specimen information in public databases allow researchers to a) observe morphological features in imaged specimens, preventing potential damage through the transfer of specimens among institutions and hastening the description of insect biodiversity before it is lost, and b) to use large amounts of data to describe broad trends often with statistical significance (Short et al. 2018). For example, skilled German amateurs were the first to quantify a continuing decline in insect biomass based on decades of saved samples from traps, and various scientific institutions in Europe are also making use of avocational entomologists to attempt further study into steep rates of insect decline (Hallmann et al. 2017). Professional scientists have also identified such trends over the course of their fieldwork (Lister and Garcia 2018).

The importance of research into the natural history of organisms—long considered to be a hallmark of the amateur—has recently come to light despite a decades-long decline in such efforts (Tewksbury et al. 2014; Heberling et al., in press). In some cases, this decline has been linked to a lack of funding for research into the natural history of organisms and a coinciding decline in the teaching of skills needed for natural history in university settings (Tewksbury et al. 2014, Hiller et al. 2017). Given that less than 2% of institutionally-held insect specimens have been databased (Short et al. 2018), there is a need for increased maintenance, growth, and accessibility of natural history collections. In the United States, there is limited funding to support natural history collections, despite the need for curatorial staff, digitization of specimen records, and space (Dalton 2003, Prather et al. 2004b, Snow 2005). This dearth of funding greatly impacts aspects of biological research that rely on geographical and time series data and often excludes additional and rare data from smaller collections (Snow 2005).

Our results suggest urgency for continuation of funding for databasing of museum specimens and greater engagement of the public in collection-based sciences. Without the availability of specimen data to researchers—particularly data pooled from multiple sources and an increase in specimen acquisition to pre-1990 levels—investigations into many areas of critical concern to the biological sciences will, at best, be stalled for an unknowable amount of time.

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